Gaspare Galati

100 Years of Radar

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To Rossella and Claudia

Foreword to “Cent’anni di Radar” by Benito Palumbo

To those who have been so lucky as to participate continuously and intensely in the developments of radar technologies and their applications, inevitably the question arises about the suitability of a heavy commitment for writing a new book on the history of radar, while the international literature (both technical and historical) is rich in valuable, well-documented books on this subject, as well as of numerous papers in reviews and magazines.

I indirectly found an explanation when reading in the text some considerations by the author about the previously published material. As a matter of fact, this material does not always provide a comprehensive representation of the phenomenon of evolution of radar technology, but, rather, is very frequently focused on contributions by single nations or by single bodies, either national or local. This, absolutely legitimate, approach unfortunately suffers from a point of view that one could define as mainly “local pride-based” (*campanilistico*) and with limited scope.

Instead, the present volume aims to offer a balanced representation of the contributions by various countries and by industrial, governmental, and research organizations, with an assessment of the events that appear to be significantly free of constraints and biases. As far as the Italian contribution is concerned, the book provides a framework of events, people and involved organizations much richer than that, very limited, of the foreign literature, especially in the case of Anglo-Saxon authors.

The book also contains a significant amount of information and a number of absolutely new images, collected from documents and witnesses that have not appeared previously in the literature. The style of the story reflects the well-known spirit of the Author, i.e., lively, rigorous, and sometimes hypercritical, who can boast in the field of radar technology a deep expertise, deriving from its industrial experience of radar systems’ analyst and designer, followed by large and demanding activities of research and university teaching. Not only does the book contain the story of important events and scientific objectives and industrial achievements, but also it analyzes the conditions and particular characteristics of environments that have allowed the extraordinary speed of evolution of the technology and of the operational capacity of radar, in all the broad spectrum of its applications. This is why the book is also a story of people having a vision to explore new ways and a lively passion for their area of activity, without neglecting the story of decisions that have sometimes affected some promising developments or hindered addresses and solutions that were accepted and confirmed only later. The author, through direct evidence of some remarkable, top-level persons, players of the development of the science and art of radar, has been able to make live and fascinating, almost as a novel, the history of radar and of the contexts that have fostered, but sometimes also delayed, its development.

In the book, which in no way neglects the technical and scientific factors, there are no purely technical discussions of the evolution of radar technology intended only for experts in the field; conversely, the representation of the intertwined stories of persons, academic institutions, companies, and research centers, to which the extraordinary pace of its progress and the achievement of some fundamental results are due, prevails. The characters and the events are described with a wealth of accuracy, highlighting the dynamics of relationships, comparisons between different positions, and their impact on the most relevant decisions.

The text begins with discoveries and experiments that provided the basis of operation, the early developments and the subsequent evolution of radar technology, clearly showing the leading role of research. From the initial pages, the role played by persons from the scientific and technical world that understood how to use the propagation of electromagnetic waves for localization and identification of distant objects is highlighted. It is shown how the period of the Second World War saw an impressive increase of the speed of evolution of radar technology in all involved countries, but also how, in the following years, the evolution proceeded at high speed. It is interesting to notice, within the succession of events as described in the book, how many technical solutions and fields of application were abandoned when there appeared insufficient consolidation for immediate use and were successfully included only later.

The multiplicity of technological areas involved in the realization of radar systems has required, from their origins, a high degree of integration and interactivity between the various actors, and I find that this aspect is correctly highlighted in the book by referring to those organizational solutions that have proved to be the most effective for design, implementation, and management and that have characterized the successes in the evolution of radar. In all of this, the Author acts as an expert guide with a “wide angle” vision throughout the events that have marked the development of radar up to now. However, the story is not finished, and I think that with this book, a window is open with a fascinating view on the future developments of this beautiful, technological adventure.

Rome
May 2011

Benito Palumbo

Preface

This book is an updated, reviewed and shortened English version of *Cent'anni di radar* (Aracne, 2012—Roma) whose motivation and content are discussed in the pertaining Introduction that follows. After the success in Italy of that book, it became clear that it would be useful to present most of its material (with some needed updates) to a wider public through an English edition. Of course, because of its international, rather than Italian, target, as well as of the need to limit the dimension of the book, *100 Years of Radar* is not a mere translation into English of *Cent'anni di radar* but, rather, a new book made up of ten chapters versus twelve in *Cent'anni di radar*. In addition to the classical footnotes, a number of endnotes (labeled [..]) constitute an "eleventh chapter" containing many elements that can be skipped at a first reading. An extensive list of references for further reading and an alphabetic index of the names of the cited persons complete this book. The general structure of the book is the following Chap. 1 describes the birth of radar (1904), both as a concept and as a demonstrating prototype, due to the young Christian Hülsmeyer, an "unlucky inventor" whose life is compared with the one of his contemporary "lucky inventor" Guglielmo Marconi. Research and radar developments in Italy (1935–1943) are described in Chap. 2, in a discussion including the main principles for the benefit of "non-specialists", while the simultaneous and independent developments done, under strict secrecy, in the other nations are synthesized in Chap. 3. The ensuing Chap. 4 analyzes the Air Defense, a powerful drive to the development of effective, long range radar sets, starting with the British "Chain Home"; as described in Chap. 5, the drive became very strong with the uprise of the Second World War, leading to the microwave era by the invention of the cavity magnetron, and to the development of a huge number of land, sea and airborne radars. Chapter 6 is fully devoted to the airborne radars, needed for night bombing and night fighting. The post-war Italian radar situation is narrated in Chap. 7 with the help of the memoirs of some key persons, while the very relevant space-based, synthetic aperture radar (SAR) is treated in Chap. 8. The most impressive recent radar developments are treated in Chap. 9, and Chap. 10 is devoted to the system integration of the radar, which in some future could disappear as an autonomous entity.

This work has been made possible thanks to the wonderful cooperation by the Springer staff, as well as by the professional and continued effort by Sergio Pandiscia, better described at the end of the following *Introduction*.

Rome
May 2015

Introduction to “Cent’anni di Radar”

This introduction contains three main elements: first, a brief mention in the genesis of this book and its location in the specific literature; second, a brief description of its structure; finally, the sincere thanks to all those who made it possible, or facilitated, the complicated work of preparation of the book (without prejudice to the always possible, involuntary omissions, for which the author apologizes).

The opportunity to write a historical book on radar[1] (with particular attention to Italy, whose role in the international literature—and in particular in the Anglo-American one—has been, and is, regularly neglected or even fully ignored) was the initiative of the new monograph on the history of telecommunications, published in two volumes by Firenze University Press, with a chapter by this Author entitled “The development of radar in Italy and abroad.” The significant amount of discovered original information and the interesting points highlighted in the course of writing this chapter led the Author, in 2010, to start preparing a whole book, entitled “Cent’anni di radar.” The main driving factor of this initiative is due to the considerations that follow. From 1945 to today, countless books and conference proceedings more or less closely related to the historical development of radar have been published. Most of them are by English or American authors, for the obvious rationale that they are from the winners of the Second World War, in which radar had an important role (and according to many people, a fundamental and decisive one). This vast literature ranges from volumes oriented to the history

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[1] An essential property of radar is its ability to measure the distance of objects (the so-called *targets*) of interest; in English, the measurement of the distance (*Range*) is called *Ranging*, hence the acronym: Radio Detection And Ranging (RADAR, which today is often written in small letters and may be considered as a noun: *radar*, sometimes, *Radar*). The interested reader in radar technology, applications, and history may see the references at the end of the present volume.

of radar technology, among which are the remarkable books [Swo 86],[2] [RDN 04], and [Bla 04], a book in French published on the occasion of the centennial of the first patent on radar (2004), up to works oriented to the history of national developments, as in [Cas 87]—dedicated to Italian radar of the wartime period—or in [Pri 89] that contains interesting data relating to defense electronics and surface radar, and finally to the more recent [Wat 09], very rich and quite complete (unfortunately, its images are small and with low definition). Within the many texts dedicated to Anglo/American developments in the radar field, it is easy to find the absurd assertion that the British, with Robert Watson-Watt, invented radar, an old issue well-clarified in various documents, e.g., the open access document [Cla 97]. In most texts, it is claimed as (really, nonexistent) primacy of Great Britain in radar techniques; for example, on page 127 of [Gou 10] is found: “France, Germany, Japan and the US had each in their different ways investigated the detection of aircraft from reflected Electro-Magnetic waves … It was only in Britain that the significance of the technique was realized at the highest level.” As a matter of fact, many of these books are not free from partial visions and self-celebratory trends, present already in their titles and subtitles, as for example in the well-known [Bud 97], the history of the Radiation Laboratory of MIT, the cradle of radar in the USA, and in [Con 03] which tells the interesting story of the entrepreneur (and inventor of the Loran C), Alfred L. Loomis, and his private research center in Tuxedo Park, near New York. Finally, [Bow 87] and [Lov 91] describe developments in microwave airborne radar, while probably, the most ancient book in this series is [Row 48].

With the notable exception of [Wat 09] and [Swo 86], two books dedicating an average of nearly five pages—synthetic but reasonably complete—to Italy, in nearly all historical volumes produced in the English-speaking world the Italian contribution is nearly ignored. As an example, [Bro 99], a volume of nearly six hundred pages, cites developments in Italian radar in only ten lines, skipping over the EC 3/*Owl* and other Italian industrial radars. Moreover, there are a very few books in the Italian language on the development of radar, and particularly on the Italian developments. These are [Mus 90] and [Dav 90] dedicated to air navigation, but rich in news also on radar, and finally, [Lom 04] dedicated to the history of the Selenia/Alenia/AMS and their Fusaro (Napoli) plant. Finally, we mention [Mar 09], a publication dedicated to one significant figure connected to the high tech and radar industry in Italy, Carlo Calosi.

Summing up, the historical texts on radar can be divided into two main categories (but in reality, there are many intermediate cases between them): (a) applications-oriented, mainly related to the Second World War, and (b) oriented to equipment and related technologies. Moreover, there are a few interesting works that make up a possible third category, that of memories of protagonists, often, but not always, written by the players themselves. In reality, the history of radar

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[2] The reader who is not expert in radar techniques may read Chap. 2 of [Swo 86], useful, clear, concise and rigorous.

is also a story of people who have developed, over the course of more than a century, this complex technology. Therefore, in addition to "historical applications" and "historical technological" works, there are those linked to the "people and their actions," a history not only individually but also choral, i.e., of groups and organizations.

In the present volume, once the choice had been made to avoid a strictly technical discussion, interesting only a limited number of specialists, it was decided to try to give priority to the third aspect. However, theories, techniques, and applications, which constitute the very reason for the development of radar, are not neglected: in the second chapter, the description of the *Owl* by Ugo Tiberio is also used to introduce the most basic, not avoidable, knowledge related to radar. Therefore, it is hoped that this book will be appreciated by non-experts in radio and radar and "even" by specialists. The discussion is by no means strictly chronological; many of the chapters, in fact, are dedicated to particularly significant elements such as a person (or group of people), a fact, an application, or an implementation.

In this frame a needed, sincere thanks is due to the companies (specifically: IDS Ingegneria dei Sistemi, Rheinmetall Italy, SELEX Sistemi Integrati and SELEX Galileo (now, Selex ES), GEM Elettronica, and finally Thales Alenia Space, Italy) which have provided useful material, especially photographs, as well as to individual researchers such as Edoardo Mosca for supplying data and images on the development of the first Italian Phased Array radar. A significant contribution of images and data for the 1930s and 1940s comes from the National Museum of Science and Technology "Leonardo da Vinci" through several persons of great availability and courtesy to which goes a heartfelt "thank you" (i.e., Fiorenzo Galli, director of the Museum; Giovanni Cella, scientific coordinator—who made possible the research by the Author in the historical archive of the Museum—Laura Ronzon, responsible for the historical heritage; Paola Redemagni, referee of the historical archive; Paola Mazzocchi, library director; and finally Carlo Pria, advisor to the Museum and secretary of the AIRE—Italian Association Radio d'Epoca). For other important contributions in terms of images, often rare, the Author is grateful to Erminio Bagnasco, director of the Publishing House Albertelli's Project Special Editions s.r.l.; to Fabio Zeppieri, coordinator of the AIRE for Rome and Lazio; to Ian White, Author of "The History of Air Intercept Radar & the British Nightfighter 1935–1959" [Whi 07]; to Francesco Caltagirone from the Italian Space Agency; and finally to Franco Iosa for the ATC console. With regard to the first Italian radar, the *Owl*, and to its Author Ugo Tiberio, many elements (data, images, original documents) were kindly provided by his son, Professor Paolo Tiberio, whom I would like to thank sincerely and cordially. In the course of the research on the history of "Radiotelemetri (radar) Italiani," during the last global war, the Author was able to contact Donatella Castioni, daughter of Luigi Carilio Castioni, who for about twenty years has carried out research on the subject; to her and to his brother Pier Angelo, a heartfelt thanks to you for having granted the rights of reproduction of the main job of their father. A sincere thanks also go to Prof. Giovanni Carboni for the data about the company SAFAR and its ing. Castellani, and to dr. ing. Paolo Tellini and dr. ing. Lorenzo Fiori for information on the company FIAR. In addition, a heartfelt thanks to my friend dr. ing. Andrea Adriano De Martino, colleague in the industry for many years, who has carefully and kindly reread the “almost final” version of the entire book indicating some necessary corrections.

Finally, a heartfelt “thank you”—certainly not least in importance—is due to Sergio Pandiscia from the *Tor Vergata* University of Rome, who took care of all the various, never easy, aspects of “editing” including research, collection, storage of images (and related copyright problems), and graphical realization of different drawings and schematics, needed to finalize the volume in its final form. Really, the contribution of Sergio Pandiscia was wider and of more quality than expected. The correction of several errors, inaccuracies, and inconsistencies should be recognized to him, while the responsibility for the inevitable “residual” ones is entirely by the author.

Rome Gaspare Galati
October 2012

Contents

Abbreviations, Definitions and Symbols

A. I. (AI) Radar	Air Intercept Radar (airborne radar against air targets)
Aerial	Antenna (used until the 1940s)
AESA	Active electronically scanned array
AN	Armi Navali (Naval Weapons)
ASV	Air to surface vessel (airborne radar against surface targets)
ATC	Air traffic control
c	Speed of light in vacuum, 299 792 458 m/s, *circa* $3 \cdot 10^8$ m/s
CNR	*Consiglio Nazionale delle Ricerche*, National Research Council of Italy
COTS	Commercial off-the-shelf
CW	Continuous wave
DARPA	Defense Advanced Research Projects Agency: *DARPA mission is to prevent and create strategic surprise by maintaining the technological superiority of the US military*
DeTe (Dete, DETE)	Detector Telemetro, a name used in Italy, during World War II, for German radar apparatus
DGON	German Institute of Navigation
ECM, ECCM	Electronic countermeasures, electronic counter-countermeasures
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
ESAV™	Enhanced Surveillance of Aircraft and Vehicles
ESM	Electronic Support Measurements
FM	Frequency modulation
FM CW, FMCW	Frequency-modulated continuous wave
H2S (also: H_2S)	*Home Sweet Home*: code name of Anglo-American airborne radar for night bombing
IEEE	Institute of Electrical and Electronic Engineers

IFF	Identification Friend or Foe
IMST	Istituto Militare Superiore delle Trasmissioni (Guidonia, Italy)
IRE	Institute of Radio Engineers
LPI	Low Probability of Intercept (radar)
Marinelettro	Short for Mariteleradar (telegraph name)
Mariteleradar	Short name for *Istituto per le Telecomunicazioni e l'Elettronica G. Vallauri* ex R.I.E.C.—Livorno—Italy
MIT	Massachusetts Institute of Technology
MMI	Marina Militare Italiana (Italian Navy)
M.O.V.M.	Medaglia d'oro al valore militare (Golden Military Medal)
MTD	Moving Target Detector
MTI	Moving Target Indicator
NdA	Note by the author
PPI	Plan Position Indicator
PRF (prf, p.r.f.)	Pulse repetition frequency
R	Range, i.e., distance of the target
R. Marina	Regia Marina (Italian Navy)
RCS (r.c.s.)	Radar cross section
R.I.E.C.	Regio Istituto Elettrotecnico e delle Comunicazioni della Marina Militare Italiana (see also: Mariteleradar)
RaRi (Rari)	**Ra**diotelemet**Ri**
RaRo (Raro)	**Ra**diotelemet**Ro**
RDF	Radio Direction Finder (used in the UK before 1943 instead of Radar)
RDT (RdT)	Radio Detector Telemetro (Radiotelemetro)
RSRE	Royal Signals and Radar Establishment (UK)
STAP	Space-time adaptive processing
TRE	Telecommunications Research Establishment
TRL	Technology Readiness Level
TWT	Traveling wave tube
UAV/UAS	Unmanned air vehicles/Unmanned air systems
W, kW	Watt, kilowatt
α	Bistatic angle
θ	Azimuth
λ	Wavelength
σ	r.c.s., *radar cross section*
μV	Microvolt

Chapter 1
The Unfortunate Inventor and the Lucky One—The UR-RADAR, Early Apparatus

1.1 The "Unlucky" Inventor

The definition of "unlucky inventor", referring to the engineer Christian Hülsmeyer from Düsseldorf, must be understood only in relative terms[1]: Hülsmeyer was much less lucky, in terms of acceptance of his invention (the environment was not yet ready to accept it) and hence, in terms of economic results, than the seven years older Guglielmo Marconi.[1] Although less known to the general public than Marconi, Christian Hülsmeyer[2] is, however, celebrated in the radar community[3] as the undisputed inventor of radar, thanks to filing the patent n. DE 165546[2] (see Fig. 1.1), entitled "Telemobiloskop", on April 30th, 1904. The patent describes the system developed by Hülsmeyer to detect the presence of metallic objects: the principles of radar are clearly described in it. As a matter of fact, in the claims it is written: "An apparatus that transmits and receives Hertzian waves, suitable to indicate, or give alarm for, the presence of a metallic object such as a ship or a train, in the direction of transmission of said waves", and later: "My invention … can be understood by imagining, in a given place, a transmitting station and a receiving one, side by side, in such a way that the waves transmitted by the former can activate the latter only if reflected by a metal object, which, at sea, can reasonably be another ship … My apparatus includes a transmitting station and a receiving one similar to those used in radio-telegraphy, with the difference that these two stations are very close to each other and are arranged in such a way as not to be able to directly influence each other …" where it is evident that

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[1] Bologna, April 25th, 1874—Rome, July 20th, 1937. On Guglielmo Marconi there are several biographies, for example: [Sol 11] and [Par 08], in addition to Web sites www.fgm.it, http://www.radiomarconi.com/ and http://www.marconicalling.co.uk/.

[2] A few months later, it was replaced by the equivalent patent DE 169154.

G. Galati, *100 Years of Radar*, DOI 10.1007/978-3-319-00584-3_1

the desire to differentiate the invention from the patents by Guglielmo Marconi, who had created a de facto monopoly in radiotelegraphy.

In addition, the patent shows the need for movement of the antennas in such a way as to cover the entire angle around the ship in order to avoid collisions with other vessels; to this purpose, the patent includes a system for continuous rotation of the antennas, and for an indication of the pointing angle, the forerunner of the modern "planimetric" indicators PPI, Fig. 1.2.

Well aware of the problems due to the roll and pitch of the ship, the inventor proposed a suspension of *cardanic* type—clearly visible in Figs. 1.1 and 1.3—for the entire apparatus, so as to keep its horizontal orientation.[3]

He also considered the option of sheltering the apparatus with electromagnetically transparent material to protect it from external factors: a sort of *ante litteram* Radome. According to memories of Holsmeyer's daughter, collected by Pritchard [Pri 89], the external event which led the inventor to seek a means to prevent collisions between vessels, even at night or in fog, was the despair of a mother whose son died in a collision between boats on the Weser river. Anyway, on May 5th, 1904, a few days after the patent was filed, the Society "Telemobiloskop-Gesellschaft Hülsmeyer and Mannheim" was formed[4]: the 22-year-old inventor, demonstrating a tenacious desire to develop and exploit an industrial product, made an agreement with Heinrich Mannheim, a trader from Cologne, who contributed 2000 marks. A first presentation and demonstration of the new collision detection system—with a nominal useful range between 3 and 5 km—was organized on May 17th in the courtyard of the prestigious Dom Hotel Cologne, with the presence of representatives of the main shipping lines and of some insurance companies.

The trials[5] were described in the local press on the following day, and even in the New York Times on May 19th and in the english "Electrical Magazine", as claimed by Hülsmeyer (but there are no documents to support this). The trials and demonstrations continued on the Rhine River, under the old Dombrücke,[6] very close to the Dom Hotel: at the passage of a boat, a bell connected to the receiver tolled. These results generated the interest of the director of the Holland-America-Line, Mr. Wierdsma, who, as an organizer of the *Technical conference on the safety of sea navigation* on June 9th, 1904, asked Hülsmeyer and Mannheim to participate

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[3] Mechanical stabilization of the platform of the antenna is normal in the current naval radar. Exceptions are: the navigation radars, with a wide enough antenna beam in the vertical plane, and the Phased Array ones, where the roll and pitch compensation is done electronically.

[4] Vice versa, according to a document found by A.O. Bauer, the company was established on March 15th, a few weeks before the filing of the patent. Anyway, on August 12th, 1904, a banker from Hannover, Hermann Gumpel, joined the society.

[5] According to one of the participating persons, Koelner Tageblatt, the demonstration consisted in detecting the reflections of the radio waves by a metal grid, a few dozen meters away from the apparatus; the detection occurred even when the grid was covered by a tent or was behind a wall of bricks, and caused the lighting of a lamp or a mechanism that detonated a cartridge.

[6] This bridge, also called Fester Brücke, was replaced in 1911 by Hohenzollern Brücke, cited by Pritchard.

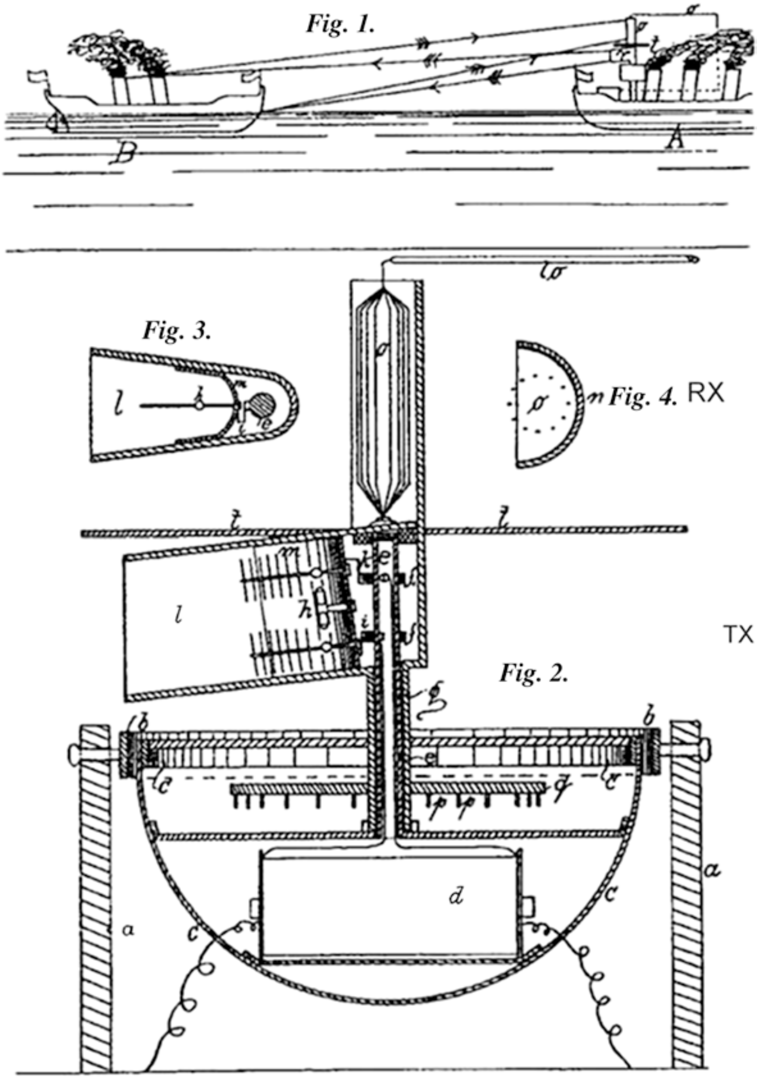

Fig. 1.1 First page of the patent 165546 by Hülsmeyer, 1904

by presenting the invention.[7] The demonstration, held in Rotterdam on June 9th, with the apparatus installed on the river ship Columbus, was a success. However, it is not clear what range was actually achieved, even if some of the publications indicate 5 km. After the conference in Rotterdam, Hülsmeyer and associates sought to

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[7] As a preliminary condition, the patent had to be extended abroad, with the high cost of 23,000 marks, according to the memories of Hülsmeyer’s daughter, Annelise.

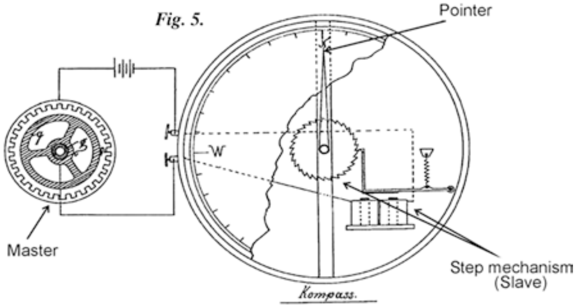

Fig. 1.2 From Hülsmeyer patent: indication mechanism of pointing angle and synchronism with a rotating platform

answer the correct objection of the lack of measurement of the distance, and applied for another patent, no. 169154, accepted on November 11th, 1904 (see Fig. 1.3). It should be added that the enterprising Hülsmeyer sought to involve also the military authorities, who, as happened in other nations, had not reacted positively: Admiral Von Tirpitz did answer indignantly to the young inventor "our Services have better ideas". Basically, a great interest from the Navies did not follow this discovery, given that it lacked (and would be missed until the 1930s) an urgent requirement. Not even the shipping companies—i.e. the first commercial target for Hülsmeyer—expressed any interest, and some UK delegates showed a clear and preconceived hostility. This commercial failure led Hülsmeyer in a short time to close the company (on October 11th, 1905 the name Telemobiloskop-Gesellschaft Hülsmeyer and Mannheim was cancelled by the register of the Chamber of Commerce of Cologne)[8] and to look at other areas in which to apply his creativity, which he did with effectiveness as described in his biography, reported in detail in the Endnotes.

The story of the unfortunate inventor could end here, but for the purposes of the history of radar it is interesting to try to analyze, as it was done by Pritchard [Pri 89], Bauer [Roh 05], and others, the possible causes of this specific failure, which, from the available documents and collected memories, is of a commercial rather than technical-scientific nature. A list of reasons follows; it is necessary to specify that it is based on logical and technical deductions rather than on any precise documental evidence:

1. distrust of possible customers about the technology which seemed not yet mature enough to bring appreciable results (radar, as compared to radio communications systems, require a much higher transmission power due to the "fourth power law" propagation in free space);
2. lack of interest in potential military applications, considered non-urgent and with low priority (specifically, the time was the *Belle Époque* in which Europe seemed to enter an indefinite period of peace and progress);

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[8] In the Proceedings of the second "Nautical Meeting" conference in London, in 1905, there appears the laconic note: "The Telemobiloskop: a new trial at the Hook of Holland has been a failure…" and later it is claimed—without explanations—that the principle of operation of the apparatus is erroneous.

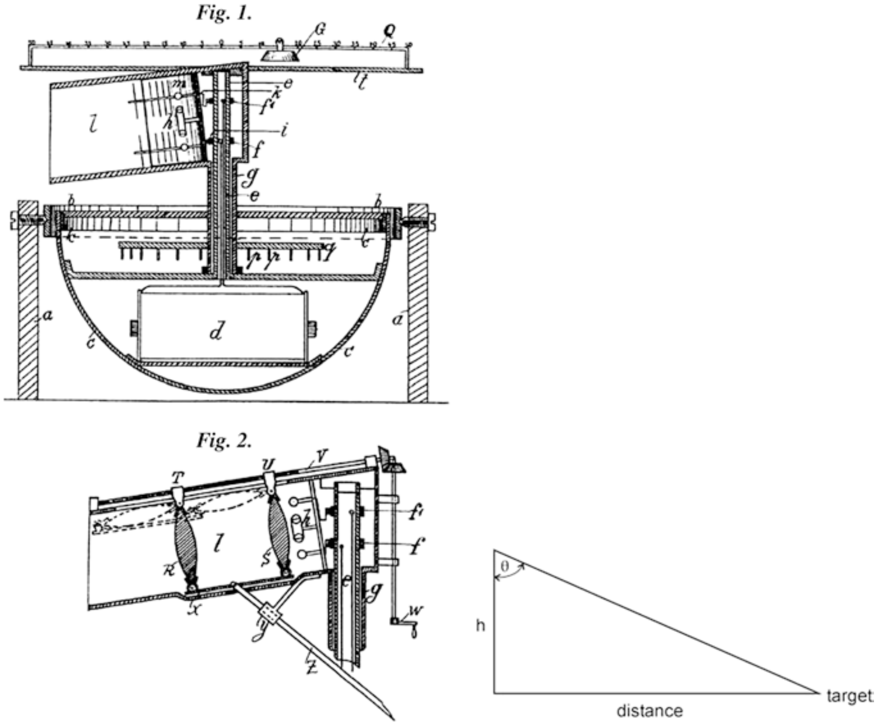

Fig. 1.3 Measurement of the distance in the radar of Hülsmeyer, from patent no. 169154, which replaced no. 165546

3. hostility of ship-owners who had already installed the radiotelegraph by Marconi and did not intend to bear other expenses[9];
4. hostility of the Marconi Company, who did not wish to have competitors even in a complementary field of navigational aids, and, in addition to items III and IV,
5. lack of frequency selectivity of the Telemobiloskop (today defined as “broadband” equipment), with the risk of disturbing other radio applications, first of which was radiotelegraphy. Some patents[4] prevented the application to the Telemobiloskop of the natural solution to tuning a transmitting antenna on a given wavelength.

Therefore, even if there is no evidence of any direct contact between the unlucky inventor, Hülsmeyer and the lucky one, Marconi, the third, fourth and fifth point above may show, at least conceptually, an indirect conflict between them, with a winner and a loser. The very complete and well-documented reconstruction by

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[9] This type of problem, in general, exists even today, for maritime transport and for aviation.

Prof. A.O. Bauer,[10] reported in pages 13–57 of [Roh 05], shows two elements that are normally ignored by—virtually all—Italian authors, who, for a kind of national pride, are, in their majority, "pro-Marconi *no matter what documents say*". These elements are (a) the patents mentioned in the fifth point above, and (b) the following, from pp. 47 to 48 of [Roh 05][5]:

> "…The Marconi Company tried, with all means, to monopolize the wireless industry world. They began with claiming anything connected to the transfer of electromagnetic waves (EM). To the objection that certainly was not him which invented the Hertzian waves, he (Marconi) responded by saying that his wireless system was not based on Hertzian waves, but on waves of a different kind."

At this point, Bauer quotes a piece from Chap. 2, p. 39 of the book [Sun 01] by the historician Sungook Hong[11] which discusses the wireless, from Marconi to the first valve:

> … the term "waves by Marconi" was coined and advertised and Marconi approved it. In an interview with McLure's Magazine, Marconi observed that "his" wave (emitted) from a vertical antenna was something different from that of Hertz. He (Marconi) claimed that its wave could penetrate virtually everything.[12]

1.2 The "Lucky" Inventor

The unlucky inventor, as we have seen, completely abandoned the radar area in 1905 looking for a different road, and did find it. Nobody spoke about its demonstrations of the Telemobiloskop for many years. As a matter of fact, an urgent operational requirement (either military or civilian) for radar was still in its infancy. Vessels were devoid of instruments capable of detecting and reporting obstacles with fog or at night. A well-know consequence was the disaster of the Titanic: on April 15th, 1912 at 02:20 AM the transatlantic ship Titanic, a pride of the British Navy, during its maiden travel, hit an unseen iceberg, filled with water and sank.

Summing up, until the 1920s a great deal of interest in radar as an industrial product was missing.

Guglielmo Marconi proposed the concept in a speech[6] at the *American Institute of Electrical Engineers* and *The Institute of Radio Engineers* on June

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[10] He is the author of documents of rare completeness and remarkable technical and scientific value, among which [Bau 92] and [Bau 04], as well as a lot of historical material available on websites such as www.cdvandt.org, very rich in information on the history of German technology (radio, radar, navigation).

[11] Currently, Professor of History and Philosophy of Science at the National University of Seoul (comenius@snu.ac.kr).

[12] Here, it is not surprising to find the following judgment by A.O. Bauer (hard, but perfectly justified) that follows the quotation: "No further comment is available to prove Marconi's arrogance and his scientific incompetency".

Fig. 1.4 The monument to Nikola Tesla in Zagreb, Croatia

20th, 1922, repeated in an article [Mar 22] in the same year. As a matter of fact, this famous speech, partly exposed here in Endnote, says nothing new with respect to the experiments, publications and patents by Hülsmeyer and, indeed, contains several elements that seem to be taken from the documents of Hülsmeyer, including: naval use, a screen between the transmitter and the receiver and, finally, the lack of any need for radio equipment on board. Moreover, the same concepts had been clearly exposed five years before by another “unlucky inventor”: the celebrated Nikola Tesla (July 10th, 1856—January 7th, 1943), see Fig. 1.4.

In fact, Nikola Tesla, in an article on *The Electrical Experimenter* published in August 1917, anticipated the use of radar. He wrote[13] “…we may produce at will, from a sending station, an electrical effect in any particular region of the globe; we may determine the relative position or course of a moving object, such as a vessel at sea, the distance traversed by the same, or its speed…”.

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[13] A further sign of the profound “anthropological” difference between a lucky inventor and an unfortunate one is the following: the 1922 speech by Marconi is cited in most books on radar while the 1917 paper by Tesla on The Electrical Experimenter is almost never mentioned!.

Marconi himself was not interested in any topic connected to radar for a long time after his 1922 speech, precisely until 1933 when, doing experiments with a radio link[14] between the Vatican City and Castel Gandolfo, Marconi reports having noticed some rhythmic disturbances in the receiver, and having discovered that they only occurred when a gardener was skimming, with a mower with metal roller, the grass of the meadow in front of the balcony on which the transmitting antenna was placed, and entered, with its to and from movement, in the beam of waves emitted by the transmitter. It has to be added that about this particular fact and those that follow this "discovery" there are different versions, all vague and inaccurate[15]; also on the wavelength used there is no consistency of the various sources, in which it varies from 45 to 90 cm. More important, these phenomena already happened years before to other experimenters. Between the former interference phenomena emerge those analyzed by Albert Hoyt Y. Taylor and Leo C. Young in September, 1922,[16] due to the passage of a wooden vessel, the Dorchester, on the Potomac river, south of Washington, which created the well-known sequence of maximum and minimum intensity on a radio link side-shore on the 5 m-long wave. In his report on September 27th, 1922, Taylor prefigured the use of interferences (beats) to detect enemy ships passing through the line joining the transmitter to the receiver: a kind of radio-barrier working on the interference between the direct wave and the reflected one.[17]

More generally, and strangely enough, it is not easy to find historically rigorous documents about Marconi's achievements, and even less about Marconi and radar. In fact, the literature, and particularly the one in the Italian language, is flooded by texts in which celebration totally prevails on correct and documented information. However, by some sources (including [Mon 91], [Par 08] and the Web Site of the English Marconi company) it is said that in January, 1935 Marconi ordered for the *Officine Marconi* of Genoa a small transmitter on the 50 cm wave length and a receiver, and that with them, some "radar" experiments were conducted by Marconi together with his assistant Solari on April 15th, 1935. The experimental area was around the *Centro Radioelettico Sperimentale* of CNR in *Torre Chiaruccia* (on the northern coast close to Rome, in the town of *Santa Marinella*). Unfortunately, about all the aforementioned experiments the author has not been able, in spite of many researches, to find additional explanations. Marconi's

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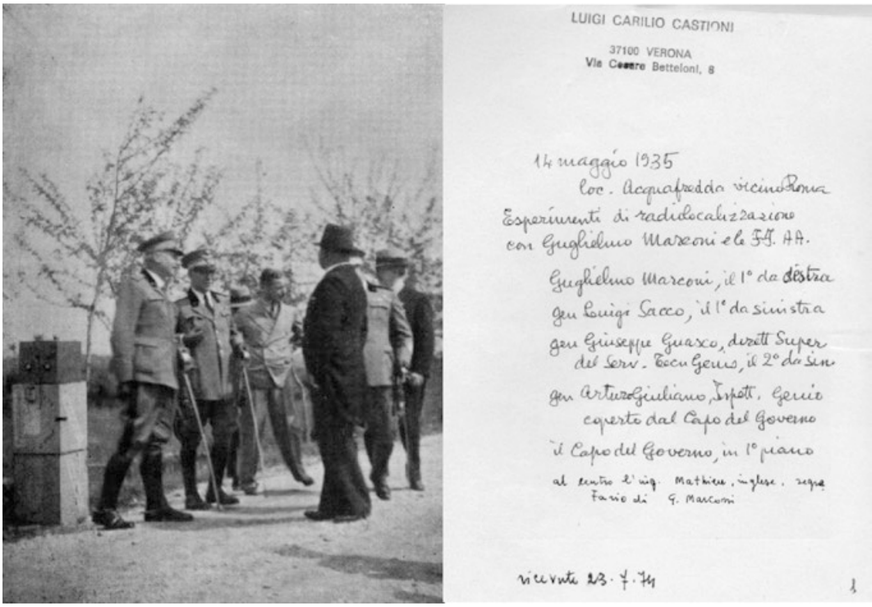
[14] According to [Cas 87], the phenomenon was noticed by Marconi in 1932, according to others, in 1933.

[15] According to other sources, the gardener did not scythe but, rather, was carrying some gravel with a metallic wheelbarrow. [Swo 86] speaks of the "rhythmic modulation of the monitoring signal" the cause of which is attributed to a steamroller (and then, to an obstacle so much greater than a mower and a wheelbarrow).

[16] That is, as much as 11 years before the Marconi's observations at Castel Gandolfo/Vatican.

[17] The first detection of aircraft with this technique, i.e. "Bistatic—continuous wave", took place in France (Pierre David) on June 27th, 1934, as well as—in the period 1934/1936—in Ukraine (Kharkov) and in the United States. See Chap. 3 for more details.



LUIGI CARILIO CASTIONI
37100 VERONA
Via Cesare Betteloni, 8

14 maggio 1935
loc. Acquafredda vicino Roma
Esperimenti di radiolocalizzazione
con Guglielmo Marconi e le FF. AA.

Guglielmo Marconi, il 1° da destra
gen Luigi Sacco, il 1° da sinistra
gen Giuseppe Guasco, dirett Super
del Serv. Tecn Genio, il 2° da sin.
gen Arturo Giuliano, Ispett. Genio
coperto dal Capo del Governo
il Capo del Governo, in 1° piano
al centro l'ing. Mathieu, inglese, segre
tario di G. Marconi

ricevute 23. 7. 74

1

Fig. 1.5 One of the two photos (front and back) that document the experiments of Marconi in the *Acquafredda* site

daughter, Degna Marconi Paresce, tells us [Par 08] that Marconi said to his driver to go slowly back and forth, a couple of km in both directions along the coastal road that was visible from Torre Chiaruccia, while Solari and Marconi alternated at the receiver and at the transmitter, keeping the projector constantly focused on the car. The story continues: "Every time the beam of microwave struck the car they were reflected causing a hissing sound, as … between the Vatican and Castel Gandolfo"[7]. Other Marconian experiments concerning the possible detection of cars and pedestrians took place in *Acquafredda* (near Rome) on May 14th, 1935, in the presence of Gen. Arturo Giuliano, Gen. Prof. Luigi Sacco and the head of government, Benito Mussolini. The experiments were repeated on May 17th, 1935 on the Rome-Ostia highway and on May 20th, 1935 (according to [Pou 60] the dates are different: May 16 and 17) on Via Boccea—Rome. In addition to some amusing echoes in the press of that time, with no significant information, only two photos remain, one of which is shown in Fig. 1.5.[18]

Although the experiments in Acquafredda, like the others related to Marconi's "radioecometri", should have to be maintained secret, a delegation such as the

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[18] Examined by the author in Milan, in the archives Castioni/SAFAR at the National Museum of Science and Technology "Leonardo da Vinci" in Milano, these photographs (reproduced also in [Cas 74b]) have the date of May 14th, 1935 written on the back.

one shown in the photos taken on May 14th, (Fig. 1.5) of course attracted several journalists. Some of them came to speak about a new Marconi's "death ray". Probably they misunderstood as charred by the radiation from the apparatus built by Marconi the remains of a sheep that in fact seems to have been grilled for lunch by some shepherds in the *Agro Romano*, the country area close to Roma. After the diffusion of this news, Marconi wrote a refutation, which was published, curiously, not in the Italian press, but in the New York Herald Tribune.

The apparatuses "Radioecometro" by Marconi (whatever they may have been; reasonably, radio bridges modified to operate as Bistatic, continuous wave radar, or microwave barriers) were, in any case, nothing new at that time. It must be remembered how, on May 1935, the electromagnetic barriers had been tested in various countries, including France and the Soviet Union, since more than one year. In the USA Hyland and Young had observed since 1930 the *beats* due to the passage of an aircraft, with a demonstration made by A.H. Taylor on December 1930, and an IRE publication by C. Englund et al. in 1932, see [Bla 04], p. 410. These "Radioecometri" were still looking back to the experiments of Taylor and Young (1922) and Gutton (1920s) and operational systems held since 1934 in France, in the former Soviet Union and the United States of America, as discussed in detail in the third chapter.

To complete the picture of the experiments started in 1935 by Marconi (it is known that he died two years later) two elements must be added, a personal and a technical-operational one. Concerning the first: that year Marconi was in precarious conditions of health, with a strong reduction of his remarkable ability to experiment; in fact, the heart disease that Guglielmo Marconi had in common with his brother Alfonso and with their father, as evidenced by a serious crisis in 1928, worsened in 1933 (Marconi did the well-known trip to Brazil in 1935 against the advice of his physicians). Second element: the "Radioecometri" of Marconi were proposed to solve the "ill posed problem" of the detection of land vehicles or troops. This was practically impossible at those times, due to the lack of highly stable frequency generators and being not yet invented the function of suppression (MTI canceller) of disturbing echoes due to stationary objects (such as soil, vegetation etc.).[19] Vice versa, as it was well understood in most nations, the real problems were initially two: the defence of a nation against attacks from the air (national air defence: see Chap. 4) and the naval defence[20] (see the very clear *incipit* of the "rediscovered manuscript" by Ugo Tiberio in Chap. 2). Therefore it is not surprising that Marconi's experiments, despite the presence of Benito Mussolini at least one of them, had no following, if not perhaps that of stimulating the general Sacco (Chap. 2) to transfer Ugo Tiberio (who never met Marconi) at the Academy of Livorno starting the de facto development of Italian radar. So the

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[19] In this regard, the interested reader may see the exemplary explanation of the "Radiotachimetro" in [Tib 45].

[20] Soon, a third problem was added, i.e. the use of radar on board an aircraft for defence, attack and bombing.

circle may close here with what is shown in Chap. 2. The needed final remark is that for indisputable historical reasons, the claim—found in various, mostly Italian sources—that the presence of the secretary of Marconi, ing. Gaston Mathieu from the English Marconi company (see Fig. 1.5) allowed the concept of radar to be transferred to the British government, and hence the development of the Chain Home, remains totally false as it will be discussed in greater detail in the following. As matter of fact, the secret memorandum by Robert Watson-Watt that was submitted to the Rector of the Imperial College of Science and Technology on February 4th, 1935 and the first experiments in Daventry, with detection of a bomber of the RAF using signals transmitted by the BBC, occurred in February 1935, about three months prior to the experiments carried out by Marconi. For those who are able to read the Italian language, the following documents are interesting, even for sociological reasons: [Pou 60], [Ban 60], [Ban 64], and the long paper by Luigi Carilio Castioni [Cas 87] with much news about the Italian Radiotelemetri (radar), published in 1987 on Storia Contemporanea[21] and untraceable to the common public.

After a careful exam of the available sources, and barring any denials (unlikely but still possible) it is possible to conclude this chapter with a result of the *negative* type which is not obvious (and, to the best of the author’s knowledge, never published before): the contribution to the development of radar by Guglielmo Marconi, as a researcher, as a practitioner and finally as an industrial leader was, for the various reasons shown, entirely negligible, or null. Vice versa, the company he founded made a significant industrial contribution to development of the first British radar: on December 1935 the British government ordered from the Marconi company transmitting antennas of the first five ‘*Chain Home*’ radar stations which allowed coverage of the estuary of the River Thames and possible airways toward London. The receivers and the display units were commissioned to Cossor Ltd and the transmitters to Metropolitan Vickers: on May 1937 an order for a further 20 stations was issued. The Marconi company was also very active on radar after the war, as shown in the following.

Conversely, the “positive” side of radar developments in Italy thanks to the work of a few, but highly valuable researchers and technicians, the first of which was Ugo Tiberio, is shown in the following chapter.

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[21] The review Storia Contemporanea (Contemporary History) was founded by Renzo De Felice and published until his death in 1997. The copies of Storia Contemporanea are not available as arrears through the publisher (Il Mulino) and are hard to find even on the used book market. [Cas 87] can be found in http://radarlab.uniroma2.it/stscradar/radar industriali.pdf, in an integral transcription without comments or corrections. However, we must add that in some places, the work reaches unreliable conclusions, which, however, are largely justified by the non-technical education of the author.

Chapter 2
The Owls and the Gufo. Birth of Italian Radar

Sous les ifs noir qui les abritent,
Les hiboux se tiennent rangés
Ainsi que des dieux étrangers,
Dardant leur oeil rouge. Ils méditent.
Charles Baudelaire

2.1 The Owls of Charles Baudelaire and the *Gufo* by Ugo Tiberio

The Owls, disturbing and mysterious appearances at night, for many centuries, since the classical age, have inspired many authors, in particular poets such as Baudelaire[1] who considers the Owls as witnesses of a meditative life whose imperative is "the fear of the tumult and of the movement" (*Qu'il faut en ce monde qu'il craigne/Le tumulte et le mouvenent*). From the second line of verse it is clear that the poet—an acute observer—noticed the habit (the only one amongst all nocturnal predator birds) for which in winter the Owls spend their days perched in a row on the same tree from which they go hunting in the evening. Baudelaire was also impressed by the fixedness and apparent depth of their gaze.[1] Very appropriately, a considerable Italian gave the name of *Gufo* to the radar he conceived and realized in the form of a working prototype.

The naval radar was the only means, used by the British and the Germans during the Second World War, which made naval combat possible at night. As explained below, none can claim the full and absolute paternity of any complex and significant invention, much less of radar; however, because of his studies and his achievements, Ugo Tiberio[2] is universally known as the *father of Italian*

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[1] Charles Baudelaire (1821–1867), "Les Fleurs du Mal", No. 67—*Les Hiboux*, first strophe.

G. Galati, *100 Years of Radar*, DOI 10.1007/978-3-319-00584-3_2

Fig. 2.1 The postcard printed for the commemoration day of Ugo Tiberio, October 24th, 1998

radar. He was commemorated on October 24th, 1998 at the University of his native city, Campobasso [SMM 98]. The postcard produced on that occasion is shown in Fig. 2.1. The first Italian naval radar, designed and implemented by Tiberio, subsequently became a series produced by industry with the name of *Gufo* (this name, most likely due to Tiberio himself, dates back to 1941).[2]

In this frame the best introduction to the *Gufo* in particular and to the surface and airborne radar in general can be found in the words written by Ugo Tiberio in 1936, in the so-called “Found Manuscript” following another (unfortunately lost) document which is considered to have been written by Tiberio in 1935. This 29-pages document handwritten by Tiberio and classified “Secret” is faithfully reported here (in a literal translation) in its main parts (some parts are omitted for the sake of brevity) in the “Annex” that follows. This manuscript was found by Paolo and Roberto, sons of Ugo Tiberio, in 1996 in their father’s home in Livorno:

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[2] Commemoration Day in Campobasso has included participation by the sons of Ugo Tiberio, Paolo and Roberto, by many representatives of the Italian Navy (MMI) and in particular of the RIEC (Mariteleradar), as well as by representatives from academia and the main national industries active in radar.

it was abandoned in a large case locked for a long time. It is reproduced in [SMM 98] both in photocopy and in a—not perfect—typewritten transcription.

2.2 Annex No. 1—The “Found Manuscript” by Ugo Tiberio, Livorno, 1936

<u>Secret</u>—Superior Military Institute for Transmissions—Ist Section
(Ing. Ugo Tiberio)

(a) Study on the possibility of using for military purposes the effects of reflection of ultra short wave.
(b) *Radiotelemetro* for night shooting from ship and aircraft, as well as for anti-aircraft shooting.

Summary: The possibility of using the effects of reflection that the ultra short waves undergo on obstacles is examined for the purposes of:

1° to detect, in open sea and in the context of the optical range, the presence of a ship invisible due to darkness or fog;
2° to measure the distance of the ship;
3° to determine its direction.

It is concluded that these three aims can be achieved, provided that the problem is appropriately set, and that it is possible to use the method even for the following other aims:

4° to refine (in visibility conditions) the measurement of the optical range finders on board of the ship;
5° to search aircraft;
6° to measure, from an airplane, its height above the ground;
7° to search a ship from an airplane for the purpose of torpedoing.

We describe two types of equipment suitable for this aim. We propose to perform an experimental research to ascertain whether, and to what extent, the theoretical deductions are true, and we indicate the method to be followed.

1° <u>Foreword</u>. The problem of night search of vessels and aircraft has been dealt with by infrared radiation, microwave and acoustic methods, with very poor results so far. The use of ultra short wave was not attempted, yet, because the effects of reflection from these waves did not appear, at a first sight, such as to enable their practical use. In fact the waves from a reflective obstacle such as a ship or an airplane go back to the transmitter with an intensity which is very small in comparison to that of the direct field in the immediate vicinity of the oscillator, so it is very difficult to detect them.

However, a careful examination of the question, and some data that I am collecting in the recent years, lead me to think that we can overcome this difficulty and use the ultra short wave also in order to measure the distance to the reflecting obstacle and estimate its direction. This method is suited to many, important military applications. In what follows, however, I am referring mainly to naval search, for which I have more data and that I studied in a special way on the invitation of S. E. Admiral V. De Feo, who has followed from the beginning the progress of this work with keen interest.

2° Value of the field returned toward the transmitter from a ship or an airplane, due to the effect of re-radiation and reflection.

The problem of determining the backscattered field from a ship hit by ultra short wave seems to have never been considered by R. Marina [*Italian Navy*], nor there is any treatment of it in the technical literature; therefore I have been forced to make a rough estimate, on the basis of experimental measurements made by those who have been involved in similar issues. Luckily, I could rely on reliable data, collected in a study by Trevor and Carter regarding propagation of waves along the surface of the sea, and in one by Seiler regarding the real re-radiation and reflection. I have shown in the Appendix the calculations and the considerations that I assumed to derive the values related to our problem.

I have also tried to perform the calculations in a purely theoretical way, but I feel that it is useless to report in this regard, since the values deducted in this way are very high, and it is wise not to rely on them.

In the following table probable values are shown for the field backscattered to the transmitter, on the assumption that the latter operates on the 2 m wavelength with a directional antenna beam and radiates a power of 1000 W, parallel to the surface of the sea. These values are listed in relation to the distance of the reflecting unit and to the nature and location of it.

Distance (metres)	Vessel—side view	Vessell—front view	Aeroplane
1000			2400
2000			600
5000	36,000	4500	90
10,000	900	120	22
20,000	30	7	5
If the transmitter radiates 100 watt in circular polarization the above values become:			
1000			80
2000			20
5000	1,200	150	3
10,000	29	4	
20,000	1		

(The considered vessel is a 10,000 tons cruiserl—field intensities are in μV/m)

It results from these values that, at the distances of interest in naval operations, the field would still be able to be detected with ordinary receivers, if it does not overlap the field that comes directly to the receiver from the transmitter, which is much more intense. In fact, with waves of the order of 2 m, it is difficult to prevent the direct field from reaching the receiver: in the best case, it is of the same order as that reflected, unless you strive with continuous reflectors of large size.

To overcome this drawback, microwave apparatuses ($\lambda = 18$ cm) have been proposed, in which they managed to achieve a directivity so perfect as to be sure that the receiver, in spite of being located close to the transmitter, receives the reflected field only. In this way a solution was reached; however it is not suitable, because the system has, for the given value of the wavelength, a small transmitted power, a poor sensitivity in reception, a limited field, a large size and the need for pointing, in such a way that little advantage is obtained with respect to the infrared optical devices.

I do believe that all of this depends on a poor statement of the problem. In fact, the reception of a weak field in the presence of a strong one remains virtually impossible until both fields have the same frequency, but, instead, it becomes extremely easy if the frequencies are different. From this observation results the principle that I expose here: "to take advantage of the time that the reflected wave employs in the return path to change the frequency of the transmitter". If the operation is such that, for example, the frequency deviation is of the acoustic order, the reflected signal can be detected by a simple beat with the direct one, as it happens in a common heterodyne telegraphic receiver. In this way, not only the direct field does not cause damage, but it is useful because it provides the necessary energy for "heterodyning" the reflection, and it is known that the reception, when takes place according to a scheme of this kind, assumes a sensitivity enormously greater than the ordinary telephone: for waves of the order of 20 m, 1 μV/m is enough for the commercial telegraph service. In the ultra short wave region, given the absence of interference, even less should suffice. It must be considered that in our case it is not to needed to receive telegraphy, but only to detect a constant hissing. In the ordinary telephony, on the other hand, we need fields of the order of 100 μV/m.

This observation makes the above tables of noticeable interest: in fact, it can be seen as, by using a transmitter power of 1 kW, it is perfectly possible to detect a cruiser, and even an airplane, at a distance of 20 km and beyond, and that a not much smaller distance can be reached on airplanes by transmitting 100 W with circular polarization. It is also interesting to note how the tables indicate an extremely rapid decrease of the reflected field as the distance increases, so that obstacles situated beyond the optical limit, such as the coastal mountains and the far out ships, do not backscatter energy in such a degree as to alter the detections.

If the intensity of the reflected fields, as calculated by me, are correct, it can be concluded that, <u>if the reception is made according to the heterodyne scheme, using the ultra short waves it is possible to determine the presence</u>

> of vessels and airplanes up to 20,000 m and beyond, i.e. to the distances that are of interest in naval tactics.

The Found Document proceeds with the following points, partly summarized here:

3° Principle of the *Radiotelemetro*

In this point Tiberio describes the possible waveforms to be used, substantially equal to that of a modern FMCW radar, i.e. in continuous wave (CW) frequency-modulated (FM) and the method for measuring the distance, which is proportional to the delay of the echo (according to the basic radar principle) by the factor (speed of light)/2, in practice 150 m for each microsecond of delay. Very wisely the 32-year-old Tiberio writes, with regard to the choice between the mechanical implementation and the electronic one (much more modern and his preferred) of the frequency modulation of the transmitted wave:

> The problem can be solved with artifices of the mechanical type (electrostatic microphones, capacitors kept in continuous motion) or of the electronic type (triodes that set on and off some reactive elements in the oscillatory circuit). In my preliminary report, presented to the Management of the Institute, I preferred an artifice of the electronic type, in order to avoid bodies in motion. But General Sacco has correctly observed that the mechanical solution, even though it may appear at a first sight quite critical, in fact is very simple and practical, and also has the advantage of an operating procedure more clear, while the one which I had preferred raises complicated questions relating to the theory of frequency modulation. On the other hand, it would be out of place to study complex schematics when the validity of the principle has still to be experimentally tested. It is therefore advisable to assign the electronic method to a possible second phase of the research, and to use, to vary the frequency, the system that, after all, is the simplest one: to rotate the capacitor of the oscillatory circuit. This method has already been used by the Radio Res. Board for the radio-atmospheric survey …

4° Schematic of the of the *Radiotelemetro*

Tiberio describes the detailed embodiment of the apparatus and suggests an experimental implementation for trials on coastal installation in the Institute (the RIEC, the Tiberio's Institute where he wished to do the trials, is on the coast of Tuscany):

> To translate into practice the principle outlined above, is needed:
>
> (a) a system of antennas;
> (b) an ultra-short, frequency modulated wave oscillator;
> (c) receivers;
> (d) devices for measuring the frequencies.
>
> Since the structure of these various elements should, in the case of mounting on a ship, be studied with special criteria that would complicate the description, for the sake of simplicity I prefer to refer to the experimental system that I propose to place on a coastal site for the execution of the preliminary tests. In the diagram enclosed here, these elements are marked with the same letters used to list them.

A description of the individual elements follows; it is noticeable the use of a single oscillator (with multiplications and divisions of its frequency) to generate both the transmitted frequency (Tiberio proposes a value of 100 MHz, i.e., a wave of 3 m, in the range of “ultra-short waves”) and the reference for the intermediate frequency conversion: a true coherent super-heterodyne transceiver, inherently little sensitive to any fluctuations in the base frequency. Tiberio concludes his report highlighting the need to measure the “re-radiation factor”, which we call today the “equivalent area” or “radar cross section” of the targets; having understood the difficulty to calibrate the radar, Tiberio correctly proposes to compare the measurements of real targets (vessels, airplanes) with those of simple objects, whose re-radiation is calculated theoretically:

> 5° Final Considerations
>
> The interesting opportunities dealt with in the present work essentially depend on the validity of the observations I have done about the intensity of the backscattered field from vessels and airplanes, and the ability to technically achieve, with the described procedure, a very high receiving sensitivity. As far as the principle of frequency modulation is concerned, it seems to me that there can be no doubt. Nor does it seem to me that the R. Marina and the R. Aeronautica [Italian Air Force] have never performed experiments and systematic measurements on backscattering. Therefore some research should begin by measuring the “re-radiation factors” of different types of vessels and airplanes, that I believe can be comfortably done with an experimental setup such as I have described before. So, I propose the following program:

1° Construction, by private industry, of the various components of the system (entrusting them to different firms for the protection of the secret). Mounting of them and tuning at the E. C. Institute of the Regia Marina in Livorno, to which I could be temporarily transferred.

2° Installation of the equipment on a coastal building, in a location next to areas in which many ships will pass, and a few destroyer boats and a few aircraft can also be available. Performing systematic measurements of re-radiation factors, deducing their real value by comparison with some simple re-radiating elements, whose characteristics can be calculated theoretically.

3° In the case that the said factors would prove to be able to allow the achievement of useful results, go to the study of a ship-borne system for the naval and anti-aircraft shooting, leaving it to other researchers to study the apparatuses for the anti-aircraft defense on the ground, for the search of the vessels by airplanes, etc.

I omit a report in detail about the issues related to anti-aircraft firing (**2**) both to avoid lengthening it, and because it seems to me to have said enough to explain to the Bosses the interest of new research about the problem of re-radiation.

Please bear in mind the desire by S. E. De Feo to see carefully examined reports which will be communicated with promptness to R. Marina as the present state of the work.

I wish to thank General Sacco for the useful criticisms made to my earlier report, and for his comment about the opportunity to prefer a mechanical way for the modulation.

27-4-936 XIV
Engineering Specialist
Head of the 1st Section
Ugo Tiberio

(**2**) In the field of anti-aircraft search, there are two very interesting possibilities: the measure of the height simultaneous with that of the distance, and the measurement of the speed of the target. In fact, the backscattered waves reach the receiver either directly or indirectly after being reflected from the ground: the difference between these two paths must give rise to interference effect with highs and lows of sound that allow us to measure it and to derive the height of the aircraft by means of geometrical relationships. To infer the value of the speed, it should be borne in mind that the tone perceived at the receiver side is the sum of that which would occur if the aircraft were immobile and that due to its speed, which has a frequency equal to twice the number of wavelengths that the aircraft travels in one second: since the latter value does not depend on the speed of the motor, it suffices to make two

> measurements with different speeds of the latter to obtain the speed of the airplane. Englund, Crawford and Mumford (Proc. I. R. E. 933 Vol. 1 p. 475) have already noted that an airplane passing along a link to ultra-short waves gives rise to beats.

At the point 5°—final considerations—a part is of particular historical interest: Ugo Tiberio, since 1931 engineer at the *Instituto Militare Superiore delle Transmissioni* in Rome, requests his transfer to R.I.E.C. in Livorno (the current Mariteleradar), which took place in the same year 1936.

The “Found Manuscript” does not end with the date and the signature by Tiberio: in an interesting Appendix, reported in [SMM 98], Tiberio analyzes the measurements by Trevor and Carter of the propagation of a 5 m wave above the sea, published in March 1933 in the IRE Proceedings (Vol. 21, No. 3) and the reflections of waves by metal plates studied by W. Seiler (*Zeitsehr für Hochfreq*., Vol. 37, March 1931, p. 79). The aim is to estimate reasonable values of the backscatter characteristics of targets such as ships and airplanes.[3]

Finally, attention should be paid to note (**2**) above. It contains two totally new concepts in Italy at that time: the measurement of the height of an aircraft and the measurement of its speed by the Doppler frequency, decoupling from the latter frequency the contribution of the distance.[3]

Summing up, in the manuscript by Tiberio most of the basic concepts and main technical solutions for the future radar are anticipated, including:

- the measurement of the distance in frequency modulated continuous wave (FMCW) systems by beating the reflected wave with the generated one;
- the superheterodyne receiver with a single reference oscillator, with the intermediate frequency being obtained by frequency multiplications and sums;
- the measurement of the radial velocity of the target via the Doppler frequency;
- the measurement of the height of an aircraft using the reflection on the sea surface[4] and, of even more recent interest,
- the use of two time delay measurements (via beats, in the FMCW mode) from two antennas located in different positions in order to obtain the azimuth angle of the target (a sort of *ante litteram* interferometer).

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[3] Tiberio paid much attention to the very fundamental concept of reflectivity of radar targets, today expressed in terms of “radar cross section”. He applied this concept to complex targets by decomposing them into elementary reflectors such as plates and wires. He emphasized the importance of the measurements of the backscattered field and of the calibration of the measurement setup with simple reflectors with known characteristics.

[4] This method is applied in modern radar systems for airborne surveillance such as the E2-C (Hawkeye).

Fig. 2.2 General Luigi Sacco

From the mention of the "Preliminary Report" read by General Sacco,[5] a remarkable person, "instigator" of the Italian radar (Fig. 2.2), it is clear that, likely at the end of 1935, Tiberio presented his "first" report in which the problem of radiometering and localization was theoretically developed and resolved, with calculations and an examination of the experiences abroad. That report, which of course was secret, shows, for the first time, the fundamental equation, which permits computation of the radar range. Unfortunately all traces of this document were lost, together with all the monographs of the *Gufo*, due to the war events.

In fact, because of the bombings, the RIEC was decentralized (together with the laboratory in the site Le Selci-Firenze for the development of the power tubes wherein prof. Nello Carrara[4] worked) in the—less exposed—Campo San Martino, in the town named Piazzola sul Brenta (Padova). In [Tib 79], Ugo Tiberio recalls that the numerous technical documents related to the *Gufo* were destroyed on September 9th, 1943, in Campo S. Martino. After the armistice of September 8th, 1943 the group of researchers was dispersed; the Naval Academy—and with it Tiberio, Carrara, Lombardini and others—, was transferred to Brindisi where, anyway, they created a small laboratory for teaching and research, which was equipped by using some radar equipment and electronic interception receivers recovered aboard an airplane abandoned at the nearby air force base. Professor Tiberio regretted more than once the loss of the documentation produced at the RIEC until September 8th, 1943, showing results ahead other researchers in the

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[5] Luigi Sacco (August 1st, 1883—December 5th, 1970), is the author of the celebrated "Manual of Cryptography" and is considered to be the "inspirator" of the Italian radar; at the time, he was chief of Transmissions in the "Direzione Superiore Studi ed Esperienze" of the military Engineering. In 1926, in order to characterize the antenna radiation at great distances, Sacco introduced the concept of *Cimomotrice* force, then used by Tiberio and Barzilai.

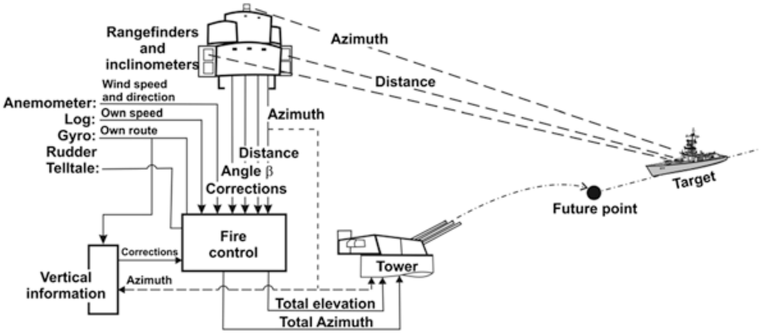

Fig. 2.3 Fire control system and naval telemetry

world. Fortunately, as already shown, in 1996 the members of the Ugo Tiberio family found a hand-written copy of this “second” report dated April 27th, 1936–XIV, a few months after the “first” destroyed report written in 1935. The “Found Manuscript” is currently saved at the Naval Academy in Livorno, after the solemn ceremony in which the son Paolo Tiberio delivered it to the Chief of Staff of the Navy, Admiral Guarnieri, in February, 2000. The very few R.I.E.C. documents, classified “secret”, that were not destroyed, including the “Found Manuscript” by Tiberio, made long laps: from Livorno they were transferred to Campo S. Martino (Padova) where the Naval Academy was transferred, and then to Brindisi, then back to Livorno.

The manuscript, as shown, is very interesting both under the technical-scientific point of view and under that of operations, i.e. the use of radar. The application part is summarized in the table of contents of the manuscript, where the following aims are listed:

1. to detect the presence of a ship, invisible due to darkness or fog,
2. to measure its distance,
3. to determine its direction.

Obviously the problem of naval combat was quite clear to Tiberio: in low visibility conditions it was impossible to correctly perform the classical procedures of (a) to detect an enemy ship, (b) to determine its direction and distance with optical means (naval rangefinder) (c) to calculate the aiming of the guns, (d) to adjust (tune) the shooting (gun laying), lengthening if the columns of water resulting from the projectiles were in front of the enemy ship, shortening in the opposite case. The rangefinders (see Fig. 2.3) by their own nature had an increasing error at increasing distances, just where accuracy was essential.

Tiberio concludes that these three aims can be achieved, and that the method can be used even for the following purposes:

4. to improve, in visibility conditions, the indications of the optical range finders of the Navy;
5. to detect enemy aircraft;

6. to measure, on board an airplane, its height from the ground;
7. to detect a ship from an airplane for the purpose of torpedoing.

In an almost prophetic way, Tiberio anticipates the air defense radar (item 5°), the radar altimeters (or radio-altimeters) (item 6°), and finally the airborne radar for actions (e.g.: torpedoing) against naval targets, those that will soon be called ASV: *Air to Surface Vessel*. Summing up, in these sentences by Tiberio all the radar developments in the convulsed period of the Second World War are outlined, with the only exception of radar imaging to aid night bombing: in fact, in 1936 it was inconceivable, also to Tiberio, that in a few years the resolution of radar could improve so dramatically. A similar awareness of the operational requirements for radar, for example, is totally absent in what Guglielmo Marconi has written, or said, during those years, as already shown.

Before proceeding with the adventure of the *Gufo*, it can be interesting, especially to readers having no special knowledge in radar, to remark some of the technical and scientific concepts present in the manuscript.

The first, fundamental, point in radar is the choice of an operating frequency. Tiberio has clear in his mind two fundamental aspects (a) the maximum power that can be generated in the microwave region was much less than in the metric wave, at that time called "ultra-short wave" region; in general, the power decreases (even today) as the frequency increases; (b) the directivity of an antenna[6] (at the time of Tiberio the term "aerial" was used) depends on the ratio between its characteristic dimension (e.g., its diameter) and the wavelength. Tiberio, probably aware of French experiences on wavelengths below 30 cm, uses the word "microwave", proposed for the first time by Nello Carrara (Carrara's works and French experiences will be discussed later).

The range of frequencies that can be used for radio communications and radar is depicted in Fig. 2.4.

The second element of Tiberio's Manuscript is the substantial difference between radar transmission and reception in a continuous wave mode and in a pulse mode. In the former, directly derived from the radio communications, a beat of the transmitted oscillation with the received one (i.e., the target echo) is created. The difference of their frequencies is due to the Doppler effect, with values often in the audible range, then, detectable by the operator with a headset. However, if the target has zero radial velocity (because of being stationary or transversely moving with respect to the radar), there is no audible tone, but Tiberio teaches (see above) to "take advantage of the time that the reflected wave employs in the return path in order to change the frequency of the transmitter". That is, to modulate the transmitted frequency, in particular with the simple "saw-tooth" law (shown in

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[6] When the wavelength is of the same order as the size of the antenna, an antenna is "poorly directive" with radiation, roughly speaking, in "all directions"; vice versa for wavelengths somewhat smaller than this size, an antenna can be designed so that it radiates in a "narrow" angular sector, which is also called the "main lobe" or simply the "antenna beam".

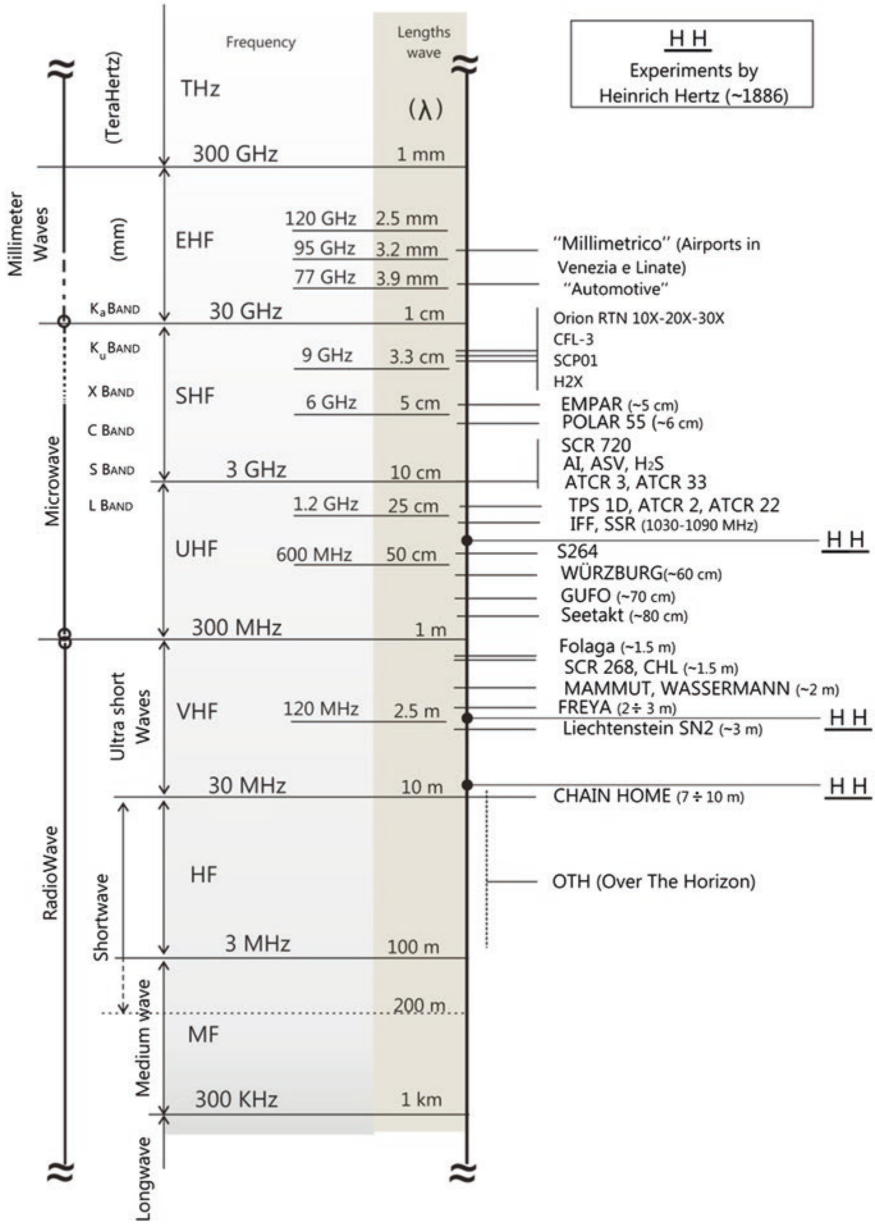

Fig. 2.4 The range of radio and radar frequencies and the placement of some radar equipment

Fig. 1, drawn by hand, of the original Found Manuscript and substantially equal to the one shown in Fig. 2.5). Today we speak of FMCW signals, such that the frequency deviation of the beat is proportional to the distance R of the target, as shown in Fig. 2.5.

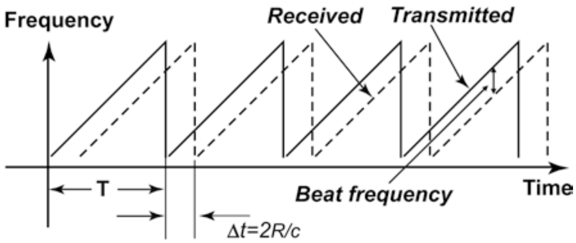

Fig. 2.5 Distance measurement in an FMCW radar (T: waveform repetition period, *R* distance, range)

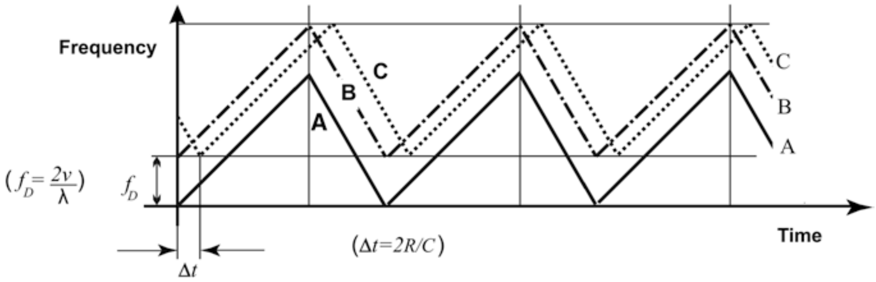

Fig. 2.6 Double-slope "saw-tooth" frequency modulation to measure the distance and the radial velocity. (*A* transmitted signal, *C* received signal from a target at distance *R* and radial velocity *v*, *B* as C, with R going to zero)

When the radial velocity is not negligible, following the ideas proposed by Tiberio in his Manuscript, it is necessary to change the modulation frequency; see, for example, Fig. 2.6: from two values of the beat frequency it is possible to obtain both the delay Δt (and then, the distance R) and the Doppler frequency f_D (and then, the radial velocity).

As Tiberio explains, using the FMCW system the sensitivity increases due to the video integration during the modulation period[7]: thanks to the gain in signal to noise ratio it is possible to transmit with a relatively low power. On the other hand, with this system, the measurements are more difficult with multiple targets and unwanted echoes such as those of the waves of the sea. In fact, today the majority of the surveillance radar uses the pulsed technique, as described in Fig. 2.7, by accepting the disadvantage, as compared with the FMCW, of a much greater peak power with the same range performance.[5] The continuous wave radar is

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[7] The beat, followed by a video amplifier which acts as a low-pass filter, is equivalent to a correlation receiver, implementing a matched filter, [Tur 60].

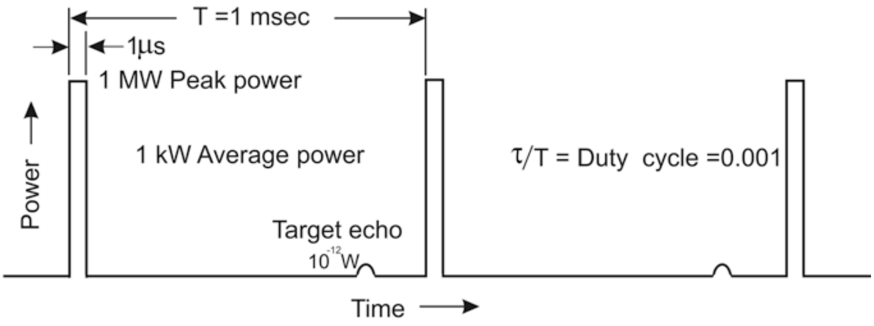

Fig. 2.7 Typical waveform for a pulse surveillance radar with a pulse duration of 1 μs and a pulse repetition period of 1 ms

appreciated today, in military applications, for its low peak power that makes it more difficult to be intercepted by the enemy (LPI, Low Probability of Intercept, characteristic).

In this regard, it should be remembered that Tiberio, who in the Found Manuscript presents the FMCW system as the only solution, with his research and experimentation going on, becomes convinced very soon that, at least for the naval applications that interest him, the most suitable solution will be the pulse radar; however, he must obey his superiors, in particular Giancarlo Vallauri,[6] a proposer of the continuous wave technique, considered “simpler and cheaper”. In his memories, Tiberio speaks of the period dedicated to a continuous wave radar as a waste of time.

The choice between pulses and continuous wave is present in the whole radar history. The continuous wave (CW) solution was preferred in some periods and neglected in others. For example, at the end of the 1990s, it was neglected at least by one of the most well-known researchers and authors, Merrill Ivan Skolnik, who in [Sko 01], third edition of his well known book, reduced the chapter on CW radar, present in the previous editions, to only four pages (pp. 193–197), in which he substantially maintains the superiority of “Pulse Doppler” radar on the CW one, and lists in detail the limitations of the latter. On the other hand CW radar has resumed its position, especially for applications at medium and short range, in this century.[7]

The birth of radar from radiotelegraphy made it initially “Bistatic”; this term (due to someone who obviously was not deeply familiar with the ancient Greek, otherwise he would have preferred the term “distatic”) indicates the physical separation between the receiving antenna and the transmitting one, which is natural in CW applications. The *Gufo* (with its predecessors) was and remained Bistatic (it had two identical antennas, rotating together), like many of the radars used at the beginning of the Second World War. On the contrary, a “Monostatic” radar uses one antenna in “time-division”, which is natural in pulse systems, having a small portion of the time (often, in the order of a thousandth) dedicated to transmit, and

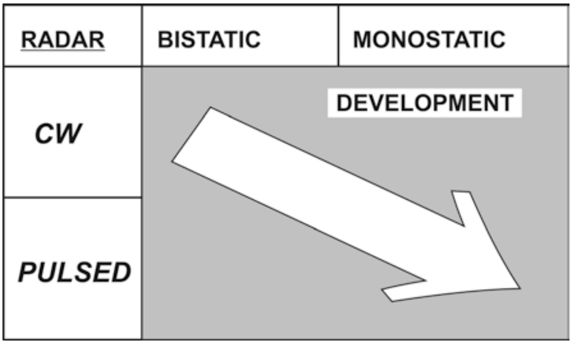

Fig. 2.8 General trend of radar systems in the second half of the last century

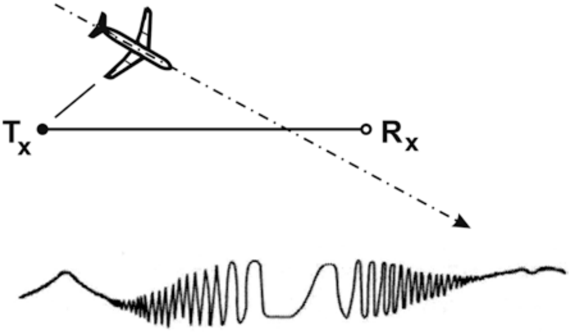

Fig. 2.9 The "beat" phenomenon when an air target crosses a radio bridge. Note that when the target is on the line joining the Tx (transmitter) antenna with the Rx (receiver) one, the Doppler frequency goes to zero

the remainder to receive, Fig. 2.7. As a conclusion, from the end of the war, the evolution has followed the direction of the arrow in Fig. 2.8, but not without the "backfires" in cycles of 20 or 25 years, well highlighted in Chap. 2 of [Wil 07].

Finally, as shown before, Tiberio was aware of the experiments that did occur in the USA in 1932 and were reported in the scientific literature in 1933 in which an airplane, passing along a link to ultra-short waves, gives rise to beats. This is (see Fig. 2.9) the phenomenon today called *Forward Scattering*, in which the scattered field from a moving target, the frequency of which is modified by the Doppler effect, adds constructively or destructively with the radiated field, generating in reception of the "beats". For targets as fast as aircraft, the frequency of beats is often in the audible range: as discussed in the previous chapter, Marconi himself (without showing to have read the work of Englund, Crawford and Mumford (1933)), observed, like many others,[8] the phenomenon.

The beating method was applied in France from its main inventor, Pierre David, who organized tests on June 1934 in Le Bourget, and subsequent ones in November. In about a year, he gathered more than 500 recordings of "beats" due to

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[8] On pages 15 and 16 of [Wil 07] there is a list of experiments (1922–1933) in which the presence of moving objects (but not their exact position) was detected due to their crossing of a radio link.

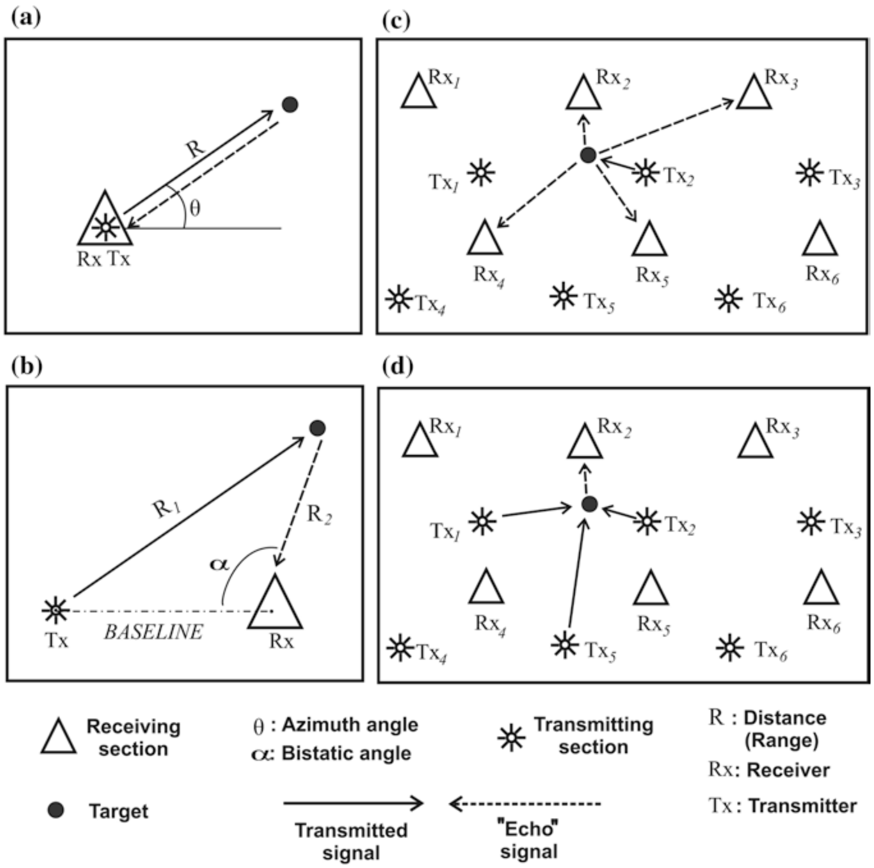

Fig. 2.10 Configurations: **a** monostatic, **b** bistatic, **c** multistatic with transmission from Tx_2, **d** multistatic with reception from Rx_2

the passage of aircraft in “electromagnetic barriers” and tried to relate their parameters with the direction and speed of the aircraft. As is evident, the “experiments” by Marconi in May 1935 (Chap. 1) are a very poor thing in comparison. David organized a network of barriers called “*maille en Z*”, i.e. in the form of a Z, in which he tried to overcome the problem of the lack of information of the distance by exploiting more detections of the same aircraft. In fact the time instant of crossing the line that connects a transmitter and a receiver was known, but not the crossing point. By combining more measures for aircraft in uniform rectilinear motion, in was possible to determine the velocity with errors of about 30 % and the direction with errors of about 20°. This system was made operational in 1939; the French navy planned the coverage of the coastal area of Britain around Brest, the main French military base, and around the ports of Cherburg, Toulon and Bizerta (Tunisia) [Roh 05]. This system can be considered as a forerunner of the modern *multistatic* systems, in which multiple transmitters and multiple receivers cooperate.

The concept of monostatic, bistatic and multistatic radar is shown schematically in Fig. 2.10; it can be seen that in the monostatic case, the measurement of the position of the target on the horizontal plane (plane of the drawing) requires at least two measurements, the distance R (the so-called Range), and the angle θ (the so-called Azimuth) with respect to a predetermined direction, typically the North; in the bistatic case, the circle centered on the radar with radius R becomes an ellipse with foci the transmitter and the receiver, calling for other information: the bistatic angle α, or (going toward the multistatic system) a second measurement from another pair of points. In the multistatic case, the position may be obtained from measures of delay (and possibly of Doppler frequency), without the need for angle measurements.

Figure 2.10 shows a multistatic situation in which the transmission is only from Tx_2 and the reception is in the four stations closest to the target: with three receiving stations, three ellipsoids are generated as constant-delay curves, the intersection of which determines, in principle, the position of the target. If the other stations, e.g. Tx_1 and Tx_5, transmit, simultaneously with Tx_2, orthogonal signals, a much greater wealth of information can be obtained for a better identification and localization of the target with a lower risk of ambiguity. This topic will be also treated in Chap. 10.

2.3 Birth of Radar in Italy

Let's go back to 1936 in Italy, where the working group led by Ugo Tiberio at the *Regio Istituto Elettrotecnico e delle Comunicazioni* (R.I.E.C.) of the Navy, in Livorno,[9] was entrusted with the task of going from theoretical studies to the experimental phase of radar development. Tiberio, in the meantime, was appointed officer in the body of the Naval Weapons and transferred to the Academy as a professor of physics and of radio-techniques. The financial resources and the staff available to the development of radar were, however, limited (four petty officers, some workers and an annual allocation of 20,000 lire—about 13,000 Euro), for which Tiberio had to carry on, almost alone, the development and implementation of a prototype of the *Radiotelemetro*. Soon Nello Carrara, another professor of physics at the Naval Academy, joined Tiberio. By 1924 Carrara, a young physicist, was working at the R.I.E.C. and, since 1932, did research in the field of microwave; he was mainly responsible for the design and implementation of power tubes,[8] basic components in order to obtain acceptable values for the radar range. Carrara and Tiberio never interrupted their commitments to teach (lectures, tutorials, training handouts, committees of examination). In 1937 another notable person joined the group of researchers: the captain of the Naval Weapons Alfeo

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[9] The Institute, which was commonly called "E.C." or Mariteleradar, or, from the telegraphic initials, "Marinelettro", is dedicated to Prof. Admiral Giancarlo Vallauri who was its first director.

Fig. 2.11 E.C.-1 Radar in test on a terrace of the R.I.E.C., 1936

Brandimarte[9] who immediately began to work on construction of the new prototype of the E.C. 3, a pulse radar, which will be described soon. This collaboration, however, was short lived because the possibility of career progression in the Italian Navy was precluded to Brandimarte (who in 1944 fell as an opponent in the "Resistenza") for the strange and inappropriate fascist law "on celibacy"; therefore, the research team again consisted substantially in the tandem Tiberio-Carrara.

With scarce resources, Tiberio implemented several experimental sets, starting from (in 1936 and in a few months) the first experimental Radio Detector Telemetro (the name used in Italy at that time, abbreviated as RDT). This frequency-modulated continuous wave radar, designated with the initials E.C. 1 (*Elettronica e Comunicazioni* 1, to indicate the R.I.E.C.), dedicated to the practical demonstration of the RDT concept and to the measurements of radar cross section.[10] It worked at 200 MHz (i.e. at the wavelength of one meter and a half)[10] in the just described FM-CW mode (the reasons for the choice of the continuous wave solution was explained before), had a pair of reflector antennas with a parabolic cylindrical section and was used for the practical demonstration of the theory of the radar equation. On that occasion, an experience was set up with the apparatus being installed on a terrace of the Institute (Fig. 2.11) with the use of a boat as a target of opportunity (Fig. 2.12).

The first results, although not fully satisfactory, served as an experimental verification of the calculation of the maximum range (radar equation). The maximum distance at which it was possible to receive useful radar echoes, of the order of 2000 m, in fact, was too little for tactical naval applications. This apparatus was also used in experiments to identify a friendly unit at night, in practice as an IFF: *Identification Friend or Foe* for naval units, see Figs. 2.12 and 2.13. In this

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[10] We will use either the *wavelength* λ (preferred at the time of Tiberio) or the *frequency* f (preferred today in the West, while in the former-Soviet Union the wavelength is more often used); it is well known that their product is the speed of light, about 300 m/μs, hence the practical conversion rule:

$$\lambda(\mathrm{m}) \cdot f(\mathrm{MHz}) = 300.$$

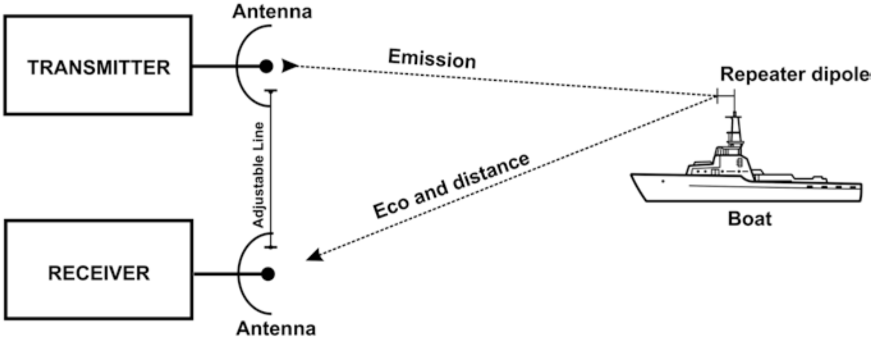

Fig. 2.12 Radio detector telemeter (RDT) E.C. type used for *identification friend or foe* (IFF), 1938

Fig. 2.13 Radar trials for ship detection (1937), from *left* A. Brandimarte and N. Carrara

application, the radar operated at a fixed frequency and received the modulated echo produced by a rotating dipole on the unit to be recognized as friend.

In this first embodiment of a radar prototype in Italy, the problem of the transmitted power arose immediately. In fact, while in radio broadcasting and radio-telegraphy the received signal—assuming a free space propagation—is spread over a spherical surface centered on the source and then fades in proportion to the square of the distance, the radar signal has the outward and the return path, and the power of the echo fades with the fourth power of the distance, as shown in [Tib 39], the first published version of the "fundamental radar equation".[11] As many others, the paper [Tib 39] published on *Alta Frequenza* in May 1939 was summarized in "The Wireless Engineer", August 1939, in a brief note (no. 3175). The limited availability, in Italy, of technologies suited to the required high power levels (from hundreds of W to some kW) in the frequency ranges of interest was one of the main limitations to the development of operationally efficient radars; once the RIEC made the choice of the pulse solution, the problem was exacerbated by the fact that the technique of vacuum tubes in those times, especially of their cathodes, was developed for the continuous wave radio: it was unsuitable to the high peak power, pulsed operation.

The ensuing version of the RDT, named E.C.1-bis, (1937) differed from the previous one by the use of a superheterodyne receiver (for the remaining aspects, it was very similar to the E.C.1), but did not gave satisfactory results for complications in the development of the heterodyne device[12]; therefore it was promptly abandoned.

Very different was the ensuing prototype (in the same year, 1937) named E.C.2. It was based on the pulsed technique and used RCA triodes model T 800 (i.e. produced in the USA, a nation that would become an enemy in short time), operated on the 1.7 m wavelength, slightly higher than the E.C.1, had a equal-phase dipoles antenna and an oscilloscope-type display. Unfortunately, the results were unsatisfactory for a combination of practical disadvantages (some strong shocks within the transmitting tubes prevented the smooth operation of the system). In 1938, the Naval Weapons Directorate of the Navy, eager to reach in a short time to a working prototype, signed a contract[13] with the company SAFAR.[11] It has been reported that this agreement did not lead to successful results[14] because of the different views between SAFAR and Marinelettro, and more specifically, according to somebody, between Ugo Tiberio and the technical director of the company, Dr. Ing. Castellani[12] (he was a remarkable engineer, inventor and designer of radio equipment and radar).

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[11] In the formulation by Tiberio, who uses field strength in place of power density, the square of the distance appears in place of the fourth power.

[12] A complex mechanical device modulated the heterodyne frequency with constant offset with respect to the transmitted frequency. The heterodyne receiver is due to Lucien Levy in 1917, and patented by Armstrong in the following year.

[13] A clarification is needed, as in [Tib 79] and in [Cer 95] a noticeable aspect is clearly indicated: the contract was signed with the clause "without fixed expenditure limits", a remark entirely absent in the always well documented works by Castioni such as [Cas 87], presumably because that clause contrasts the claim by Castioni that the Italian Navy was severely limited to expenses for the radar development, at least until the Capo Matapan defeat.

[14] See [Cas 87] where, however, for a likely clerical error, the contract Marinelettro-SAFAR in 1938 is referred to the E.C.3 instead of the E.C.2.

The discussion between Marinelettro and SAFAR basically ended with the request by SAFAR—obviously, not accepted—of secondment of R.I.E.C.[15] staff to that firm. The always balanced and elegant Ugo Tiberio, who certainly knew the matter very well, sums up this situation in a single, elegant phrase that deserves to be given in full, from [Tib 79]: "This initiative could not take place due to the difficulty of recruiting the needed technical staff".[13]

However, given the slowness with which the industry implemented what was designed by the researchers and given the small produced quantities, the Navy had to find other ways to obtain the peak power required for an acceptable radar range. With the international market still open, they could initially purchase from the USA, at the RCA, powerful enough vacuum tubes needed to meet the requirements of the researchers. Two prototypes were tested at the R.I.E.C. from 1939: the coastal apparatus called RDT 3 (in some documents: E.C.2-bis), and the naval one called E.C.3, (from December 1940 modified as E.C.3-bis). These trials showed some possibility of achieving significant operational results. However, only with the introduction of the E.C.3 set (a pulse radar, with a double horn antenna, operating on the 70 cm wavelength, developed at the R.I.E.C. from the end of 1939, using conventional Philips triodes in transmission and a new, highly sensitive super-reaction receiver) the possibility of obtaining significant results in truly operational uses was open. The next model E.C.3-bis (1941) had a simpler but less sensitive superheterodyne receiver and a higher transmission power (1 kW) thanks to the new Philips tubes (again of the conventional type, for radio-communications) with a greater cathodic efficiency. Unfortunately, because of the chronic lack of funds (and probably a not complete understanding of the operational value of these new equipments) from 1940 the research and development work had a slowdown both by the need for further tuning, and by the limited interest by the summits of the Italian Navy. As Pietro P. Lombardini, who was the youngest collaborator of Tiberio, recalls, the first detection (by acoustic receiving) of a tug at approximately 2 km offshore from the Academy of Livorno took place on April 14th, 1941.

The hectic restart of Italian radar activities during the wartime period, precisely in April 1941, immediately after the well known Cape Matapan night naval battle, with the involvement of the industry, will be explained later in the following. Summing up, at the date of Cape Matapan two types of prototype were available at R.I.E.C. One of them, designed for coastal installations[16] (Figs. 2.14 and 2.15),

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[15] To highlight the difficulties in which this small *team* operated, it seems appropriate to reproduce, verbatim, what Ugo Tiberio wrote in 1951, always with his "understatement" and, notably, without mentioning the name of the firm: "In 1938, due to the difficulty in finding other researchers to devote to his studies on radar, the Ministry of the Navy decided to try to involve an important radio industry in Milan, which, however, having all own staff already engaged, limited itself to ask the needed technicians to the Navy: the Navy could not fulfill this request, so, also this attempt remained without success" (U. Tiberio –*Sullo sviluppo delle cognizioni radar durante la Guerra*—Rivista Marittima—Aprile 1951).

[16] The set was not suitable, because of its large size and physical features, to the naval use.

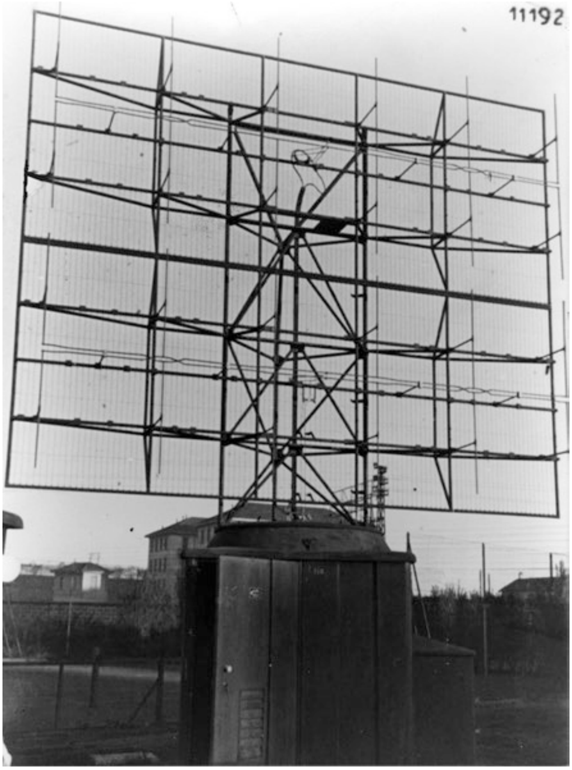

Fig. 2.14 Array antenna of the "Folaga" radar

operated at wavelengths in the range of 1–2 m, nominally 1.5 m, and was called RDT 3 and, later, *Folaga*[17] (or, in the version that, according to some sources, was made by Magneti Marelli, RDT 4/*Folaga*).

The other one, named E.C.3-ter, or *Gufo*, was derived from the E.C.3-bis with the novel FIVRE triodes model 1628, due to Prof. Nello Carrara (Carrara developed the cathodic resonator with high quality factor Q, solving the problem of internal discharges that made, in fact, poorly efficient the previous prototypes). The transmitting modules, implemented in order to be easily replaceable due to their very short average life, were called, because of their shape, the "Carrara's pots", see Fig. 2.16. The *Gufo* had interesting performance thanks to its transmitting system having a peak power as high as 10 kW, with which it was possible to detect air targets up to a distance of 120 km and naval targets up to 15–30 km (depending on the installation height of the antennas, typically: 35 m on large battle ships such as *Vittorio Veneto* or *Littorio*, 25 m on cruisers such as *Scipione Africano*, 15 m on destroyers such as *Carabiniere*, *Fuciliere*, *Velite* or *Dardo*).

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[17] In English: *Coot*.

Fig. 2.15 Video detector of "Folaga"

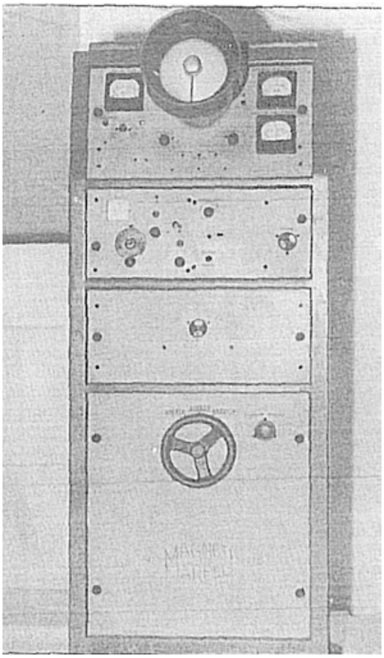

Fig. 2.16 A "Carrara's pot"

Then, the series production of *Gufo* and *Folaga* was entrusted to domestic industry, but this point will be discussed later; however, it is worth mentioning that the reported progress in terms of performance by these last-release sets was truly remarkable.[18]

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[18] Because of the secrecy and of the well-known events of the war, most original documents of that time that, today, could be a sure reference (such as detection tests, test reports or similar) are unfortunately lacking. A few significant documents found in the SAFAR/Castioni archives are reprinted in the Appendixes and Complements of [Gal 12].

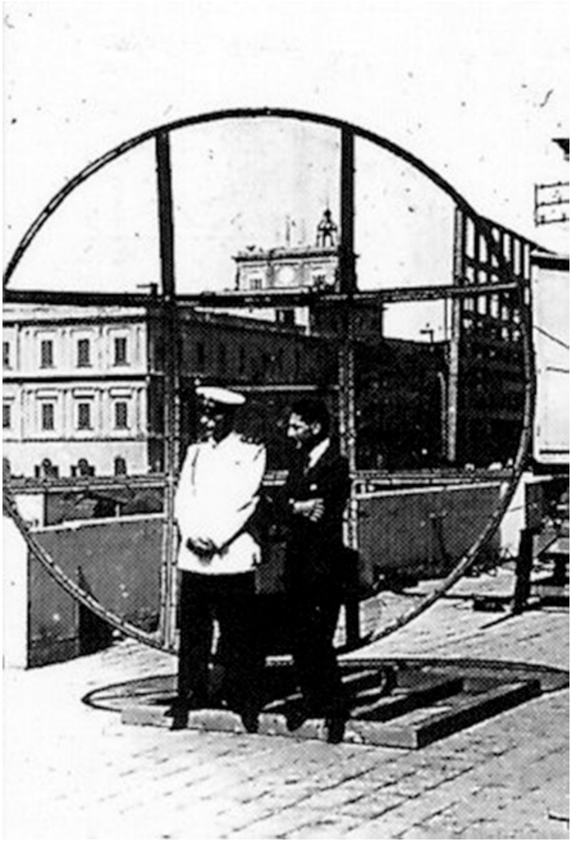

Fig. 2.17 Antenna of the "*Folaga*" radar on the R.I.E.C. terrace (May 1943)

In this respect we recall that with the latest version of the *Folaga* during the experimental tests on May, 1943 (Fig. 2.17), a mass raid of one hundred American aircraft arriving from Sardinia to bomb the city of Livorno was detected at more than 200 km [SMM 98]. In [Cas 74a] p. 30, a range of 300–400 km on air targets is claimed. This is an unrealistic value even with the considerable Folaga's transmitted power of 50 kW; other documents indicate a, probably conservative, radar range of 50 km[19] or, more optimistic, of 113 nautical miles, i.e. 209 km, a value

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[19] By applying the radar equation to the estimated technical data of the *Folaga*, it appears that an aircraft target of good reflectivity (radar cross section of 10 m^2) at a distance of 200 km in free space would have generated an echo below the noise (precisely, with a signal-to-noise ratio of—4 decibels), hardly detectable even with assuming a gain of 10 decibels due to the integration of the pulses by the operator. Maybe, being the instrumental range equal to 300 km (due to the p.r.f. of 500 Hz) there has been some confusion with the real, operational radar range.

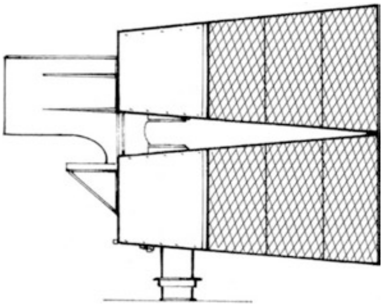

Fig. 2.18 Side view of the E.C.3-ter “Gufo” antenna with the wind-compensating rudder

found at p. 109 of [Cer 95]. In this respect, for the *Gufo*, in [Tib 79] range values on air targets from 80 to 120 km[20] are indicated.

The initial phase (1937–1938) of low activity of Marinelettro on radar can be explained by the lack of qualified human resources: in addition to teaching, since the summer of 1937 Tiberio had to deal with other technical problems (in particular, to the development of radiotelegraphy equipments for the Regia Marina), which presumably were judged by his bosses more important than the RDT.[14] Then, at the beginning of spring, 1937 the lieutenant of *Genio Navale* (Naval Engineering) Ugo Tiberio was flanked (putting him at his orders in spite of being of an higher grade) by the captain (AN) Alfeo Brandimarte, who oversaw the development of the E.C.3 (it seems that this name was used twice) with the new triodes T 800 by RCA, finally able to provide a non-negligible peak power.

A peculiar feature of the *Gufo* (see Figs. 2.18, 2.19, 2.20, 2.21, 2.22, 2.23, 2.24, 2.25 and 2.26)—not found, as it results, in any other radar of that period—was the antenna, or better the pair of antennas of the horn type, with, at a quarter wave length from the bottom, the feeding dipole, usually vertical but that can be rotated by 90°. In [Tib 79] Tiberio explains that this solution permitted the operation in both the vertical polarization, which was normally used, and in the horizontal one. It did not appear possible to install more than just one radar set on each naval unit, and therefore it was necessary that the only apparatus on board could operate in both naval mode and anti-aircraft mode.[21] On the other hand the use of two antennas, a transmitting and a receiving one (Fig. 2.18), was common at that time, as Italy and

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[20] On naval targets, the radar range depends on the height of the antenna above the sea level (and on the operational wave length). Range values of at least 20–30 km were necessary, especially in the battle at night or in fog, when using the major naval guns, e.g. the 381 mm (15″), which, with 381/50 mod. 1934, was the main weapon of the battleship *Littorio*, able to hit up to 42 km (36 km when shooting at 30°).

[21] Obviously, Tiberio knew the different propagation behavior of the two polarizations in the presence of the sea surface. However, the horn solution, as compared to the equiphase dipoles one, most used in surveillance radar, had the significant disadvantage of a greater resistance to the wind. In fact, the revolution engine of the antenna of the Gufo, in critical condition for wind or speed of the ship, was unable to perform its function, forcing the radar operators to rotate manually the antenna by means of a hand-wheel.

Fig. 2.19 The light cruiser *Scipione Africano* with the antennas of the RDT E.C.3-ter "Gufo". The position of the antennas allows us to distinguish, at the rear, the rudder added to compensate for the insufficient power of the electric motor in the presence of wind

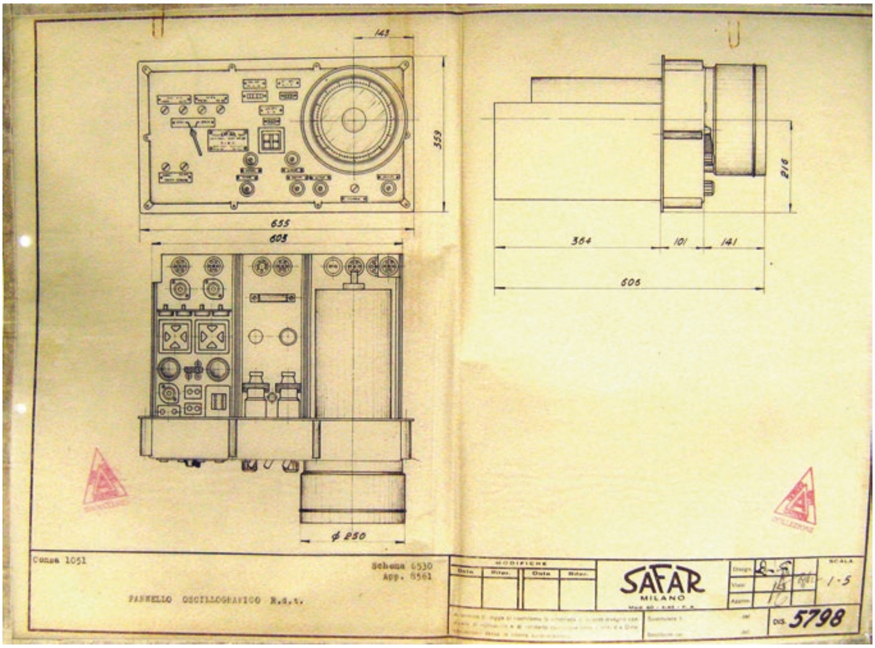

Fig. 2.20 The "Gufo" radar control panel by SAFAR

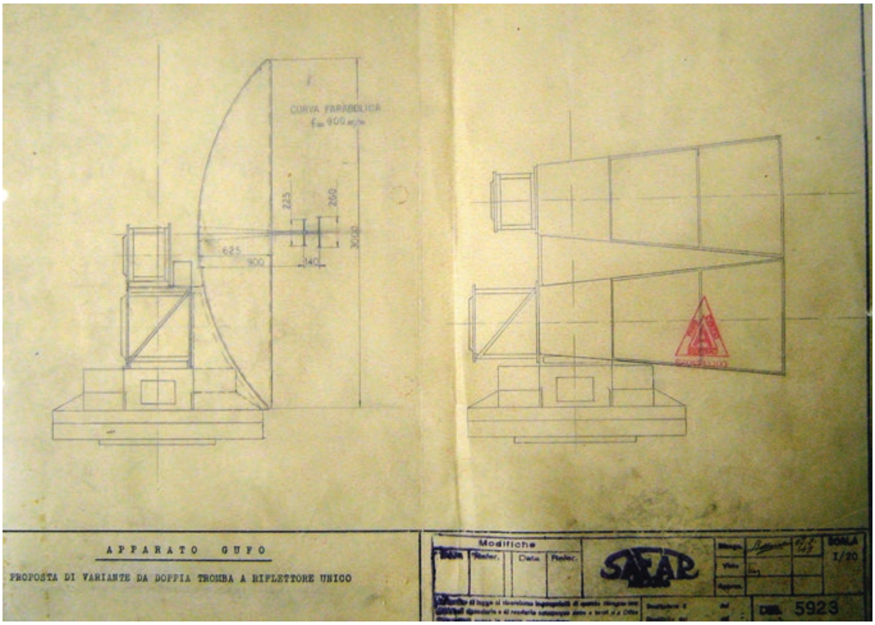

Fig. 2.21 "Gufo" radar—drawing of a reflector antenna to substitute the double horn one

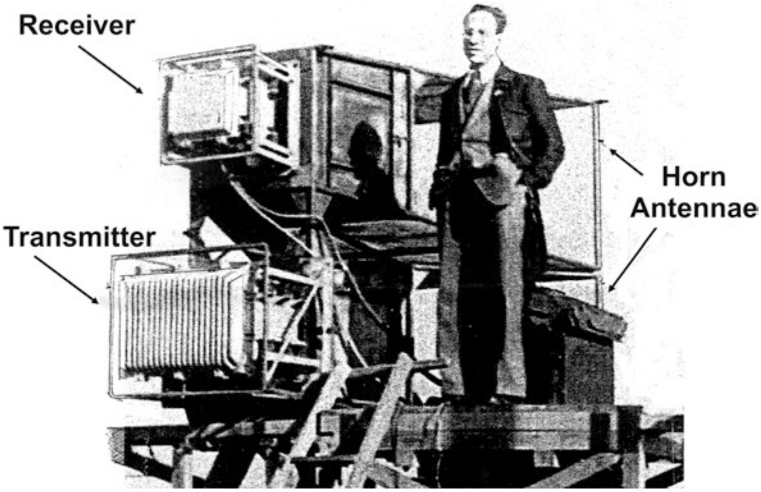

Fig. 2.22 The E.C.3-ter "Gufo" and Federico Brando from SAFAR

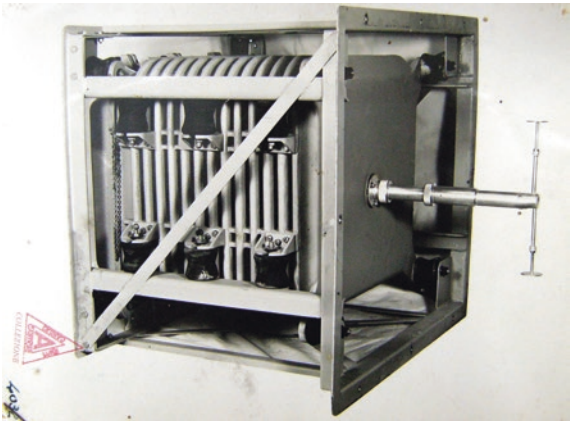

Fig. 2.23 The transmitter of the E.C.3-ter "Gufo"

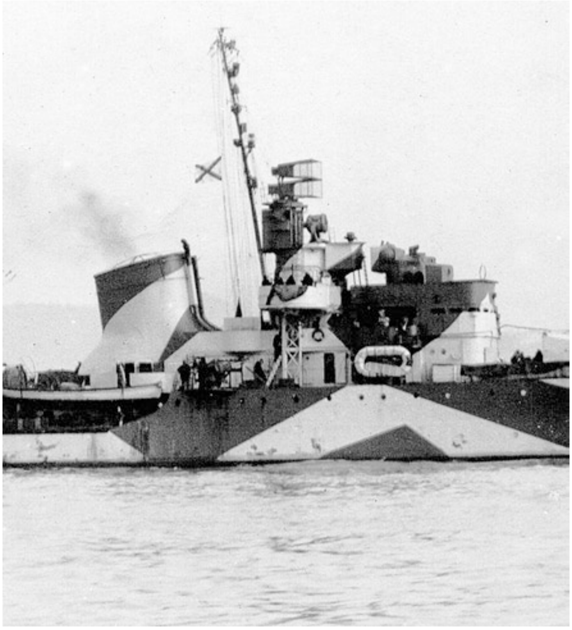

Fig. 2.24 The destroyer *Fuciliere*, equipped with the radar E.C.3-ter "Gufo" from January 1943

other nations lacked the necessary technologies to realize the "duplexer" with which an antenna is connected to the transmitter during emission of the pulse and to the receiver in the remaining time. To solve the problem of the limited gain of this type of antenna, an alternative solution with a parabolic reflector was devised, Fig. 2.21, but it is not known if this was really implemented or, more likely, not.

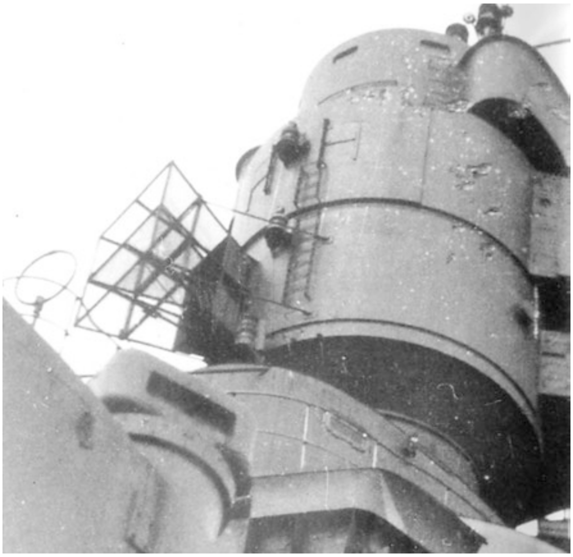

Fig. 2.25 A detail of the tower of the Battleship *Littorio*, end of 1941. The large antennas of the RDT prototype E.C.3-bis embarked for experimental purposes are visible, with the “horns” for transmission and reception

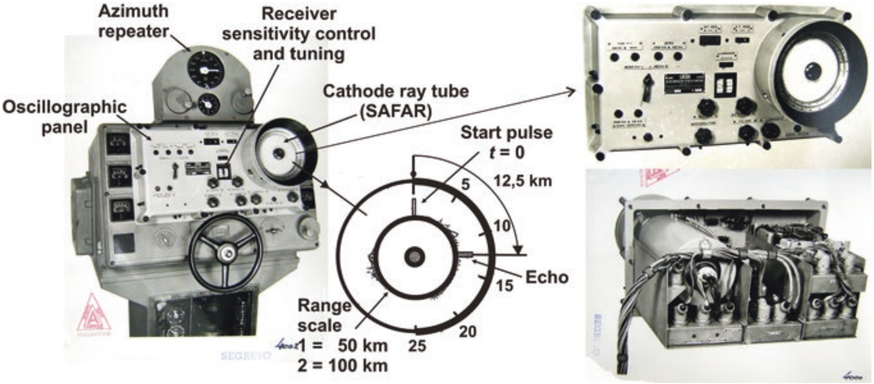

Fig. 2.26 Operating console for the control of radar *Gufo* and G.III, built by Galileo-Firenze (the polar oscilloscope: by SAFAR—Milan); the synchro-repeaters, in the *upper part*, were used to transmit data to the fire control unit

The “Gufo” operator used the console shown in Fig. 2.26, with the hand-wheel (bottom) for the manual rotation of the antenna when necessary. Among the very few block diagrams of the Gufo remaining after the war, in Fig. 2.27 is shown a document which, according to its title and content, clearly is the second drawing

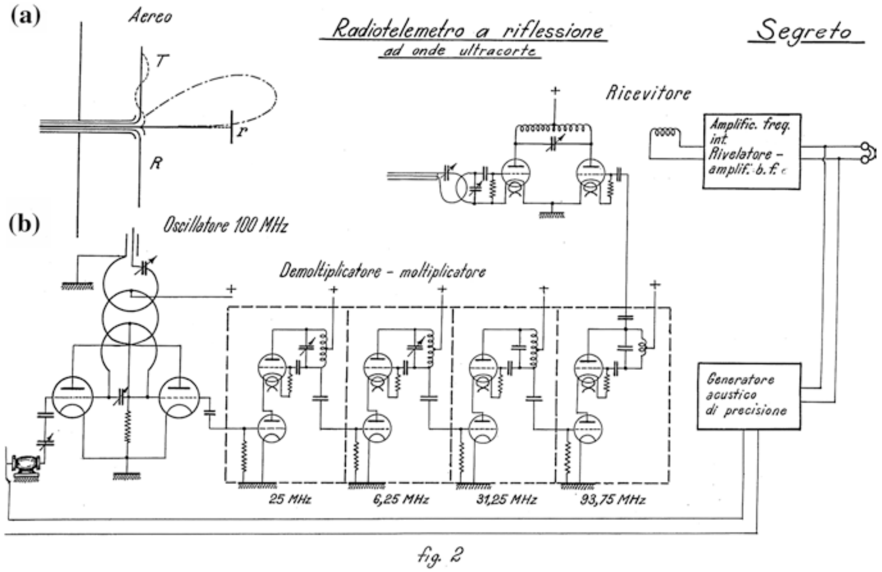

Fig. 2.27 General scheme of the first RDT conceived by Ugo Tiberio, April 27th, 1936

of the "Found Manuscript",[22] quoted in its paragraph 4 ("…in the document here enclosed…").[23]

A diagram of the circuits of the receiver (1941) is shown in Fig. 2.28, highlighting the differences with the scheme of 1936, while the circuit diagram of the transmitter is shown in Fig. 2.29.

After the war, Tiberio continued to deal with radar and radio techniques as professor at the University of Pisa, producing, among other things, the remarkable text books [Tib 51] and [Tib 51b], in which he explained some topics that are still interesting today, such as that of "stealth"[15] targets and of the radar jamming. He had many pupils, some of whom assumed important positions in the nascent national radar industries, which are described in the following. Of course, he was invited by many scientific and industrial institutions for lectures and seminars. During one of these visits, the photograph shown in Fig. 2.30 was taken.

The "RaRi mobilization", with the development of—unfortunately, a few—industrial Italian radars in the early 1940s, will be further discussed in the following; here we present, from pp. 49 to 50 of [Tib 51b], the part where Tiberio very clearly synthesizes the development of radar.

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[22] The first drawing of the "Manuscript" is simply the sketch of the "sawtooth" frequency-modulated signal.

[23] This scheme, which is not physically attached to the "found manuscript", was luckily saved by professor Paolo Tiberio who, on July 2011, has generously provided the A. with the copy presented here, finally allowing a complete reconstruction of this important Manuscript.

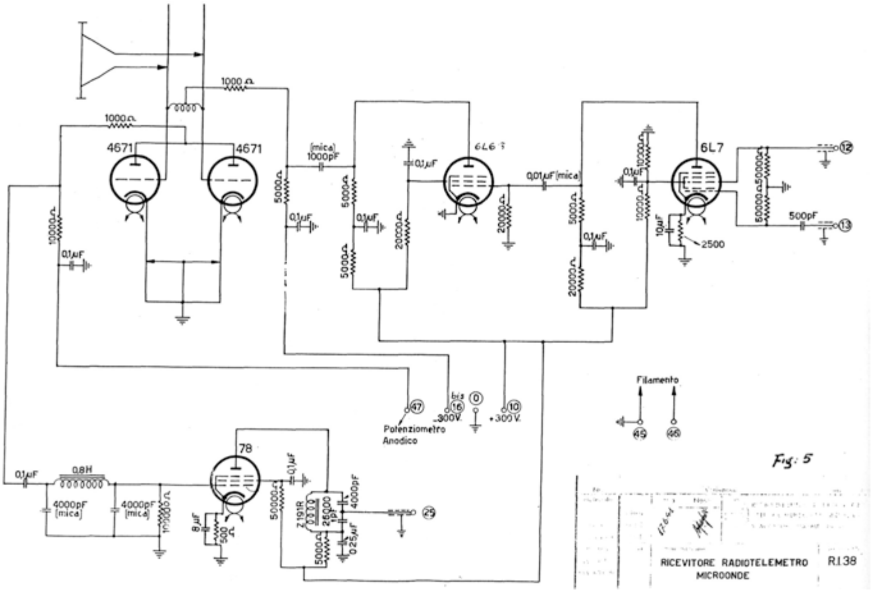

Fig. 2.28 Circuit scheme of the receiver of the E.C.3-bis/ter, June 17th, 1941

"The beginning of the evolution that, from the techniques of ionosphere survey, led to the birth of radar, can be dated in the years '34 and '35, and was determined by two concurrent causes: the development of the of ultra-short wave technique on one hand, and, on the other, the finding of the theoretical possibility to detect the echoes of airplanes up to distances in the range of 100 km. The imminence of the war, however, pushed each of the principal nations to develop—for its own account—secret researches, so that scholars worked at the various countries, in an independent manner up to '40 ÷ '42, after which a first collaboration began inside of each of the two opposite fighting parts. In 1945, the winners proclaimed the end of military secrecy on the general aspects of radar, and began publications of the well-known 28 volumes of the Radar Series.

While addressing the reader calling for a complete knowledge of the history of the former radar research to the specialized publications, we wish to recall that in Italy the initiative was taken by the Navy (Regia Marina), with which, from '34 onwards, the author of this text has carried on research aimed to clarify the theory and to provide equipment suitable to military requirements. A first type of them, operating in continuous wave, was made in '36–'38 with some first, inadequate results; then different types operating in pulse mode were realized in '39 ÷ '40. The first satisfactory results were obtained in '40. In the course of the war, various types of apparatus were constructed and used to an extent which however, for the poverty of the national industry on the one hand, and for the lack of cooperation

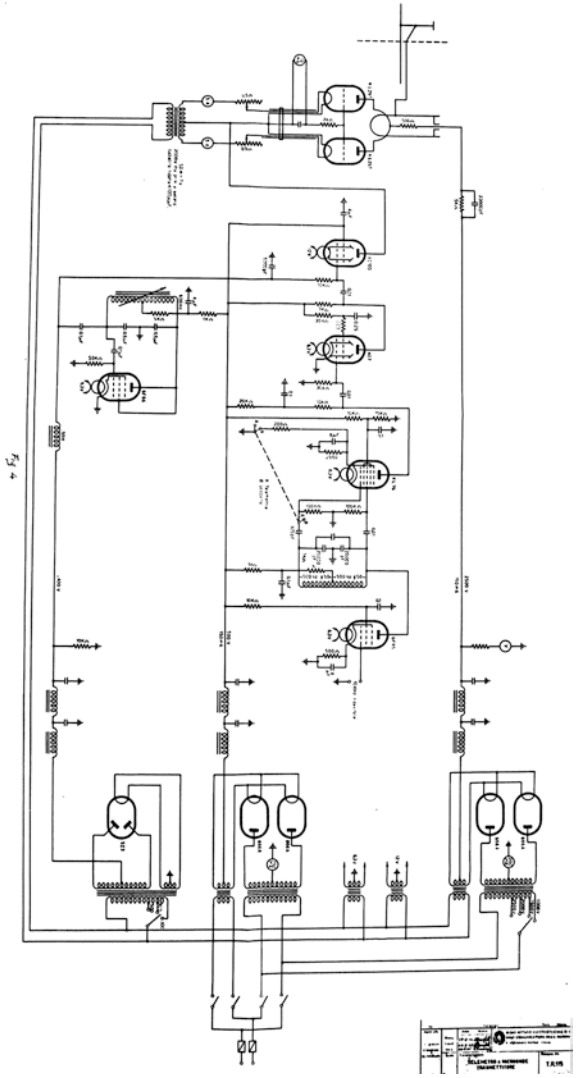

Fig. 2.29 Circuit scheme of the transmitter of the E.C.3-bis/ter

between the military authorities and the scientific ones on the other hand, was truly inadequate in relation to that times and to the value of events."

Perhaps at this point the reader may be curious to know if the *Gufo* was actually used and on board of which ships. Jumping, for now, the war context and the "wobble" of the decision-making process with regard to radar developments in Italy on 1939–1943, in Table 2.1 are listed, according to [Cer 95], the E.C.3-bis or

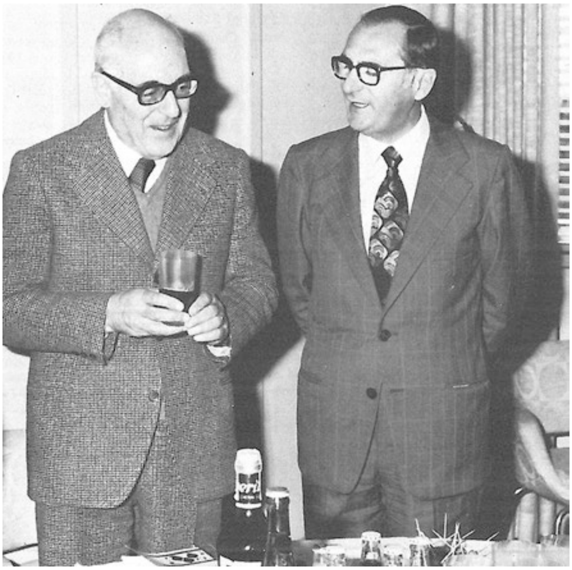

Fig. 2.30 Prof. Ugo Tiberio (*left*) and dr. Bianucci during the meeting on November 8th, 1976 at the firm Contraves Italiana (now Rheinmetall-Italy), Rome

E.C.3-ter radars installed on ships of the *Regia Marina* (a total amount of 15 sets on 14 ships) and operational until the end of hostilities.[24]

There are a very few images of Italian ships during the period 1941–1945 with radar on board, and in fact there were a few such ships and, see [Cer 95]. Moreover, sometimes a planned radar was not installed (and when installed, did not always work correctly). Some of these rare images, taken from [Bag 05], are shown in Figs. 2.31, 2.32, 2.33, 2.34, 2.35, 2.36, 2.37, 2.38 and 2.39, courtesy of captain Bagnasco.

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[24] Among the vessels of Table 2.1 it is worth mentioning the battleship *Roma*, sunk on 9 September 1943 (i.e. the day after the armistice) by the Luftwaffe with a raid of two-engine Donier 217 k using radio controlled gliding bombs (forerunners of air—surface missiles) Ruhrstahl SD 1400 “Fritz X”. In that dramatic day Admiral Carlo Bergamini and most of his crew died [Amc 10]. The wreck of *Roma* was found at 1000 m depth, and 16 miles off the Asinara Island, on June 28th, 2012.

Table 2.1 Italian ships equipped with the national radar during the Second World War (adapted from [Cer 95], courtesy of MMI)

	Type of vessel	Name	Apparatus	Remark	Also cited in
1	Torpedo Boat	**Carini**	E.C.3-bis	**Experimental**—installed in April 1941	
2	Battleship	**Littorio**	E.C.3-bis	**Experimental**—installed between the end of 1941 and the spring of 1942	[Cas 79]
3	Battleship	**Littorio**	E.C.3-ter	Second apparatus installed in September 1942	[Sad 06], [Cas 79]
4	Destroyer	**Carabiniere**	E.C.3-ter	installed in January 1943	[Sad 06], [Cas 79]
5	Destroyer	**Leone Pancaldo**	E.C.3-ter	Installed in January 1943	[Sad 06], [Cas 79]
6	Destroyer	**Fuciliere**	E.C.3-ter	Installed in January 1943	[Sad 06], [Cas 79]
7	F 14 Tug	**Urania**	E.C.3-ter	Installed in April 1943- ship for trials and experiments	
8	Cruiser	**Scipione Africano**	E.C.3-ter	Installed in April 1943	[Cas 79], [Bag 78]
9	Battleship	**Vittorio Veneto**	E.C.3-ter	Installed in April 1943	[Cas 79]
10	Destroyer	**Ugolino Vivaldi**	E.C.3-ter	Installed in April/May 1943	[Bag 78]
11	Battleship	**Roma**	E.C.3-ter	Installed in June (August?) 1943	[Cas 79]
12	Cruiser	**Eugenio di Savoia**	E.C.3-ter	Installed in August 1943	[Cas 79], [Bag 78]
13	Destroyer	**Nicoloso da Recco**	E.C.3-ter	Installed in August 1943	[Bag 78]
14	Cruiser	**Raimondo Montecuccoli**	E.C.3-ter	Installed in August 1943	[Cas 79], [Bag 78]
15	Cruiser	**Attilio Regolo**	E.C.3-ter	Installed in August 1943	[Cas 79], [Bag 78]
16	Destroyer	**Velite**	EC.3-ter	Installed in August 1943	[Cas 79], [Bag 78]
17	Destroyer	**Dardo**	E.C.3-ter	Installed in August 1943	[Cas 79], [Bag 78]

The **bold** in the 4th column aims to distinguish between operational and experimental radar sets

Remark (a)*—According to [Bag 05], an E.C.3 prototype was installed on the battleship Littorio in August 1941 and sea trials were performed from November 1941; it was later (September 1942) replaced by E.C.3- ter Gufo, which had been tried for a long time at land and on board the tug boat Urania*

Remark (b)*—Immediately after the armistice, with the ships of the Italian Navy "cobelligeranti" with the Allies, the presence of German DeTe radar was correctly considered very dangerous given that the Germans knew perfectly their frequencies and various characteristics. Therefore, they were often replaced either with the Gufo or with the British radar Type 286 or Type 291*

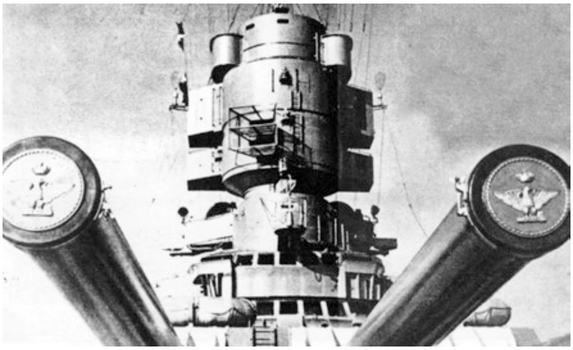

Fig. 2.31 The Battleship *Littorio* with the radar Gufo (1941)

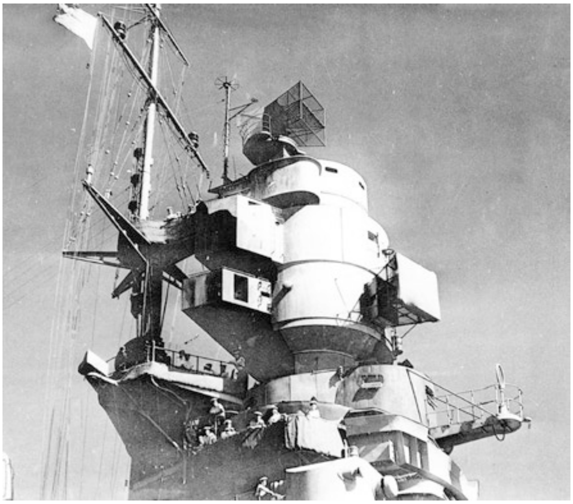

Fig. 2.32 The *upper part* of the tower of the battleship *Italia*, previously *Littorio*, on September 11th, 1943: on the *top*, the rotating antennas of E.C.3-ter "Gufo" on board from a few days and, on the telemetric turret, those, covered by a hood in canvas, of the previous "Gufo" apparatus

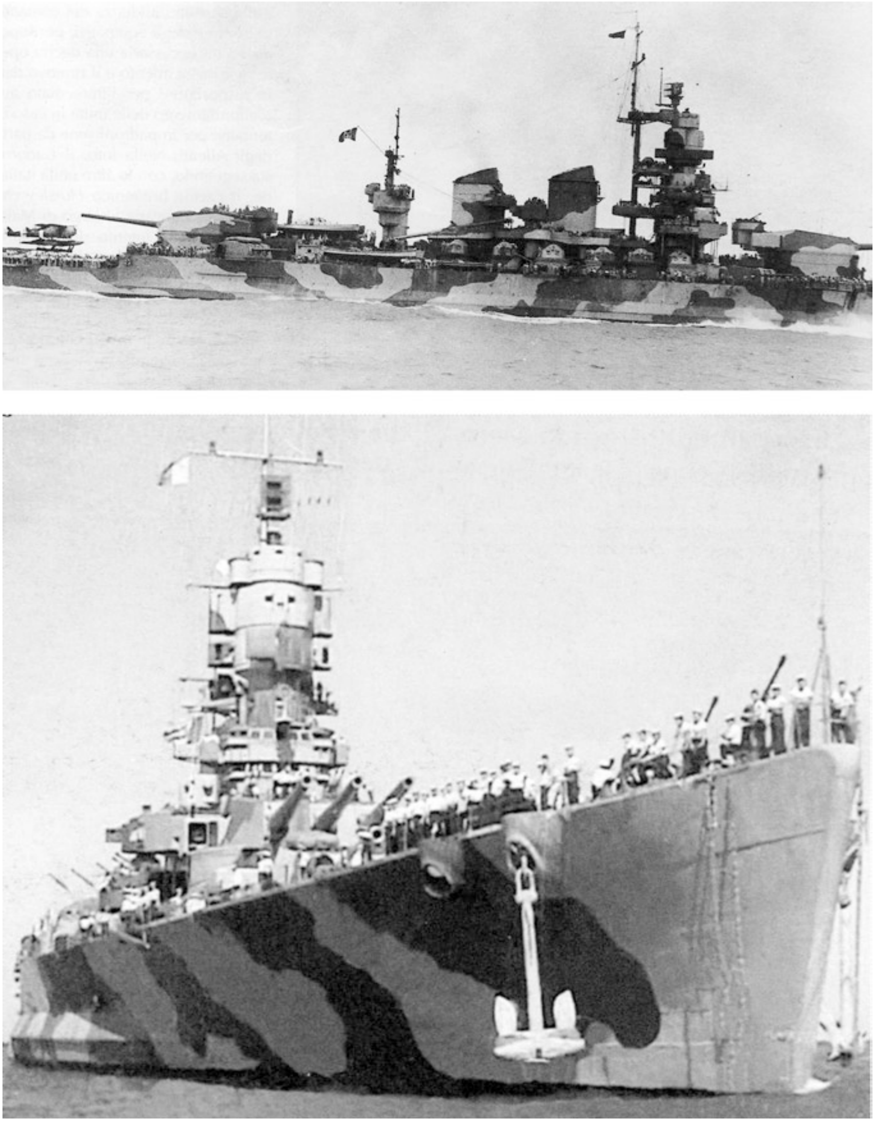

Fig. 2.33 The battleship *Littorio* with the *Gufo* radar (September 1943)

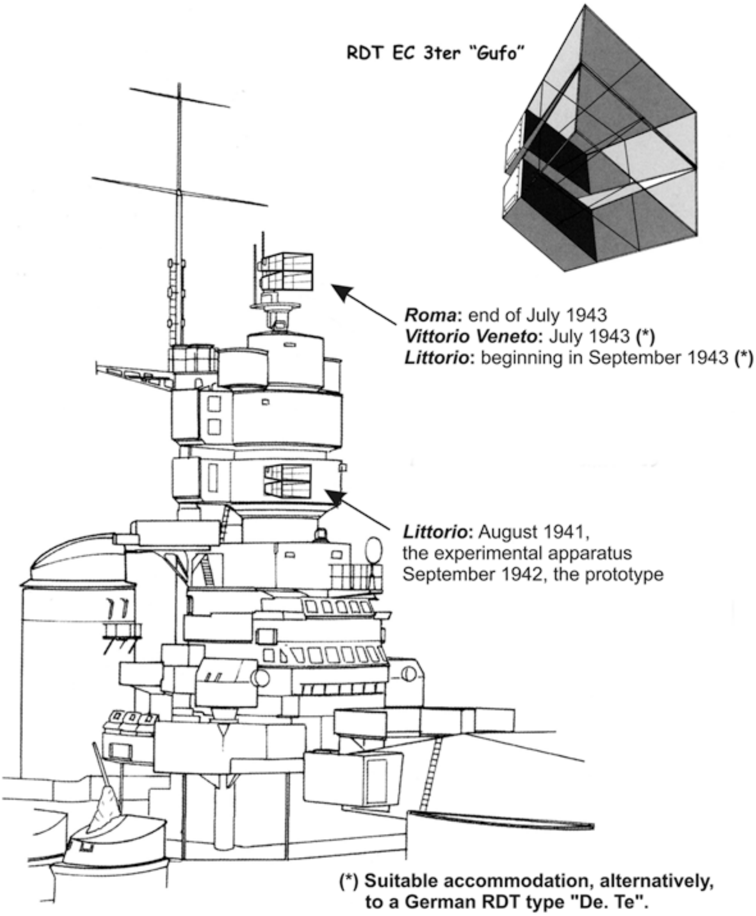

Fig. 2.34 Siting of the antennas of the E.C.3-ter "Gufo" and of the first experimental apparatus on board the battleships of "Littorio" class (Drawing by M. Brescia)

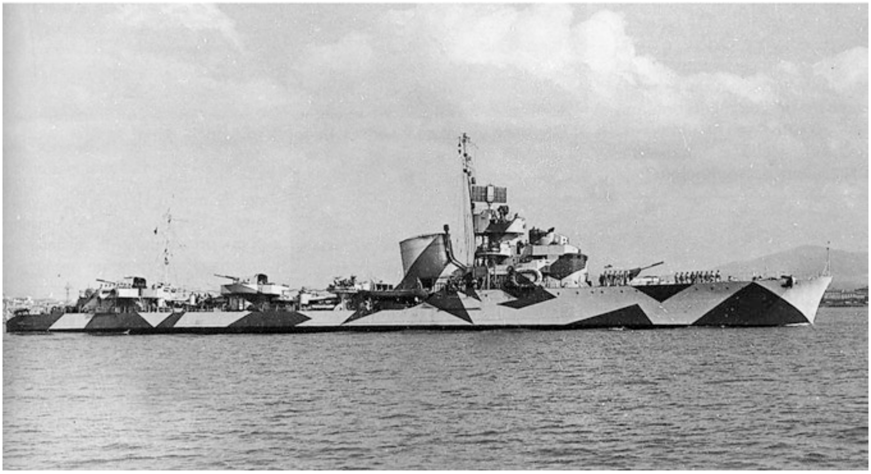

Fig. 2.35 The destroyer *Legionario*, first Italian unit equipped with an operational radar, photographed on May 18th, 1942. The antenna of the German radar "De Te" type FuMO 21/40 G is visible, after its installation in March 1942

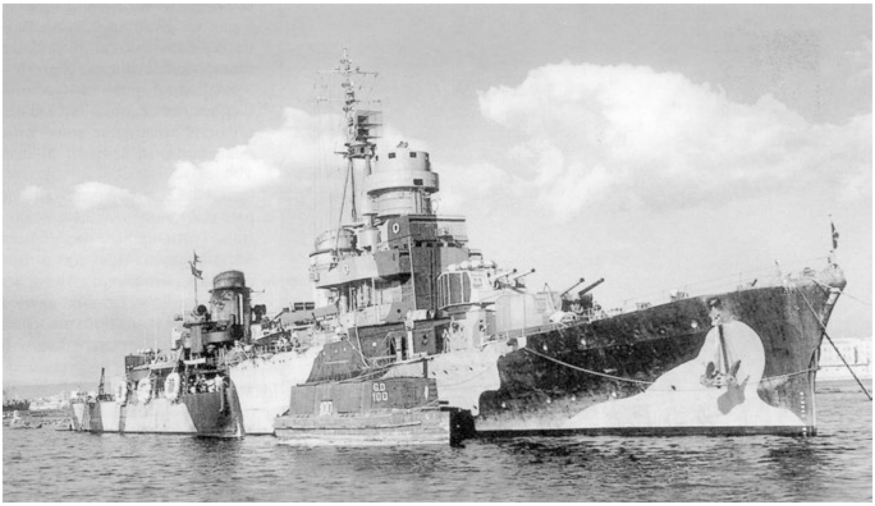

Fig. 2.36 The Cruiser *Scipione Africano* with the radar *Gufo* (October 1943)

Fig. 2.37 The Destroyer *Velite* with the radar *Gufo* (1944/45)

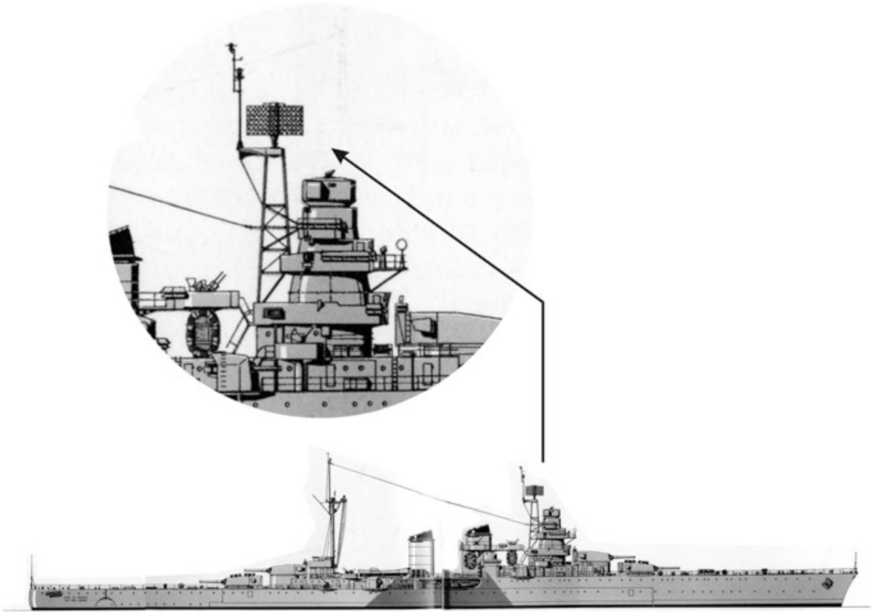

Fig. 2.38 The Cruiser *Luigi di Savoia Duca degli Abruzzi*, in 1944,with on board the German radar FuMO 21 G

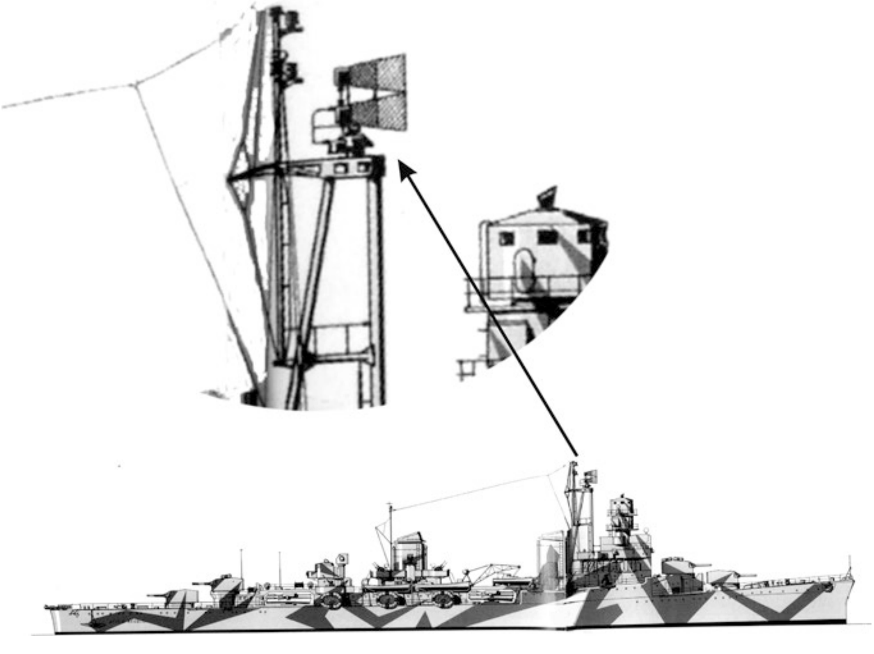

Fig. 2.39 The Cruiser *Attilio Regolo* (1943) with the radar *Gufo*

Chapter 3
A Simultaneous Invention—The Former Developments

The birth of radar, as well as that of radio-telegraphy or “wireless telegraphy”, happened in Europe in a period that has never been equalled for fruitfulness in science and technology as well as in a framework of extraordinary cultural and economic development. To this period, beginning at the end of the Nineteenth Century,[1] with Europe being in peace since twenty years, the somewhat nostalgic name was given of “*Belle Époque*” (from the language spoken in the city where *everything seemed possible*, i.e. Paris, see Fig. 3.1).

The liveliness of Parisian life produced brand new artistic phenomena such as Impressionism, Futurism (the *Manifesto* of the Italian artist Marinetti was published in *Le Figaro* in 1909) and Cubism. In this great framework for innovation and development, and despite emigration in America of more than 30 million Europeans, between 1870 and 1910 there was also an exceptional population growth in Europe, going from 290 to 435 million. Key events of the *Belle Époque* were, of course, the Universal Exhibitions aimed to show the latest innovations, the most celebrated of them being those in Paris, 1889[1] and 1900, and in Italy, 1906.[2] During the *Belle Epoque*, technology exerted a very strong cultural and social attraction. The large cities saw totally new technical services and facilities such as distribution of electrical energy which substantially contributed to construction of the underground lines in the major European towns. A new Style from Belgium, there called “Art Nouveau”, spread throughout Europe with the names of *Jugendstil*, *Liberty* and *Floreale*. The automobile and the airplane (Wilbur and

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[1] Some people define its beginning in 1889, with the great Universal Exhibition in Paris. All agree that the event that closes this era is the outbreak of W.W.I, the Great War.

[2] The “Exposition Universelle” (April, 14th–November, 12th 1900) had 50 million visitors and saw the inauguration of the first underground line of Paris (Line 1) and of important works as the Grand Palais, the Petit Palais (Fig. 3.1), the Gare de Lyon and the Gare d’Orsay, now Musée d’Orsay. The “Esposizione Universale” in Milan on 1906, was dedicated to the transportation system and took place in the area behind the *Castello Sforzesco*, today *Parco Sempione*, named from the *Sempione* tunnel, opened in the same year.

G. Galati, *100 Years of Radar*, DOI 10.1007/978-3-319-00584-3_3

Fig. 3.1 The Petit Palais, Paris, 1900

Orville Wright 1903) made their appearance with the birth of the "civilization of machines", and the telephone, invented by Antonio Meucci (1808–1889), a Florentine immigrant who died in poverty in New York after being defrauded by Western Union, underwent a rapid spread. The modern consumer society was born and, with it, advertising, which began to fill the pages of the newspapers and the walls, sometimes using true artists such as Alphonse Mucha (1860–1939).

On April 15th, 1912 the largest, luxurious passenger ship, the Titanic, launched on May 31st, 1911 in Belfast, sank because of an iceberg collision. This mournful event was a sort of "beginning of the end" of the *Belle Époque* to finish with the First World War. At the turn of the century the Nobel Prize was born, awarded annually to people "contributing considerable benefits to humanity", for research, discoveries and inventions, for literary work and finally for commitment in favor of universal peace. This award was established according to the last will of Alfred Nobel (1833–1896), written on November 27th, 1895. The first Nobel prizes were attributed in 1901, for literature, chemistry, medicine and physics.[2] At the turn of the century, scientific knowledge grew dramatically thanks to scholars such as Max Planck,[3] Albert Einstein,[4] and David Hilbert.[5]

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[3] Max Planck (Kiel, 1858–Göttingen, 1947) set up in the year 1900 the basis of quantum theory, by the basic hypothesis according to which exchanges of energy in the emission and absorption of electromagnetic radiation occur in discrete "quanta" having an energy proportional to the oscillation frequency. He was also an excellent pianist, and remained active until his late age; the last part of his life was blighted by the death of his son Erwin, killed in 1944 by the Nazis because of his involvement in the attack against Hitler in July.

[4] In fact, in 1905 Einstein (Ulm, 1879–Princeton, 1955) published several works in which he discovered the photoelectric effect of metals and the role of the quantum theory, provided a quantitative assessment of Brownian motion, and finally, introduced the theory of special relativity.

[5] During the International Congress of mathematicians (Paris, August 1900), David Hilbert (Königsberg, 1862–Göttingen, 1943) presented his famous list of 23 unresolved mathematical problems.

In this context, humanity learned how to generate and receive radio waves. The domains of electricity and magnetism, distinct at their discovery, began to converge in the nineteenth century, after the experimentation by Faraday, who in 1831 demonstrated an intimate connection between electricity and magnetism.[3] After the formalization of electromagnetism due to James Clerk Maxwell[4] and published in 1864, discovery of the basic principles of radio and radar dates back to the 1880s with the former experiments by Heinrich Hertz[5] with the generation of electromagnetic waves and their reflection on metal bodies (1886–1888). The same historical period saw development of the basic elements for emission and reception of electromagnetic waves: in 1884 Temistocle Calzecchi Onesti[6] implemented the first detector, the *coherer*. The Russian physicist Aleksander Stepanovic Popov[6] continued the experiments by Hertz and by other pioneers of radio waves and in 1894 built a receiver of the *coherer* type, with the ends connected to the ground and to a vertical conductor respectively, i.e. the first receiving system capable of detecting electromagnetic signals generated at some distance. Developed as a lightning detector, the system by Popov was presented to the Russian Physics and Chemistry Society on May 7th, 1895, a day that in the Russian Federation is celebrated as "radio day",[7] while the publication of the results by Popov is dated December 15th, 1895.

In addition to the transmitting and receiving subsystems with relevant antennas, another critical element of radar, the display, originated with the cathode-ray tube due to the scientist Carl Ferdinand Braun (Fulda, 1850–New York, 1918) who, together with Guglielmo Marconi, was awarded the Nobel prize for physics in 1909.

We have discussed Hülsmeyer and Marconi in Chap. 1, showing how the invention of the former, in a not favorable context and in the absence of clear and urgent operational requirements, was almost completely forgotten for about twenty years. In the same period, an important contribution to the knowledge of the propagation of radio waves, in particular the "shortwave" or "meter" ones, came in 1902, when Oliver Heaviside (1850–1925), and Arthur Edwin Kennelly (1861–1939) assumed the existence of the ionized layer of the ionosphere known today as the Kennelly-Heaviside layer. Heaviside proposed to use this layer for the propagation of radio signals over the optical horizon. The reflection and bending of radio rays on the ionosphere is implemented today in long distance radio communications using the

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[6] A. Popov, born in 1859 and died in 1906 (according to some, 1905), was little interested in practical applications: he did not patent his inventions, contrary to the clever Marconi, who, conversely, was very interested in the economic developments (and not at all in science). It is well known that the young Marconi, equipped, thanks to his family, with the necessary resources, patented the basic elements of wireless telegraphy early and quickly.

[7] Of course, this celebration is not shared outside Russia: in Italy Marconi is celebrated, in France, Branly, in the United Kingdom, Lodge, in the USA, Tesla, in India, Jagadish Chandra Bose …; the interested reader in the topic of the invention of radio can find a recent synthesis in [Gar 11].

HF band, as well as in some radar of the OTH (Over-The-Horizon) type.[7] At the same time two Italians, Bellini and Tosi, contributed to the development of techniques and equipments similar to those related to radar.[8]

In the work published by Nikola Tesla in August, 1917 on "The Electrical Experimenter" the brilliant inventor proposed the use of continuous-wave radio signals with a variable frequency to detect and locate movable objects, with the possibility to determine their distance and, through the frequency deviation, their radial velocity. Alternatively, Tesla suggested the use of pulses; he also anticipated the display of signals on a fluorescent screen. These techniques would be widely used in the operational radar of subsequent decades through today. Seven years later, on December 12th, 1924, Edward V. Appleton,[9] together with his pupil Miles Barnett, began a series of experiments with which he proved existence of the various layers of the ionosphere and determined their height, using the continuous-wave technique as proposed by Tesla.

In 1925, the American geophysicist Merle A. Tuve (1901–1982)—founder of the well known Johns Hopkins University Applied Physics Laboratory—together with the physicist Gregory Breit (1899–1981) measured the height of the layers of the ionosphere by the delay between the emission of pulses and their reception, giving rise to an "instrumental" version of the pulsed radar,[10] intended as a scientific instrument rather than a sensor capable of detecting and locating obstacles or targets. About ten years later, i.e. in mid 1930s, various nations pursued the latter goal, with generally *parallel* research and development activities. In fact, given the confidentiality of the topic, the communications between the different groups of researchers were minimal or null.

Also for radar, as for telegraphy, every historian (with some notable exceptions) tends to ascribe the most significant developments to the researchers of his own

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[8] Alessandro Tosi (1866–1936), engineer and captain of the *Regia Marina*, in 1907 invented with Ettore Bellini (1876–1943), which was also an assistant of Marconi, the *Bellini-Tosi radiogoniometer*, which, connected to two antennas at a right angle to each other, and to a receiver, measured the direction of arrival of impinging radio signals. The first patent was applied by Tosi and Bellini on September 28th, 1907 and registered with the number 2199/UK on May 7th, 1908. In 1912 the company Marconi purchased this patent, and started their own production. The first studies in this area date back to 1903 with experiments by Alessandro Artom (1867–1927).

[9] Sir Edward Victor Appleton (Bradford, September 6th, 1892–Edinburgh, April 21st, 1965), a British physicist, received the Nobel prize in 1947 for his studies on the ionosphere and on short wave propagation at long distances.

[10] The early bistatic radar by Breit and Tuve operated with a variation of the transmitted wavelength (metric or decametric wave) from a minimum (destructive interference) to a maximum (constructive interference) of the signal resulting from the *beating* between the transmitted signal and the echo. It is readily shown that such a variation depends on the distance; more precisely, the length of the round-trip path is equal to the speed of light divided the entity of the variation of the transmitted frequency. For a detailed explanation of the measurement methods of the height of the ionosphere, see: [Bre 26]; Appleton and Barnett, *Nature*, Vol. CXV, March 1925; Breit and Tuve, *Nature*, Vol. CXVI, September 1925.

nationality. But, while about the invention (not the patent) of radiotelegraphy, as shown before, the debate never ended, today there is a general consensus on the paternity of the radar being up to Hülsmeyer.

According to [Swo 86], the nations that contributed to radar development were: Great Britain, Germany, United States of America, France, Italy, Japan, Russia (or better Soviet Union, including Ukraine), the Netherlands and Hungary. In [Wat 09] some of the most advanced nations of the Commonwealth: Australia, New Zealand, South Africa and Canada[11] are added to the list.

The term **radar** itself was born and spread roughly at the end of this period of "parallel developments". In the 1940s the term "radar" quickly substituted those used in the various European nations, among them: *Detection Electro-Magnetique* (DEM) in France, *Radiotelemetro* or *Radio Detector Telemetro* (RDT) in Italy,[12] *Radio Direction Finding* or RDF in the United Kingdom and *Funkmessgerät* (i.e., radio measuring apparatus, abbreviated FuMG or *Funkgerät*—FuG, or even FuMO where O stands for *Ortung*, localization) in Germany; in particular, the German navy initially used the term DE.TE deriving from "DEzimeterTElegraphie" and then went to FuMO (FunkMessOrtung).

The term radar (sometimes written Radar or more seldom, recalling the original acronym, RADAR) is now used in almost all nations, with the notable exception of Russia and Ukraine, which chose the—perhaps more correct—term "Radiolocator". This well-known contraction of "**ra**dio **d**etection **a**nd **r**anging", was first suggested by Lt-commanders F.R. Furth and S.M. Tucker, responsible for the acquisition office of radiolocation equipment within the U.S. Navy. These officers[13] proposed the use of the acronym "radar" in the autumn of 1940.[14] Showing a noticeable sense of humor, Yves Blanchard, on p. 21 of [Bla 04], asks whether or not Furth and Tucker knew the ancient Persian language, the Farsi, as in this language **râ** means

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[11] An interesting history of the radar developments in Canada from the beginning of the Second World War is analyzed in [Mid 81] (see also: Revue d' histoire de l'Amerique française, vol 36, no. 2, 1982, p. 269–270, http://id.erudit.org/iderudit/304054ar). The early development of radar in Canada, started after the visit of the Tizard mission in Washington and in Ottawa in the summer of 1940, involved, as early as at the end of 1941, over two hundred researchers and technicians, mainly at the National Research Center (NRC). The Company *Research Enterprises* (REL) in Toronto produced, on orders of the Allies, over two thousand radar sets between 1940 and 1946, for the value of more than 220 million dollars, before its closure in 1946 by a (probably, not wise) decision of the Canadian government. About radar developments in Canada in the wartime period, please see: http://www.physics.uwo.ca/~drm/history/radar/radar_history.html, http://radarlab.uniroma2.it/stscradar/tizard%20canada.pdf.

[12] To maintain confidentiality, the radar committee of the Italian defense establishment was curiously named "Ra.Ri. Committee" by taking the first and the last two letters of the word *Radiotelemetri*; they also used the—even more peculiar—singular version RaRo, sometimes: Raro (which in Italian means rare, uncommon).

[13] Later, Furth and Tucker received the degrees of Rear-Admiral and Admiral, respectively.

[14] With an order on November 18th, 1940, Admiral Stark, the Chief of Staff of the American Navy, authorized the use of the term "radar" in place of the previous "Pulse Radio Equipment" and "Radio Echo Equipment". The use of this word was "authorized for all official correspondence, even unencrypted or classified … and also in the context of conversations …".

street, path, and **râdhar**[15] means *someone who makes the road*, the keeper of the track, that is, the sentry that guards the wayfarers and shows them the path. The Royal Navy used initially the terms "Radio-Location" and "Radio Direction Finding" (RDF), and adopted the new United States terminology only in 1943.

Summing up, in the early 1930s different groups of researchers and technicians worked on radar in different nations, creating a plurality of parallel histories rather than a common history. It is beyond the purpose of this volume to draw these multiple parallel histories, for which the interested reader is invited to refer to the Bibliography, which includes: [Bla 04], [Blue 94], [Bro 99], [Bur 88], [Gue 87], [Pri 89], [RDN 04], [Roh 05], [Swo 86], [Wat 09], [Whi 07], http://radarlab.uniroma2.it/stscradar/iee%20seminar%201985.pdf, and many others. As a matter of fact, after twenty years of oblivion of the invention by Hülsmeyer, in the 1920s and in the early 1930s a renewed interest arose in what we now call *radar*, mainly addressed to scientific and civilian applications.

The former were essentially devoted to ionospheric soundings, with measurements of the round-trip time (and therefore, of the height of the various ionosphere layers) realized, as we have seen, by means of frequency-modulated continuous wave (Appleton and Barnett, United Kingdom, 1924) or pulsed signals (Breit and Tuve, USA, 1925). However, these systems [Moo 78] are not generally regarded as "true" radars: unlike the radar, in "ionospheres' sounders" the concept of detection is missing, the location is in a single dimension, and in the case of stationary or slowly varying phenomena, the analysis time can be much longer than a typical radar scanning of the operational environment.

On the other hand, civilian applications of radar originated from the early problem of collision avoidance at sea, the one that stimulated the creativity of Hülsmeyer.

A first "rediscovery" of the idea of the "unlucky inventor" took place in the USA on September 1922, when Albert Hoyt Taylor and Leo C. Young from the Naval Research Laboratory (NRL), Washington, D.C., observed that the passage of boats over the river Potomac was causing interference (due to the well-known *beats* between signals). In fact, the signal of a radio link between both shores was seen to become periodically weaker and strengthened, and it was immediately clear that with such a mechanism, some detection of hostile ships would have been made possible. A report by A.H. Taylor to the Bureau of Engineering dated September 27th, 1922[8] indicated the possibility of using the "beats" method for detecting vessels, even at night and in fog. Again in 1922, Taylor and Young observed that—overnight or in poor visibility conditions—some destroyers in scattered formation could identify other naval units that crossed the borders of the formation by detecting, with special equipment, the entity of the distortion of the radio signals transmitted from ship to ship.[16] Similar observations were

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[15] This word, however, is seldom used in the modern Persian language.

[16] It must be remembered that, unlike the United Kingdom, the primary requirement of the USA in the 1930s was not the defense of their homeland (air defense), but, rather, the defense of ships and airplanes: transportable sets were needed for this aim. To implement a light and compact radar, the American designers went to higher and higher operating frequencies with relatively (transmitting and receiving) small antennae. As explained in the following, the antenna system was soon reduced to a single antenna thanks to the invention of the *duplexer*.

made in November 1930 when, in tests made at the NRL, L.C. Young and L.A. Hyland detected an airplane with a short-wave receiver-transmitter pair. A few years after Albert H. Taylor, Leo C. Young and Lawrence A. Hyland obtained the US patent No. 1981884 “System for detection of objects by radio” issued on November 27th, 1934 (application submitted on 13th June 1933), which refers to a continuous-wave bistatic system of the type “waves interference”, in which a moving object is detected through the “beats” between the signal received by direct path and the other one received after reflection by the target.[9]

Leo C. Young proposed to use, instead of the electromagnetic barriers, the pulse method, already used, as we have seen, in the ionospheres’ sounding, but very soon it was clear that to detect air targets with a kind of “pulse radar” there was a need for power levels, bandwidths and pulse repetition frequencies well above those useful to the measurements of the height of the ionosphere, and, at that time, very difficult to implement. Similar discoveries, made in different nations, brought, as already shown, the development of systems of the ‘barriers’ type, capable of detecting, by interference, air or naval targets crossing the line joining a transmitting station with a receiver. Of course the exact location of the target was hardly determined. Early barriers were due to Pierre David, as mentioned in Chap. 2; here it should be recalled that, in France during the 1920s, Camille Gutton and his assistant Émile Pierret at the University of Nancy worked on communications in the range of decimeter wave, i.e. at frequencies much higher (but with levels of transmitted power by far lower) than other scientifically advanced nations. In fact, as soon as in 1927 Gutton and Pierret worked with wavelengths of only 16 cm, and showed the possibility of detecting the presence of an object in experiments performed in the courtyard of the University. Developments of radio techniques (called TSF—*Telegraphie Sans Fil*) in France were greatly contributed by the captain, then general, Gustave Ferrié (1868–1932). Ferrié founded the *Laboratoire Central de TSF* (later called *Laboratoire National de Radioélectricité*, LNR, and directed by Camille Gutton), which opened in 1926 in a frame of civil-military collaboration between the Post Office and the Ministry of War. Working in this laboratory, in 1928, Pierre David proposed to detect aircraft with a beam of shortwave. In 1934[17] David experimented what today would be called a bistatic radar operating at continuous wave, with an emitter at the wavelength of 4 m and a receiver some km away. After the operational tests in 1937, through 1939 the “Barriere David” protected the French naval bases across the English Channel, on the Atlantic Ocean, the Mediterranean, and even the air routes of approach to Paris from the north-east.

In the Soviet Union, the first observations of the “beats” date as early as in 1897, during the experiments by A. Popov with a radio link between two warships on the Baltic Sea. In 1934 the bistatic continuous wave technique was experienced, with the subsequent production of five sets which ended in October 1934.

The book [Wat 09] describes the first experiment in radio detection of aircraft, which took place in Kharkov (Ukraine) in January 1934, when Y.K. Korovin built a radio bridge at the wavelength of 50 cm, with a limited power of 200 mW obtained with a Barkhausen-Kurz tube, and two parabolic antennas of 2 m

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[17] The first detection of an aircraft took place on June 27th, 1934.

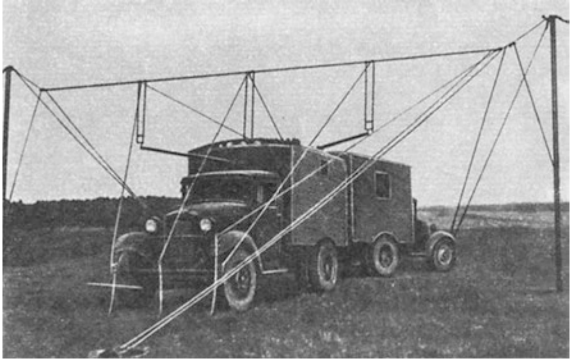

Fig. 3.2 The radar RUS-1 (receiving section)

diameter. Korovin observed the phenomenon of beating due to an airplane at 600 m distance and 100–150 m height. Further experiments, with higher power levels, in frequency-modulated metric wave (length of 5 m) permitted detection of aircraft to an initial distance of a few km, which was soon brought as much as to 75 km. These experiments were the basis for the first Soviet radar, the RUS-1,[18] shown in Fig. 3.2, that was produced in fifty sets and used in the 1940s during the war against Germany.

The first applications of pulse techniques to the radar are attributed (with a general agreement) to American researchers. On March, 1934 A.H. Taylor, who from 1930 directed the Naval Research Laboratory (NRL), entrusted to one of his researchers, the young and smart Robert M. Page,[19] the task of developing an experimental apparatus with a pulse transmitter.[20] According to many authors, the prototype by Page was the first pulsed radar, and operated for the first time on December 1934. The tests took place—just 8 months after the start of the program—on two terraces of the NRL, where separated transmission/reception antennas (the *duplexer* was still to be invented) were placed and pointed toward the Potomac river. In the pointing direction a small airplane, at a distance of about 2 km, was flying at low altitude. In these early tests the wavelength used was about 10 m, with a pulse duration of 10 μs, and a listening time of 90 μs after each pulse. Initially the receiver, not yet optimized for pulsed signals (at the time it was not clear how to implement a broadband receiver with high gain) and with a remarkable gain of 35 dB, went into oscillation due to of the pulses. However, clear echoes were seen on the oscilloscope at each passage of the plane: the

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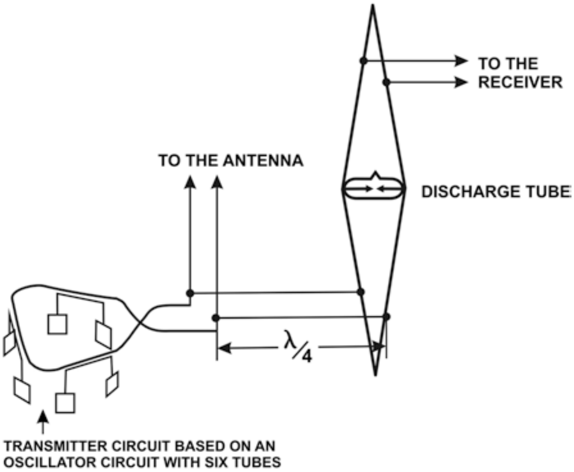
[18] The acronym RUS indicates *Radio Ulavlivatel Samoletov*, Radio Detector of Aircraft, which was of a bistatic system, with a distance of about 35 km between the transmitter and receiver, each mounted on a truck; the transmitting antenna had to be stretched between two poles. In the configuration with two receivers, the operators tried to determine the target distance by means of triangulation.

[19] Robert Morris Page (1903–1992), an American physicist, went to the Naval Research Laboratory (NRL) in 1927, and became Research Director of the Laboratory from 1957 to his retirement in 1966. For his contribution to the development of the monostatic radar has received from IRE the *1953 Harry Diamond Memorial Award* and from IEEE the *1977 Pioneer Award.*

[20] The written order to Page is dated March 14th, 1934.

Fig. 3.3 The Duplexer by R.M. Page



tests showed that the method worked. With the funding approved downstream the success of the first tests, Page improved dramatically the system, increasing both the antenna gain (using antennas made up by array of dipoles) and the transmitted power, brought to as much as 16 kW[21] with 4 μs pulses. The receiver had a sufficiently fast response time (in 1 μs, 90 % of the stationary value was reached) for a proper display of the received pulses. With those improvements, the new set was a complete success: on April 28th, 1936, always working on the 10 m wave, Page detected a small airplane at the distance of 46 km. Clearly, such a long wave was not suitable for a naval apparatus, and on May, 8th a research and development activity started aimed at bringing the wavelength to one meter and a half. This result was obtained in only 8 weeks: the first echoes on the new wave of 1.5 m (i.e., at a frequency of about 200 MHz) were observed on July 22th, 1936. The chosen frequency allowed for the reduction of size of the antenna to make it compatible with naval applications.

Another contribution due to Page, very relevant to naval applications, was the *duplexer*, a component allowing for use of only one antenna in a pulsed radar. It is a very ingenious device[22] (see Fig. 3.3) based on quarter-of-wavelength transmission lines and either "spark gaps" or gas discharge tubes.[23]

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[21] Page managed to obtain peak power levels of several kW by combining the power tubes in an annular configuration, more exactly, by creating a ring oscillator circuit with 4 to 16 power triodes: a sort of "cavity Magnetron made in short wave", see Fig. 6 of [Pag 77].

[22] During the transmitting period a gas discharge tube, or equivalent device (spark gap, …) inserted on a quarter-wave line, is excited by the transmitted pulse and conducts; thus, it operates as a short circuit, which isolates the receiver. In a similar way, during the reception, the signal is sent to the receiver rather than toward the transmitter. This operation is often identified with the designation "TR/ATR switches" where TR denotes Transmit-Receive and A, Anti.

[23] In Chap. 2 it is explained that, in lacking such a device, the *Gufo*, like other radars of that time, operated with two antennas. In naval applications, where room is always very limited, the operation with only one antenna is a great advantage.

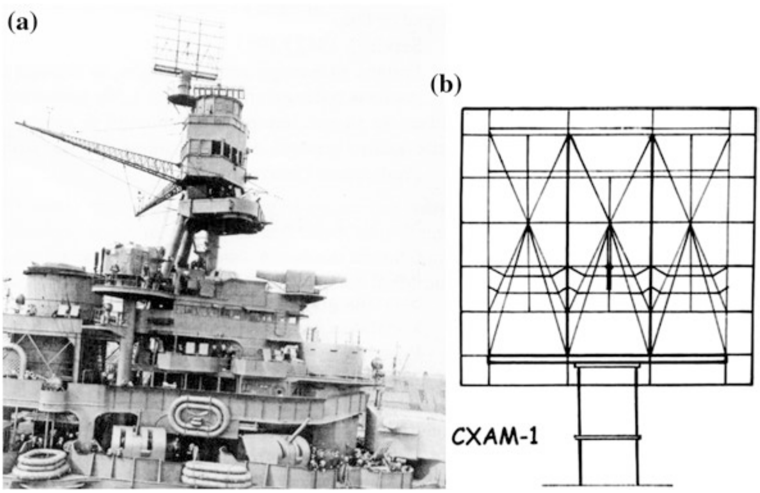

Fig. 3.4 **a** The search naval radar CXAM-1 installed on the battleship *Pennsylvania* (BB 38) in the arsenal of Sea Island (S. Francisco), February 3rd, 1942; **b** drawing of its antenna

The Page's duplexer worked for the first time, on a meter and a half wave, in July 1936, and, similar to many other strategic devices, was not unveiled outside the NRL. Using such new concepts and devices, the group of Page at NRL developed a prototype, called "Pre-XAF" [Pag 77], tested on April 1937 on board of the destroyer *USS Leary*. With a four tubes ring transmitter and a simple Yagi antenna, they obtained radar ranges were up to thirty km on a small plane, and a satisfactory detection of surface targets.

Using, in a ring configuration, six of the new tubes EIMAC 100-T and 100-TH, which at 8000 V operated well, in pulse mode, at 200 MHz, a remarkable transmitted power was obtained, which, associated with a square antenna with a side of 5 m, permitted, in the tests of February 1938, to reach ranges of 180 km on small aircraft (with pulses of 3 μs and 50 kW of power). Soon, the U.S. Navy ordered a radar set able to withstand the environmental conditions of the vessels, and the design of the operational set, called XAF, started in June 1938 and led to a prototype that was installed on Battleship *USS New York* in December 1938.

An extensive campaign of sea trials took place from January to March 1939, with detection not only of aircraft and vessels but also of navigation buoys and of 406 mm bullets in flight. Echoes from anomalous propagation, from mountains well beyond the optical horizon, were also seen. Moreover, by installing on a destroyer a rotating group of dipoles, a first system was realized for the naval identification friend/foe, or IFF: the destroyer was recognizable in a fleet of twenty ships. The US Navy ordered 20 sets of the XAF, renamed CXAM, at the RCA in 1939; these radars, both in the early, still experimental version called simply CXAM, and, in 1941, in the next version CXAM-1, (see Fig. 3.4) were installed on different large naval units (including: *California*, *Yorktown*, *Chester*, *Lexington*, *Saratoga*, *Ranger*, *Texas*, *Pennsylvania*, *North Carolina*, *Washington*) in 1940/41.

The CXAM radar, characterized by a large (5.1 × 5.4 m) array antenna with fifteen dipoles, remained operational until 1943, when it was replaced by its evolution, the SK model by General Electric, a de facto standard for battleships, cruisers and aircraft carriers, with ranges up to 100/150 nautical miles thanks to the high transmitted power of 330 kW[24] and the large antenna (a rotating "mattress" of about 5 m side). From January 1943 to April 1944, 250 SK sets were produced.

The military applications of the radar will be treated in the following, and here we come back to the first developments. It has been seen that, after the "false start" by Hülsmeyer, in the first thirty years of the XX century the radar was mainly considered useful to the detection of obstacles and vessels for the safety of maritime traffic in low or absent visibility. For example, the French patent No. FR788795 (A) "Nouveau système de reperage d'obstacles et ses applications" published on 16.10.1935 (filed on 20.07.1934) relates to a bistatic radar, with sentences that very clearly describe the application: "*Les applications de l'invention sont nombreuses et variées; elle peut servir par example à avertir de l'approache d'un obstacle un navire ou un avion navigant par temps de brouillard ou la nuit, et même à repérer la position de l'obstacle par rapport à l'émetteur, par example iceberg pour un navire, montagne ou sol pour un avion*".

In the 1930s there were, in this regard, interesting achievements, such as the radar of French production installed in November 1934, as a prototype, on the *Oregon* cargo[25] and in 1935 on the liner *Normandie* [Bla 04], [Bla 14]. This apparatus, with two parabolic antennas for transmission and reception, operating at a wavelength of 16 cm (extraordinarily small at that time) was capable of detecting boats in an arc of 45° to bow, up to about 12 miles, as well as to view the coastline, thus making safer night navigation, or navigation with fog.

In the studies and experiences that took place in France, of course before the German invasion on June 1940, there was a considerable development of *magnetrons* for radar applications at decimeter wavelengths, unlike what happened in most nations, which, at least until 1940, used metric wavelengths or, in any case, waves longer than about half a meter. The *magnetron*, a radial symmetrical tube with the cathode in its center, has the paths of the electrons emitted from the cathode controlled not by a grid, but, rather, by a steady magnetic field with lines of flow perpendicular to the path of the electrons, which, growing the magnetic field, assume trajectories more and more curved due to the Lorenz's[10] force, until they do not reach the anode any more. The acceleration due to the curvilinear motion of the electrons creates a radio frequency signal, which can be taken with a probe to be sent to the antenna for transmission. The version used in many radars of the Second World War, i.e. the

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[24] In 1941 [Pag 77] R.M. Page by connecting in a loop 6 groups, each of them made up by 2 tubes in parallel, succeeded in producing transmitting power levels as high as one MW!

[25] The initial aim (in 1935) of the Oregon trials [Bla 14] was to compare two apparatus: one with a 80 cm magnetron obtained from the first Ponte's experiments, the other with a Gutton's UC-16 triode obtained using a variant of the Barkhausen scheme; both tubes worked in CW mode. The 16 cm triode solution was adopted for the first Normandy prototype. The UC-16 triode was replaced later with a M-16 magnetron, on a pulse scheme, after the 1938 trials.

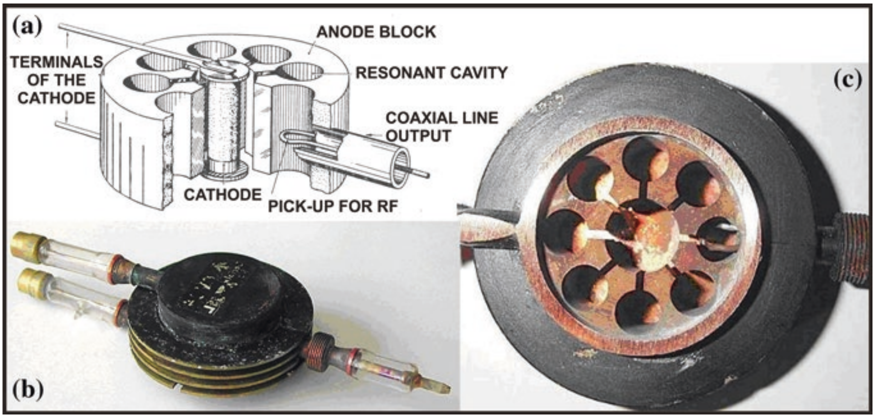

Fig. 3.5 A cavity magneton: **a** general view, **b** photo of a magnetron operating at 10 cm wavelength, and **c** the inner block with eight cavities

Cavity Magnetron, has the anode shaped by an even number of cavities (typically six or eight), so as to form a resonant structure at microwave: the energy supplied to the electrons is transformed into a microwave oscillation at the resonance wavelength. A magnetron with resonant cavities (cavity magnetron) is shown in Fig. 3.5; the applications of this device to different types of radar will be discussed later.

In the historical and technical literature, the first microwave magnetron for radar is often presented as the invention of a British team. In reality, this is not the full history, as discussed with more details in the recent historical paper [BGvG 13] significantly entitled “The Cavity Magnetron: not only a British Invention”. The experimental radar of the ship Oregon operating as early as in 1935 used a magnetron oscillating at a wavelength of 80 cm, soon replaced by the type UC 16 at the 16 cm wavelength [Bla 04]. The M-16, No. 8 Magnetron by Gutton is shown in Fig. 3.6, from [BGvG 13].

In France, Maurice Ponte and his group at the CSF company (Compagnie générale de la télégraphie Sans Fils) made an important contribution to the development of power tubes and in particular of the magnetron. It is well known that, during the Second World War, the British magnetron was the device which played an essential role in the microwave radar development by the Allies, which will be discussed later, but it is also true that on May 8th, 1940, M. Ponte brought personally in Britain the drawings of a “split anode” magnetron, [Bla 04]. An interesting example of the state of the art of French radar before the war can be seen in the patent by Elie, Gutton, Hugon and Ponte (1938), granted in the USA with the number 2433838 on January 6th, 1948.[26] This is a magnetron-based pulse radar

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[26] The original application was filed in France on December 1st, 1938, and the USA application, on December 30th, 1939 with the title “System for object detection and distance measurement” coping almost exactly with the “detection and ranging” of the acronym Radar. Likely, for the issue of the patent they expected about ten years to clear the topic from constraints of military confidentiality.

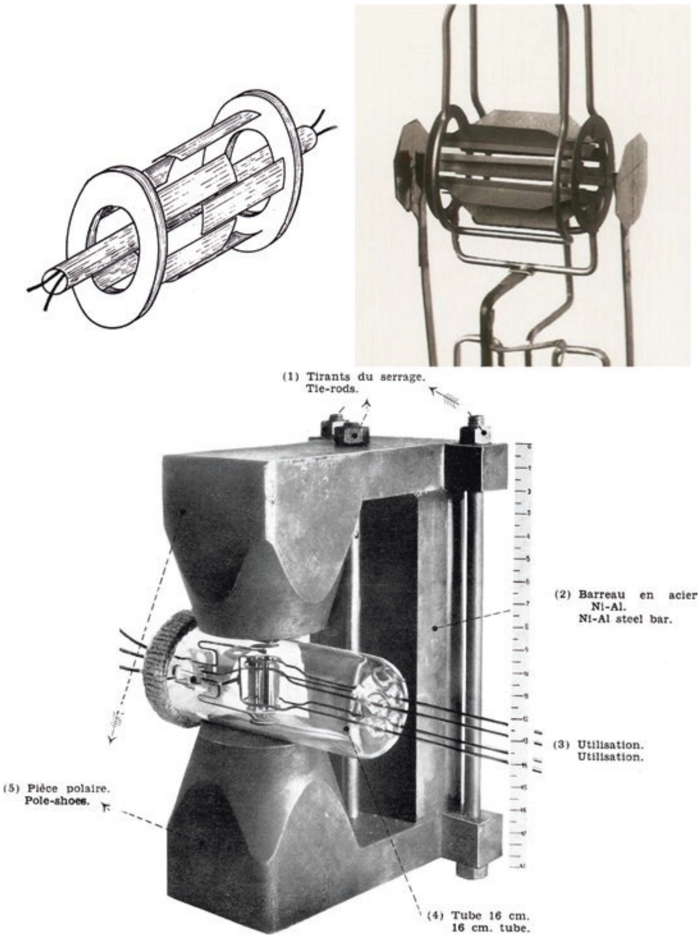

Fig. 3.6 The M-16 No. 8 magnetron—this valve gave 10 W at $\lambda = 16$ cm, with a 15 % efficiency (from [Gut 38], [BGvG 13])

with a single antenna for transmission and reception and display on a Braun's tube; the overall structure is similar to a modern pulse radar system. Figure 3.7 shows the first table (two drawings) of this patent, which, in addition to the principle of the pulsed radar with repetition period T (Fig. 1 of the table), shows (Fig. 2): (1) the parabolic antenna, (2) the feeder of the antenna, (3) the transmission line, (4) the magnetron.

The magnetron was in fact invented, in its early form, by Albert W. Hull (1880–1966) who worked at the General Electric research laboratory of and was a professor of physics at Worcester Polytechnic Institute. In 1917 he proposed to use a magnetic field to control the electronic current in a valve in order to circumvent the famous triode's patent by the well known scientist, inventor and film producer Lee de Forest

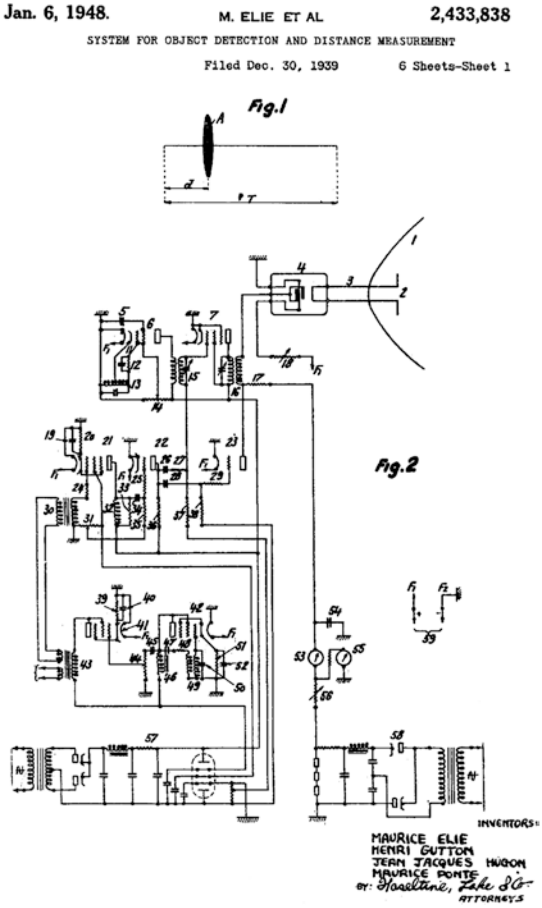

Fig. 3.7 First drawings of the US Patent No. 2433838 "system for object detection and distance measurement"

(1873–1961).[27] Substituting a magnetic for an electric field was a quite natural idea, but not without drawbacks, and General Electric found it better to buy the triode's patent. Therefore the "magnetron", whose name appears for the first time in a paper of 1921 [Hul 21], remained a lab curiosity for a while. In the 1920s, studies and achievements by Japanese, Czechoslovakian and German researchers followed,[28] up to the patent (Berlin, 1935—released in the USA in 1938) of the first resonant cavity magnetron, due to the German H.E. Hollman,[29] see Fig. 3.8.

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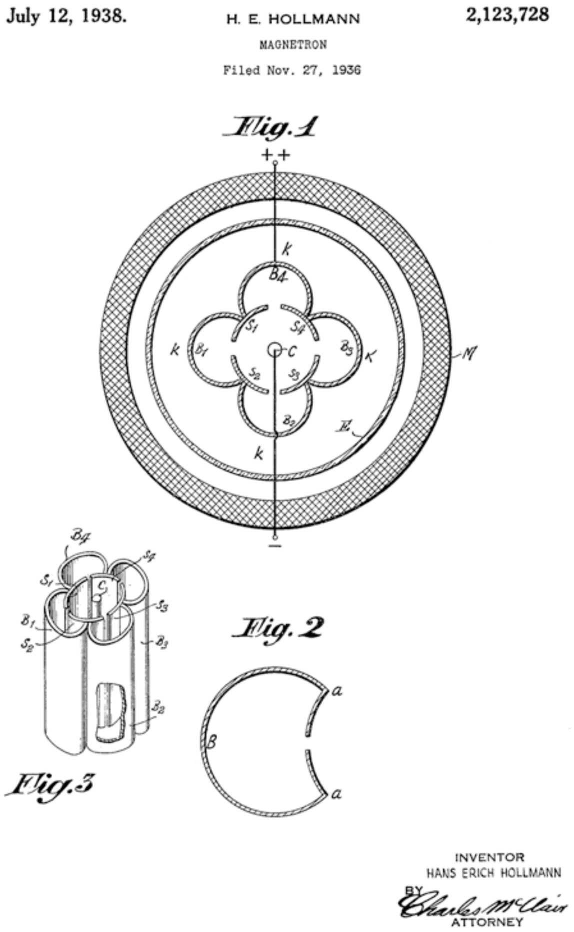
[27] The first three-electrodes tube by De Forest is the Audion, 1906; the Lee De Forest's U.S. Patent on triode no. 879532, applied in 1907, followed soon, dated February 18th, 1908.

[28] Other significant contributions to the magnetron development are due to Klaas Posthumus from Philips (NL), E.C.S. Megaw from GEC (UK), Henri Gutton (1905–1984), who succeeded in CSF M. Ponte in 1934 and others; the interested reader is addressed to [Lec 10], [Hul 21], [Gut 38], [Meg 46] and [BGvG 13].

[29] Hans Eric Hollmann (Solingen 1899—Los Angeles 1960) conceived and realized some major innovations in radar and communications in the microwave range; with Hans-Karl von Willisen and Paul-Günther Erbslöh he was one of the three main founding members of the GEMA.



July 12, 1938.
H. E. HOLLMANN
MAGNETRON
Filed Nov. 27, 1936
2,123,728

INVENTOR
HANS ERICH HOLLMANN
BY Charles McClain
ATTORNEY

Fig. 3.8 The Hollman's patent on resonant cavity magnetron

The German development of a magnetron was limited by the lack of interest of the German military authorities[30] who preferred the more stable *klystron*: this was a serious error, that did cost a lot to the Germans, as shown below.

Also in Germany, in the 1930s, they worked for the maritime safety: in autumn, 1934, Hans Eric Hollman, Hans-Karl von Willisen and Paul-Günther Erbslöh founded the company GEMA (the acronym stands for: *Gesellschaft für Electroakustische und Mechanische Apparate*). As described in the following, GEMA implemented the first commercial German naval radar; the interesting history of that firm, which, like the Italian SAFAR, did not survive the war, is narrated in [Kro 00]. Working on the wavelength of 50 (and subsequently, 60) cm, the GEMA radar could detect vessels up to 10 km (but without the information of direction and distance); this prototype was the father (in 1935) of the military radar

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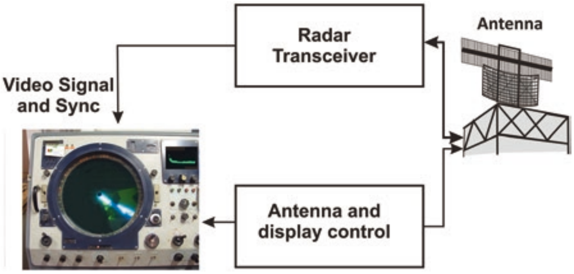
[30] Also the French military authorities paid little attention to the experiments on the magnetron that took place in France in the second half of the 1930s.

Fig. 3.9 The plan radar display (plan position indicator, PPI)



Seetakt. In fact, in 1935 GEMA, using a pulsed emitter, was able to locate the light cruiser *Königsberg* at a distance of 8 km. With the same system, aircraft at 500 m altitude were detected at a distance of 28 km. The main architects of these developments were Hans Hollmann and Hans-Karl von Willisen. Hans Hollmann—first in Germany—suggested the use of the cathode-ray tube, called a "Braun tube" from the name of its inventor, for the panoramic display of radar echoes,[31] Fig. 3.9.

Developed by GEMA and patented by Hollman in 1940, this type of display was first used in the large, metric band, long-range radar "Jagdschloss"[32] whose rotary antenna had a width of 24 m, a large value required to attain an acceptable azimuth resolution, see Fig. 3.10. The *Jagdschloss* was developed after the *Tremmen Panorama* by Siemens, able to show—over 360° and up to 300 km—the air situation, which was transmitted by cable to the surveillance center in the bunker of the Zoo at Tiergarten.

A tremendous boost to the development of German radar[33] was given by a remarkable person, general Martini.[34] Thanks to him, also Germany quickly came from the basic knowledge to a variety of efficient and reliable operating systems. A limitation to these efforts was the rivalry between Kriegsmarine and Luftwaffe, and the consequent lack of coordination between the firms: *Gema* which—on orders of the German Navy—developed the *Seetakt* and the *Freya*, and *Telefunken* which developed the various versions of the *Würzburg* for the German Air Force.

At the beginning of the 1930s the military studies on radar in Germany were entrusted to the NVA (*Nanchrichtemmittel Versuch Anstalt*: Experimental Institute

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[31] It was the ancestor of the display the Germans called "Panorama", now better known as PPI (*Plan Position Indicator*).

[32] The FuMG 404 *Jagdschloss* had a 3 m × 24 m panel antenna rotating on the whole 360°; with an output power of 150 kW on a variable wavelength between 1.2 and 2.4 m, this radar had an effective range from 80 to 200 km, with the display limited to 150 km.

[33] This development, from 1904 to 2004, is synthesized in the German Web site http://100-jahre-radar.fraunhofer.de/.

[34] Wolfgang Martini (September 20th, 1891—January 6th, 1963), was the head of the telecommunications service of the *Luftwaffe* and, from 1941 to 1945, was *General der Luftnachrichtentruppe.* He had bad relationships with his direct superior in the Wehrmacht, the Reichmarshall Hermann Goering, who underestimated him. However, Martini was able to stimulate the development of famous German radars *Seetakt* and *Freya*. After a period of imprisonment, he went back to Germany in 1947, where he resumed his career in the Bundeswehr and then in NATO.

Fig. 3.10 The Jagdschloss radar

for Communication and Detection) of the German Navy which in 1933 did the first experiments at a wavelength of 13.5 cm.

In Germany the first detection of naval targets (and, incidentally, airplanes) came in the course of NVA experiments (Dr. Rudolf Kühnold): on October 24th, 1934 at *Pelzerhaken* in the bay of Luebeck the echoes of the *Grille* boat were received up to a 12 km distance. The emission was obtained with a magnetron device at the operating wavelength of 50 cm, i.e. at a very high (about 600 MHz) frequency for that time. The success convinced the Navy to fund further studies aiming at the elimination of double antennas (development of the Duplexer), the pulse modulation and the display on the Braun tube. In the meantime the NVA realized an apparatus operating at a wavelength of about 80 cm (i.e. from 368 to 390 MHz). It was industrialized by the GEMA in Berlin (director of the technical office was Prof. Pintsch) and, as seen before, called *Seetakt*. The German Navy decided to install it since 1937 on its units, hence becoming the first Navy[35] using operational radar equipments.

After one year the ground-based radar *Freya* entered service, operating in the metric wave (around 2.4 m) where it was possible to generate high power levels (tens of kW). This surveillance radar was developed by GEMA in 1938. The Freya (Fig. 3.11) operated on frequencies around 120 MHz (waves from 2.3 to 2.5 m), and with an initial peak power of 8 kW raised to 20 kW later, see Fig. 3.12. This radar detected bombers at a height of 5000 m over distances up to 70 km (subsequently brought to 160 km)[36]; over a thousand *Freya* sets were built during the war.

The name *Freya* is an example of the fact that most nations involved in radar developments used, for these sets, acronyms or cryptic names not related in any way to the purpose or nature of the equipment, such as city names like *Würzburg*. In the Norwegian mythology[37] Freya (or Freyja or Freja) was the goddess of love and fertility (but also of war and death) that, according to the legend, had seized the

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[35] In 1938, i.e. a year later, the U.S. Navy followed on this road, as previously described.

[36] The Freya operated with a pulse repetition frequency, PRF, of 500 Hz, a pulse length of 3 μs, was not able to measure the height of a target and had a resolution of 5° in azimuth.

[37] See for instance the famous poem of the 13th century *Edda* by Snorri Sturluson.

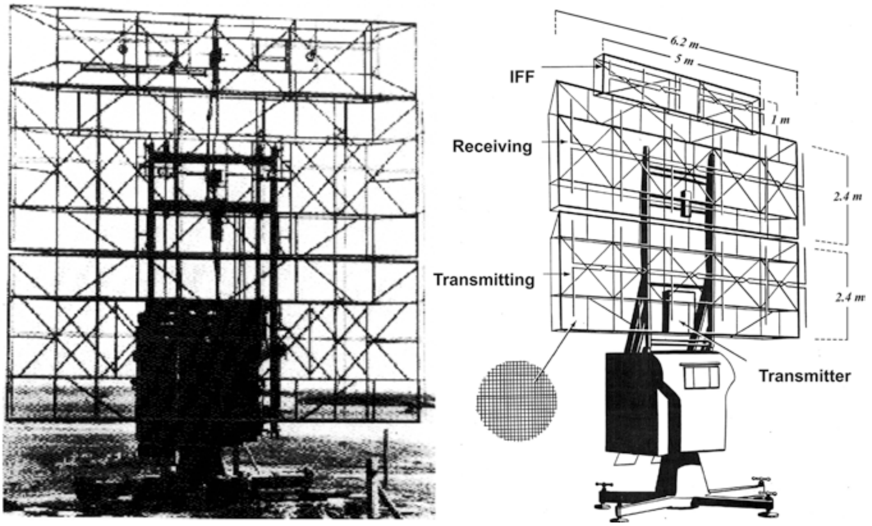

Fig. 3.11 *Freya*, one of the first German ground surveillance radars, used a wavelength about 2.4 m, with 360° coverage thanks to the rotating antenna. The concept of the identification friend or foe, IFF, with an upper, co-rotating antenna has been applied through today

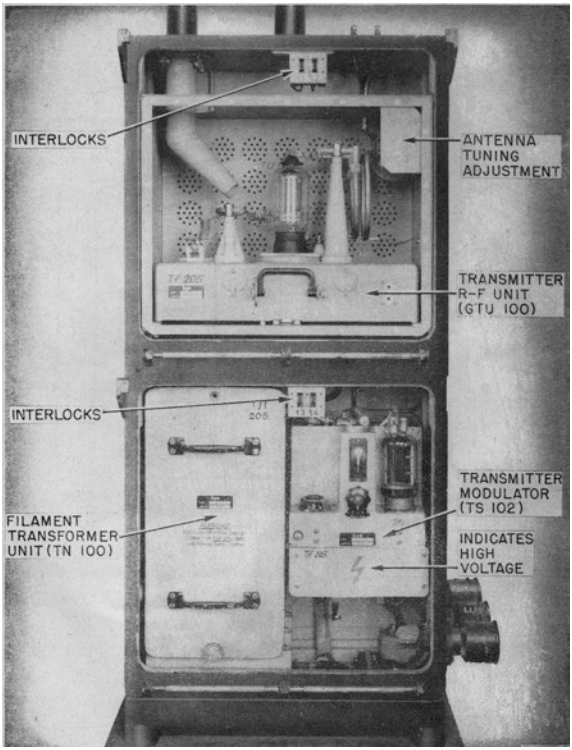

Fig. 3.12 The transmitter of *Freya*

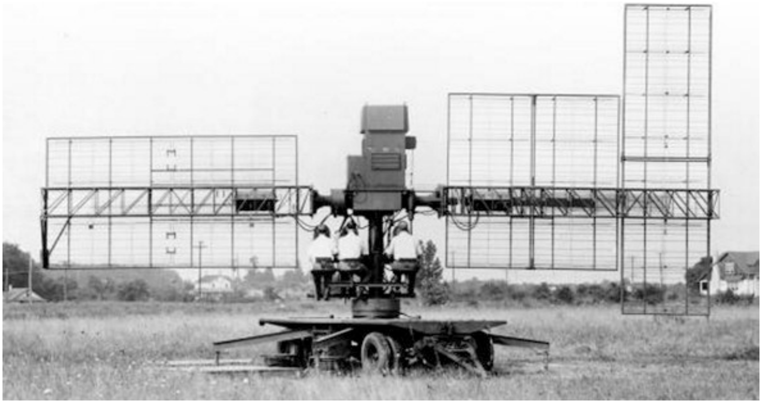

Fig. 3.13 The USA army radar SCR-268

beautiful, priceless necklace Brisingamen. The guardian of the Scandinavians, *Heimdallr*,[38] could see in all directions up to one hundred miles away. Therefore the choice of the name *Freya* was one, albeit small, exception to the above rule of safety.

Radar sets were developed in those years also in other, not yet mentioned nations, such as Japan, Holland and Hungary. The experiments and achievements across the Atlantic, in the United States, have been discussed before with the experiments with continuous wave radar and, then, with pulse radar at the Naval Research Laboratory and at MIT. In addition, the Army's Signal Corps was involved in gun-laying and ground surveillance radar, with the celebrated SCR (Signal Corps Radio: another nickname). The SCR-268 is the first (its prototype was developed in 1938) tracking radar for the guidance of anti-aircraft artillery (AAA).[39] Built by *Western Electric* and delivered from February 1941, was the only tracking radar for AAA until the beginning of 1944, when the much more accurate microwave radar SCR-584 went into service. The SCR-268 was made up three sections, co-located and co-rotating (see Fig. 3.13).

The central antenna transmitted with a relatively wide beam (of the order of 20°), while the receiving antenna on the left side was dedicated to the measurement of the azimuth, and the one at the right, of the elevation. Three operators read the values of distance, azimuth and elevation after having pointed the antenna to the target by the technique "lobe-switching", i.e. since to match the intensity of the signals of two lobes (both in azimuth and elevation) that intersected the pointing direction (i.e. the *boresight*, perpendicular to the plane of the antenna),[11] see Fig. 3.14.

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[38] This name was later anglicized in Heimdall and Heimdal. Today, in the world of communication networks, the name Heimdal indicates a version of the *Kerberos 5* protocol of the *Network Authentication Service*.

[39] This pulse radar operated on the wave of 1 m and a half (205 MHz), with a peak power 75 kW. It transmitted 4098 pulses—of duration 6 μs each—per second.

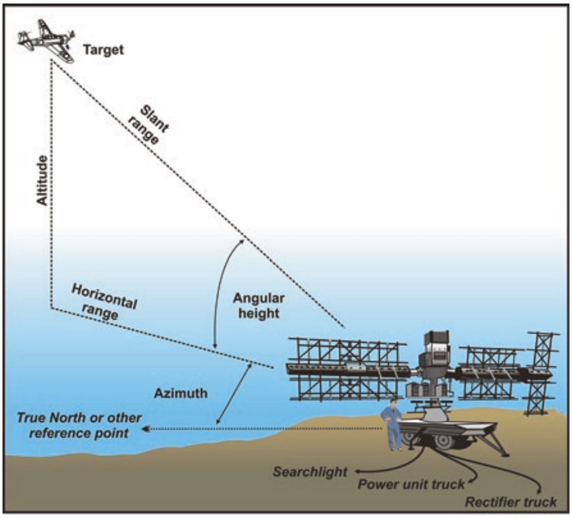

Fig. 3.14 Artist's illustration of a typical SCR-268, operation seen from the back, showing the azimuth receiving array at *left*, the elevation receiving array at *right*, and the transmitting array in the *center*. AAA guns would be sited further away, but would be connected to the radar and control units by cables

The SCR-270 and the SCR-271[40] (fixed version) were developed for air surveillance and search in the same period as the 268, and were used during a large part of the conflict.

The SCR-270 is known as the radar of Pearl Harbor[41]: the Japanese attack was detected by this radar which worked regularly, but the echoes, correctly recorded and reported by the radar operators, were attributed to those of friendly bombers B-17 aimed to the American territory, and devoid of IFF. Ironically, the B-17 arrived just in time to be destroyed by the Japanese attack. Unlike the British, the Americans had not yet developed an air defense system with integration of the information in a command and control center. Just as in other nations (including Italy), the mistrust of the military toward the new and the lack of preparation of the staff damaged the correct use of radar. However, like in Italy after Cape Matapan, the USA armed forces after Pearl Harbor developed a strong interest toward the radar. The US Army quickly installed five new SCR-270 around the island of Oahu, and two officers, William E.G. Taylor from the Navy and Kenneth P. Bergquist from the Army, began to built an "Information Center", similar to the one known as "filter room" in the British Chain Home (as described in the following chapter), to collect and integrate the radar information.

Finally, the Signal Corps studied the problem of determining the height of an aircraft with respect to the ground. In 1937 the Signal Corps charged the RCA to

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[40] SCR-270 and -271 operated on the 3 m (100 MHz) wave with a peak power of 100 kW, a pulse length from 10 to 25 μs, and a PRF of 621 Hz. They were less precise than the 268, and had no *lobe-switching,* not needed for the surveillance function.

[41] On December 7th, 1941 numerous torpedo bombers took off from the aircraft carriers of the Japanese Imperial Navy to attack the USA naval base at Pearl Harbor in the Hawaii, causing massive damage and many casualties, with the USA not yet being at war at the moment.

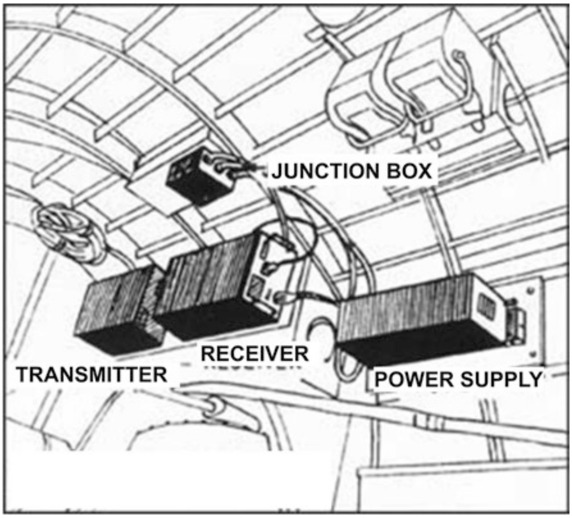

Fig. 3.15 The radar altimeter SCR 518 mounted in a B 17

develop an early Radio-Altimeter[42] (or Radar-Altimeter) which in 1940 led to a production set, the SCR-518, working on the wavelength of 58 cm. Its weight went down quickly from the initial 40 kg to just 12 kg, and was capable of an of accurate height measurement[43] from 15 m up to 6 km from the ground, see Fig. 3.15.

Further elements on the development radar in the USA are reported in [IEEE 00] and in [Bar 10].[44]

The arrival of the war caused an acceleration of the development of radar equipment. The first operational installations for the national air defense were made in 1937 by the British. The two major allied powers intensified, during the Second World War, the joint efforts to achieve operational reliable systems. The main basis of their collaboration was the already mentioned cavity magnetron. The Anglo-American technical and scientific cooperation and the radar developments in the course of the Second World War will be treated in the following chapters. On the other side, pushed by the fear of an imminent war with Germany, the United Kingdom authorities at the beginning of 1939 invited in England some

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[42] The radio-altimeter is basically a radar which, equipped with a system of pointing down antennas, measures the distance between the aircraft and the ground. The main antenna lobe must be large enough to compensate for the pitch and roll of the aircraft with respect to the ideal case of flight on a horizontal plane. A radio-altimeter often uses the FMCW technique with separate antennas for transmitting and receiving.

[43] The nominal error of the model SCR-518-A was ±15 m or ±0.25 % of the height, the greater of them.

[44] A remarkable exhibition of some USA radars used in the World War II, in the Cold War and in the recent periods is located at the National Electronics Museum of Baltimore. This was established thanks to an initiative by some employees of the Westinghouse (now Northrop Grumman) and is currently supported also by the IEEE. The website of the museum is: http://www.nationalelectronicsmuseum.org/.

representatives of most industrialized nations of the Commonwealth to transfer them the radar technology. Thus, by September 1939, radar developments began in Australia, Canada, New Zealand, and South Africa. The Australians used the British technology on the wavelength of one meter and a half to build surveillance radars aimed to protect the city of Sidney; these sets were installed a few days after Pearl Harbor. Other radars of the same type were used from the beginning of 1942 to protect the north coast of Australia from Japanese attacks. In addition, at the beginning of the war Hungary developed its own, independent radar technology, arriving to receive radar echoes from the Moon in 1946, see Chap. 5 and [Bay 47].

Particularly close and fruitful was the collaboration between the United Kingdom and Canada, where in 1940 as many as five thousand workers between radar technicians and mechanical technicians (according to somebody, six thousand) were trained at the request of the Royal Air Force. A trace of this story, secret until 1991, remains today, given that in 2003 in Canada (London, Ontario) the museum "Secrets of Radar" was opened.[45] The Canadians developed radars of the CSC model (Canadian Sea Control) and SW1C (Surface Warning 1st Canadian) that were used on board the ships of the Canadian Royal Navy from 1941 for the protection of convoys.

In Japan, long before the start of the Second World War, there were the main technologies suited for radar development [Yag 28], [Kog 10]. Kinjiro Okabe developed the "split anode" magnetron in the late 1920s, reaching with it the wavelength of 12 cm, and, shortly after, of 5.6 cm. Hidetsugu Yagi, who in 1926 collaborated with Shintaro Uda (both were from the Tohoku Imperial University) to the invention of the famous antenna, at the end of the 1920s described the technologies of the magnetron and of the microwave transmission and antennas. These elements would have allowed a more timely development of the microwave radar—but in his homeland Yagi was not heard, and his work remained virtually unknown. When the Japanese troops dismembered a British fire control radar in Singapore, they were surprised to read, in the operating manual, the term "Yagi aerial" which was obviously related to an invention by a compatriot, this invention being widely used in Great Britain, Germany, USA and Soviet Union, but very little in Japan.

Even having kept the U.S. radar sets (SCR-268 and SCR-270) in the Philippines, the Japanese, although advanced in the radioelectric technology, did not succeed to proceed quickly in the development of efficient and reliable radar sets. This is probably due both to the rivalry between the army (IJA: Imperial Japanese Army) and the imperial navy (IJN: Imperial Japanese Navy) and to a not complete understanding of the operational role of radar. Only at the end of the conflict, too late to influence it actually, the Japanese had gun laying radar, naval radar range in centimeter wavelengths and airborne radar.[46] Once having

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[45] This Museum (see: http://secretsofradar.com) is mostly the result of work of some of the volunteers that had been part of the ancient radar training center.

[46] These airborne radar were installed on the fighter Nakajima J1N1, on the bomber Mitsubishi G4M and on the reconnaissance aircraft Kawanishi H8K.

discovered radar on board the vessels of the Allies, the Japanese developed in a short time a ground-based search pulse radar, the IJN Mark I Model 1 in production from autumn 1941, which was built in about 80 sets.[47] The IJN Mark II Model 1 followed for naval applications, operating on the wave of 1.5 m (200 MHz), built at about the same number of sets as the Mark I. From the SCR 268 the Japanese derived a fire control (AAA) radar, the IJN Mark IV Model 1. The Japanese knew the technology of cavity magnetron before the Allies, and developed the naval radar IJN Mark II Model 2 in 1942: a magnetron radar on the wave of 10 cm, power 2 kW, range 35 km, with two separate antennas, transmitting and receiving, of a conical shape (horn type), manufactured in about 400 sets. The IJA developed other radar equipment an almost completely independently way of the IJN. Among them, the IJA Tachi 6,[48] is noticeable.[49] Details on radar of the Japanese army are available in http://en.wikipedia.org/wiki/List_of_Japanese_World_War_II_radars.

Summing up, the *conclusions* chapter of [Swo 86] is correct in stating, first, that "The political support, the management and the effective collaboration between the involved realities were the main factors for the effectiveness of the development of radar in each nation. These factors seem to be have been strong in the United States and the United Kingdom, but somewhat weak in Italy and Japan" and, second, that "radar was a natural development for each nation equipped with active radio industries.....his arrival in the 1930s, added a whole new dimension to radioelectric science and technology".

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[47] The IJN Mark I Model 1 worked on the wavelength of 3 m (about 100 MHz), had a peak power of 5 kW (with a pulse length from 10 to 30 μs), and a range up to of 145 km on air targets.

[48] This particular Japanese designation has to be explained. Tachi (or Ta-chi), a contraction of "Ta", "Tama Institute", the Institute of research and development, and "chi", which derives from the Japanese word that indicates the earth, is to say the "Tama Institute—ground based radar". Similarly *Tase* indicated a naval radar and *Taki* an airborne radar.

[49] This radar operated on the 4 m wave, with a wide transmission beam such as the Chain Home, a transmitted power from 10 to 50 kW and a range up to of 300 km; about 350 sets were built, with operations from 1942.

Chapter 4
Air Defense and the *Alleged Father* of Radar

The development of radar in Europe, particularly in the period 1937–1945, has been strongly influenced by the need for a defense against air attacks (i.e. from bombers) as well as by Navy requirements. In fact, in the 1920s and 1930s aeronautics had a fast development, with payload capacity and maximum flight range strongly increasing, up to making possible first, mail flights and then, commercial flights with passengers.[1]

The new aeronautical techniques also created a new potential threat in bombers[1], which could not be effectively contrasted by the defense systems at the time. The air threat became more dangerous by the increasing capability of night flight (and of night bombardments), with new precise navigation systems and guidance [Pri 09]. The preface by G. Alegi[2] to [Pri 09] contains the following concept: "*The various applications of radio systems—from navigation to search, from communications to radar interception—acted as a multiplier for the effectiveness of the aircraft, both in offensive and defensive usage… One of the pillars of the theory of air power … was … to cross the border safely and make the whole enemy territory as an objective. This concept was based on the idea that stopping an air attack was impossible because … in the sky it is not possible to lay barbed wire. The history of air operations of the Second World War showed the limits of this conception … (with) the introduction of a radio defensive network able to discover the bombers raid and to direct fighter aircraft against them… On the other hand, different radio systems helped the aviation to find the targets and to return home safely…*"

So the bases of modern systems CNS (Communications, Navigation, Surveillance) and C3I (Command, Control, Communications, Intelligence) were

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[1] On December 17th, 1935 the DC 3 started flying. With such aircraft, the first big airlines could operate, and in 1935/36, in the USA, the first air traffic control systems, initially private and then federal, were born.

[2] Gregory Alegi (1963) is a military historian and a journalist. His research interests are centered around the "Air Power", on which he has published numerous essays.

G. Galati, *100 Years of Radar*, DOI 10.1007/978-3-319-00584-3_4

founded, with: radio aids to navigation and landing, air/ground/air radio communications, search and tracking radar, systems for the identification of enemies versus friends (IFF: Identification Friend or Foe) and for the intercept and the disturbance (jamming) of enemy radars, and so on.[3]

In the 1930s the *Lorenz* system, of a German design, for instrumental approach was operating; at the beginning of the war, Germany had the sophisticated and very precise *X Gerät* system for the night guidance of bombers and the automatic release of the bombs, and the simpler *Knickebein* system derived from *Lorenz*, with which it was possible to guide a bomber at 6 km altitude on targets distant up to 430 km, with a theoretical precision of 1.5 km at 300 km. Some *Knickebein* stations located in Germany (and subsequently, also in Norway) permitted the guidance of bombers over London. Such systems are described, together with those—*Oboe*, *GEE*—by the Allies, in [Pri 89].

The rearming of Germany, despite the agreements of Versailles, became important with the rise of Hitler[2] to power. In 1933 Goering,[4] a famous aviator, commander of the Richthofen team in the 1914–1918 war, became "Minister of the air" and the first aircraft equipped with machine guns (Junkers, Heinkel, Focke Wulf) did appear. As soon as in 1935, the year of establishment of the Luftwaffe, there was a clear need, especially in the United Kingdom, for defense against attacks from the air. While, for the European nations, a military aircraft had essentially defensive purposes, for Goering—the head of the Luftwaffe—it was mostly dedicated to aggressive aims. Summing up, at the beginning of the Second World War (September 1st, 1939) Germany had developed aeronautics and related instruments to a better extent than any other European nation, with production capacity peaks up to 3000 aircraft per month (against 1000 at the beginning of the conflict).[5]

For air defense, the United Kingdom and other countries had to devise and install various systems of every type and size, formerly based on sound localization. Some of them were fixed on the ground and used "sound reflectors" or "sound mirrors", made by walls with a parabolic shape. In some cases they were made up of very wide (as much as 60 m) and tall (10 m) concrete reflectors; in other cases, by steerable metal reflectors with metric sizes, as shown on the cover of [RDN 04]. The surfaces were designed to reflect and transfer the sound from the engines of incoming aircraft to the ears of the operator, with or without microphones, see Fig. 4.1.

As early as in 1916 the British had built numerous acoustic reflectors made up of reinforced concrete as early warning systems and location of the *Zeppelins* that during the First World War threatened their coastal cities. These systems were

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[3] These techniques (and the related systems) are the subject of the modern *electronic warfare.*

[4] Hermann Goering (1893–1946) entered the NSDAP (Nationalsozialistische der Deutschen Arbeiter Partei) in 1920. He was designated by Hitler "his successor". Sentenced to death by hanging at the Nuremberg trials, he committed suicide in prison.

[5] During the conflict, through to its conclusion on May 7th, 1945, the Luftwaffe lost about 95,000 aircraft of every type and about 200,000 between officers and soldiers.

Fig. 4.1 Sound mirror—in *Denge* near *Dungeness* in Kent, Great Britain (in the area in front of the wall the researcher William Sansome Tucker installed 20 microphones for a better search for the direction of arrival of aircraft)

installed up to the beginning of the 1930s.[6] In fact, during the First World War, the British government ordered some scholars doing their military service to study the acoustic localization of aircraft. Among them was the physicist William S. Tucker who, during the German attack in London in 1918, became a member of the team that ran the sound surveillance system on the coast of Kent and called those sensors "sound mirrors". In that area, at the end of the 1920s the experimenters had erected five circular sound mirrors of reinforced concrete with different diameters (from 6 to 9 m) and several different focal lengths. It was soon clear that a reasonable efficiency could be reached only for a sound wave length less than or equal to about a tenth of the diameter of the reflector, and therefore for sound frequencies higher than 300–500 Hz. However, the roar of the aircraft's engines contained much lower frequencies; so, Tucker, in order to use the waves on 60–70 Hz, added a sixth sound mirror with a horizontal parabolic section 60 m wide and over 8 m high. This new system not only was much larger than the others, but had a new type of detector, the "hot wire" microphone. When the acoustic waves reach the—electrically heated—wire, the wire's vibrations increase the heat dissipation and the wire tends to become cooler. As a result, the electrical resistance changes, and the presence of the sound source is detected by the variation of the current in the wire.

In the summer of 1934 the results of the twelve-years activity by Tucker in the hills of Kent were the subject of a visit by senior officers of the Air Ministry and

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[6] Those that have not been destroyed are now a tourist attraction, see: http://www.andrewgrantham.co.uk/soundmirrors, http://www.flickr.com/groups/780291@n22/pool.

scholars including Robert Watson-Watt.[7] The latter was very interested in the technical means for the defense from air attacks. Despite the doubts related to the sensitivity of sound mirrors versus the environmental noise and to the short warning time, at the end of January 1935 the British Ministry of Defense decided to proceed with the installation of a complete alarm (early warning) system against air attacks. Tucker was therefore asked to schedule the needed communication infrastructure, consisting mainly of telephone lines and telephone switches. In June 1935 over 500 people of the Air British Ministry worked on sound mirrors. However in August a letter from the Ministry suspended its activities until the end of September 1935. The delay, which finally became a final stop, was justified by new, alternative detection means, on which Great Britain took the final decision in the last months of 1935, as will be shown in the following.

Also other nations (including Germany: see for example [Wes 01]) tried to anticipate the moment in which the roar of airplanes attackers is heard, by trying different types of "aerophones" (see Fig. 4.2). For example, Italy used them during the entire war period, often exploiting the excellent hearing of visually impaired people.[8]

Of course, these systems, being based on the sound emitted by the aircraft itself, had significant limitations. The first one derives from the fact that, due top progress in aeronautical techniques, the forward speed of the aircraft arrived quickly to be of the same order of magnitude as sound[9] speed. However, the pressing need to detect the enemies aircraft in advance led the European nations to put in place many aerophones, even on ships, where the environment is even less favorable than the terrestrial one. At sea, in addition to the effects of the relative movement between the ship and the surrounding masses of air, there is more environmental noise than on the ground, and the size of the "artificial ear" is limited by the lack of space available (see Fig. 4.3).

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[7] Sir Robert Alexander Watson-Watt (1892–1973), Scottish, in 1912 obtained a degree in engineering at the University of Dundee, where he was introduced to radiotelegraphy. From 1916 he dealt with meteorology, in particular the location of lightning, obtained with directive antennas. In 1933 he became director of the Radio Department of the *National Physical Laboratory* (NPL) at Taddington. On September 1st, 1936 Watson-Watt was appointed director of the *Bawdsey Research Station*, the new institute of the Air Ministry, the Ministry which controlled the RAF.

[8] Between the beginning of 1940 and June 1943, 826 visually impaired men in Italy overcame the tests of "listeners" and were enrolled for the discovery of air attacks. It was the first time in the Italian history that some blind people actively participated, although without weapons, to war operations with delicate and critical tasks.

[9] During the Second World War, the bombers arrived at heights of 7 km and at speeds of up to 450 km/h, almost half of that of sound, making the warning time very short. The bomber moved typically at high altitudes while the sound, when detected, has traveled a long way, from the aircraft on the ground, i.e., on the diagonal of a triangle. In [Sad 06] it is explained that the *aerophones* were inefficient since the sound of a bomber that moves toward its target by flying at two hundred knots and twenty thousand feet reaches the target after the plane itself!

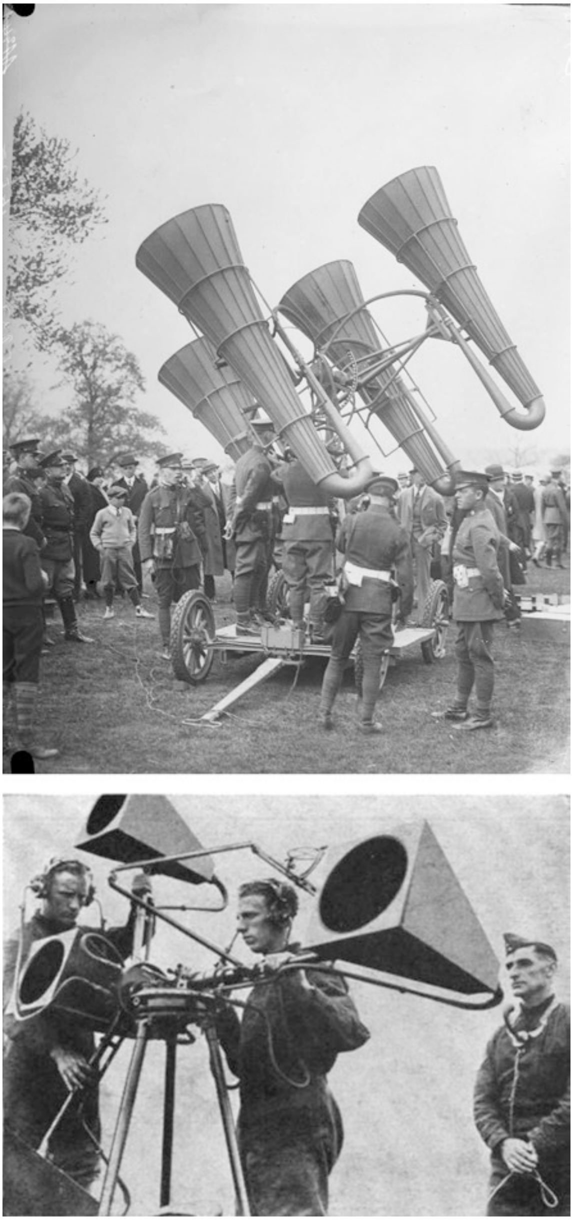

Fig. 4.2 Various types of "Aerophones"

Fig. 4.3 A naval "Aerophone"

In a speech by Churchill[10] in the House of Commons on March 14th, 1933, radar is not explicitly mentioned but the need for it is clearly expressed in order to improve the air defense: "I was disappointed to learn … that we are the fifth air power and the problem … was delayed for another year. … it would be wise from our side to focus … on the issue of the development of our air defense".

The concept was repeated by Churchill in several occasions between 1934 and 1935; in that year Churchill wrote:

> However, we should forecast that in a war in which the three military forces were employed, there will be attempts to *set fire to London* or other large cities easily reachable in an attempt to severely test the will and the resistance of the Government and the people under these terrible plagues. Moreover we must remember that the port of London and the arsenals from which the life of our fleet depends are military targets of the greatest importance. There is the odious possibility that the rulers of Germany deem to be able to break down a nation in a few months, or even weeks, by means of violent mass raids from the air. The concept of tactics based on psychological violence exerts a special attraction on German mindset… If *the aerial bombardment against our cities could be limited or prevented*, the hope (which always could be illusory) to break our spirit with the "terror" would vanish, and finally, the decision would be entrusted to armies and navies. The more our *means of defense will be reinforced*, the more the Germany will be wary about a war based solely on the air force. (W. Churchill—July 23rd, 1935).

The words of Churchill describe very effectively the anxieties of the second half of the 1930s, especially (but not only) in the United Kingdom; the countries involved waited for the war from one month to another, with the possible threat of bombing aimed to weaken the spirit of their populations, as well as to destroy their own production system.

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[10] Sir Winston Leonard Spencer Churchill (November 30th, 1874—January 24th, 1965), a politician, historian and journalist, as prime minister of the United Kingdom from 1940 to 1945 has conducted the Great Britain during the war.

Fig. 4.4 Sir Robert Alexander Watson-Watt

In 1933, the British Air Ministry appointed a committee for the modernization of the air defense of the United Kingdom, the *Scientific Survey of Air Defense*, or *Tizard Committee*,[11] from the name of its president, the colonel Henry T. Tizard (1885–1959), chairman of the Aeronautical Research Committee. In this context, H.E. Wimperis, director of the Scientific Research of the Air Ministry, wrote to Robert Watson-Watt (Fig. 4.4) who headed the Radio Research Laboratory, a part of the National Physical Laboratory, and asked him to study the possibility of radiating, through electromagnetic waves, enough energy to constitute a "death ray".[12] Hence, Sir Robert Watson-Watt asked his assistant Arnold F. "Skip" Wilkins (1907–1985) to "calculate the radio frequency power required to raise the temperature of eight pints of water from 98 to 105 °F at the distance of 5 km and at the height of 1 km". We do not know whether Wilkins understood, or not, that Watson-Watt referred to the head of the pilot of an enemy aircraft, which he wanted to bring from ordinary 36.5 °C to a fever level of about 40.4 °C and, for ease of calculation, was replaced by about three liters of water. However, Wilkins quickly came to the conclusion that the required power levels were much higher than the highest which could ever be generated. On the other hand, it seemed that

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[11] The Committee—which met for the first time at the end of January 1935—in addition to its president included some remarkable civilians, i.e. professor Hill, professor Blackett (both, Nobel prizes), H.E. Wimperis and finally the physicist A.P. Rowe (1898–1976), director of the *Telecommunications Research Establishment* (T.R.E.). With typical British pragmatism, the civilian members of the Committee immediately got full access to all the information covered by military secret, including the "top secret" ones.

[12] In 1935 this hypothesis was not fully absurd: for a long time there were rumors in the press about the hypothesis of using radio waves as a weapon capable of stopping internal combustion engines or to disable the pilots of hostile vehicles.

the reflected energy from the aircraft could be in an amount sufficient to be detected. Wisely, Watson-Watt responded to the question asked by Harry Wimperis as follows: "…what do you say if in any case we could locate airplanes before their arrival? If we could certainly establish their arrival from a certain direction, it would not be a great aid, anyway?".

Urged by the Tizard Committee, which had met for the first time on January 28th to discuss the result presented by Watson-Watt and Wilkins, on February 27th, 1935 Watson-Watt delivered the final form of a memorandum—classified *Secret*—entitled "Detection and Location of Aircraft by Radio Methods"; this document was submitted after a "draft" version presented on February 12th to A.P. Rowe and a previous one written between January and February; the full text of both is annexed in Appendix D of [Swo 86]. In this memorandum, Watson-Watts describes a radar system to detect aircraft and to locate them in three dimensions, and proposes the pulse technique (also defining the range of possible values for the pulse repetition frequency). Following his own idea, Watson-Watt obtained a first success in the experiments done on February 26th, 1935 in Daventry, where he and Arnold Wilkins realized a kind of *passive radar* using as emitter a local radio station of the BBC in the wavelength of 49 m. The trials were held in the greatest secrecy—besides Watson-Watts and Wilkins, only A.P. Rowe[13] was present. A Heyford—Handley Page bomber of the Royal Aircraft Establishment flew in the area so as to intercept several times the beam of the radio station of Daventry, and Wilkins, Watson-Watt and Rowe clearly perceived the reflection of the signal on the cathode ray display. After the success of the experiment, Watson-Watt gathered a few researchers, among which was the Welsh physicist Eddie Bowen (see next chapter), to develop the new technology.

A small laboratory was created and directed by Watson-Watt, located in a secret and isolated location (Orfordness in Suffolk, on the North Sea coast, in the area of an old military base). In a few weeks, the group developed and put into operation the transmitter and the receiver. As early as in summer, the transmitted power was brought from the initial value of 20kW up to 100 kW, always on the wave of 50 m (6 MHz). On June 17th the first target, a seaplane, was detected at a distance of 27.5 km. The detection range of air targets increased quickly, from 130 km in December to 160 km at the beginning of 1936. In order to avoid interference with the radio-communications of that time, the 49-m wavelength, initially chosen to provide the resonance condition on the wingspan of about 25 m typical of the main bombers, was almost halved. Luckily, on the wave of the 26 m, as compared to the original 49 m, the range reductions were not significant. The final wavelength, used throughout the war and beyond, was 10–15 m (20–30 MHz). Large structures were soon needed, in order to accommodate the large antennas and to

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[13] Albert Percival Rowe (1898–1976) was the Director of the *Telecommunications Research Establishment* in the period 1938–45. In Great Britain during the second world war he was one of the key personalities in the development of radar, both terrestrial (Chain Home) and airborne (H2S, see Chap. 6). A.P. Rowe wrote the first published book on the history of the radar, [Row 48]. For his non-trivial biography, see http://adb.anu.edu.au/biography/rowe-albert-percival-11572.

allow for the necessary separation between transmitting and receiving systems. For the transmitting one a 110 m high gantry was used, while for the receiving antenna they used 73 m high trestles. The new site was obtained thanks to the acquisition of Bawdsey Manor, in Suffolk, a few km south of Orford. The operation of the new Bradsey Research Center started in March 1936. In a few weeks, goniometric techniques were implemented for measuring the azimuth and elevation angles of the targets: in this way real radar surveillance was possible. Such a speed can be explained with the pragmatic approach of Watson-Watt and his theory of the "third best", according to which the "first best solution", although constituting excellence, should not be pursued because in practice it will never come, the "second solution" (after the best) is not feasible because, usually, it arrives after the user's deadline (i.e., too late for the customer), and finally the "third best solution" can be acceptable, and has to be pursued. In fact, one of the constraints of the "Chain Home" project was the use of available devices and components: the development of new elements was not considered compatible with very tight deadlines and with the acceptable level of risk. On April 12th, 1935 Watson-Watt obtained a patent for this new radar system (British patent GB 593017).

In December 1935 the British government ordered the first five stations of the "Chain Home" system to cover air approaches towards London and the Thames estuary. Three Companies were involved: A.C. Cossor, Marconi and Metropolitan Vickers. The first station was installed in Bawdsey, on the Suffolk coast. On May 1937 the government ordered twenty more stations. Using the previous five stations, in September 1938 it was possible to track the flights of Prime Minister Arthur Neville Chamberlain[14] to and from Munich to sign an ephemeral peace with Hitler.[15] At the beginning of the Second World War, nineteen radar stations were operational, ready to play a fundamental role in the Battle of England.[16] It seems that the Germans, whose radar technology used much higher frequencies than those of the Chain Home, initially believed that the network of stations equipped with high trestles was a system of long-distance communications for the British Navy. As a matter of fact, the Germans never damaged seriously the Chain Home, whose trestles, on the other hand, were less sensitive to the shock wave of

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[14] Arthur Neville Chamberlain (March 18th, 1869—November 9th, 1940) by May 1937 was the successor of Stanley Baldwin to the head of the British government. He tried to find a line of dialog with the Germany, in order to avoid the war, but he also started the British rearmament and finally decided for the declaration of war to Germany on September 3rd, 1939, a few days after the invasion of Poland. He resigned in favor of Churchill on May 10th, 1940, after the German invasion of Norway.

[15] The Munich conference was held on 29th and 30th September 1938 between the heads of government of United Kingdom, France, Germany and Italy for the discussion of German claims on the portion of territory of Czechoslovakia inhabited by the Sudeten Germans (a population of German ethnicity and language) and ended with the agreement leading to the annexation of vast territories of Czechoslovakia by the German state. In reality, only six months later, despite the Munich Pact, Hitler invaded Bohemia and Moravia, including Prague.

[16] At the end of the war the fifty stations were kept in operation for a few years. Subsequently, they were generally dismantled and some of the many trestles were recovered for other purposes.

an explosion than any stone or masonry building. Moreover, when a station was damaged, skillfully the English transmitted signals of the same type using the other stations, or even using normal broadcasting stations. In such a way the Germans got the impression that damaging the Chain Home was very difficult or useless.[17] It is well known that on August 1st, 1940 Hitler wrote the order No. 17, i.e. the start of the *Adlerangriff* (Eagle's Attack) operation with air attacks to the UK, followed by a series of successive attacks from August 8th. However, the Chain Home always worked, despite the bombing on August 12th making not operational some stations, hence creating a momentary "hole of coverage" of about 100 km, which was not discovered by the German command. The resistance of the British Air Defense and the lack of control of the air above the British Channel was one of the reasons why the invasion of England (*Unternehmen Seelöwe*) was continuously postponed by Hitler, and finally never done.

The coverage of the Chain Home in September 1939 (i.e. at the beginning of the war) is shown in Fig. 4.5, while an example of its display is depicted in Fig. 4.6 and the transmitting apparatus in Fig. 4.7.

Summing up, the radar by Watson-Watt was the basis of the British air defense system (the first in the world able to guarantee the coverage of an entire nation) which worked continuously during the Second World War. This is to say that in the years 1935–40 the British, thanks to the maturity of their industry and the collaboration between different institutions, were the first ones able to put in service (not the radar, but rather) what today is called an Air Defense system. The control of the whole system was entrusted to Sir Hugh Dowding, an Air Chief Marshal, who was a radio pioneer during the First World War.

The former stations of the Chain Home (short for *Chain Station Home Service*, with acronym C.H.) had large fixed antennas operating at decametric wavelengths, while the stations of the C.H.L. (*Chain Station Home Service—Low Cover*), for the detection of low altitude (500 ft.) aircraft, were operating at about 200 MHz[18] (i.e. a wavelength about one meter and a half), with a lower transmitted power. The antennas of the C.H. stations were fixed, while those of the C.H.L. stations (array antennas made up by 32 dipoles) were rotating and mounted on tall trestles. Until 1941 the rotation of the antennas was manual, driven by WAAF's (see later) through pedals. The operation, in principle, was simple: the volume of airspace to monitor was entirely covered, or flooded, by pulsed radiofrequency energy from the transmitting stations. The backscattered energy from targets present in this volume was picked up by the receiving stations, equipped with antennas with pairs (called X and Y) of crossed dipoles, connected to low noise and high gain

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[17] In the Battle of England the Germans did not implement what it is today known as Suppression of the Enemy Air Defenses (SEAD), which is carried on in the early hours of attack to the enemy territory, using missiles, often of the anti-radiation, or antiradar (ARM) type and cluster bombs.

[18] The rationale for such a higher frequency is that the minimum elevation angle in order to see targets above the sea is proportional to the ratio between the radar operational wavelength and the height of the antenna. The related, well-know phenomenon of *lobing* was also exploited by German bombers who learned how to fly at low altitudes during their attacks to London.

Fig. 4.5 The chain home coverage at the height of 5 km at the beginning of the Second World War

receivers. The distance was obtained by reading an oscilloscope whose time scale was synchronized to the transmitted pulse, and the azimuth was derived from the Y/X ratio of the amplitudes received from the crossed dipoles. Such a system could only work in the absence of echoes due to the ground, i.e. without "ground clutter". Therefore the Chain Home allowed only the coastal surveillance, as needed by the U.K. According to many, the success of such a rudimentary radar system was largely due to the incredible capacity of their radar operators[19] due to their specific training, and also their strong motivation. More precisely, these operators were the girls of the WAAF (Women's Auxiliary Air Force), the RAF

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[19] As a matter of fact, they were able to detect and track signals well below the noise level of the receiver. The reason why was never completely clarified; probably the operators implemented a sort of "pattern recognition" with which they could distinguish the useful signal from the noise. This hypothesis is consistent with the fact that in the Chain Home a useful signal reappears at every pulse repetition period (i.e., with a frequency equal to the PRF) and is "integrated" by the persistence of the phosphors on the Braun tube display (and by the brain of the operators).

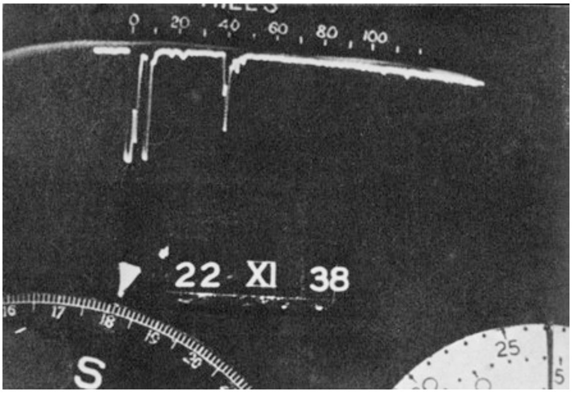

Fig. 4.6 One of the early radar experiments in Brawdsey. The screen shows a flying group of 24 Blenheim bombers coming from the North Sea on November 22nd, 1938

Fig. 4.7 Chain home low: the interior of a transmitter room at a CHL station. A corporal checks the settings on a Metro Vick Type T3026 transmitter

auxiliaries that were simply called "the Waafs". The strict secrecy concerning their activity was dissolved only on August 8th, 1945, thanks to a press release by the Air Ministry[20] that reads: "*Working under the closest secrecy since 1939, over 4.000 WAAF personnel have played an important part in the air victories achieved by radiolocation (Radar). They tracked hostile and friendly aircraft, flying bombs and rockets, German Boats and Allied merchant vessels, and have guided British and Allied fighter pilots on to enemy aircraft. Trained to use and service some of*

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[20] It could be added that from July 1st, 1939 till October 1943, the WAAF group was directed by the *Senior Controller* Jane Trefusis Forbes, who in 1966, at the age of 67, became the third wife of the 73-year-old Robert Watson-Watt: a curious post-war union between the inventor and the user of the Chain Home!

Fig. 4.8 AMES type 1 CH East Coast, 360 ft. transmitter aerial towers at Bawdsey CH station, Suffolk

the most delicate and complicated instruments ever invented, they have carried out their duties with enthusiasm, often under uncomfortable conditions and sometimes under enemy fire."

At the end of 1940 there were 22 C.H. stations and 28 C.H.L. stations in operation; both systems used two antenna sets, a transmitting one and a receiving one. In Fig. 4.8 the trestle of a transmitting antenna is shown.

The system was designed on the basis of the Watson-Watt's experience in HF (High Frequency, from 3 to 30 MHz) techniques and in radio broadcasting by the BBC. The Chain Home was very primitive with respect to German radar of the same period: each transmitting station required four metal trestles—110 m high and distant 54 m—among which were suspended the antenna wires, which statically illuminated an azimuth sector of 100°–110°. Therefore, in a direct way, the only measure of the distance was possible. To locate the target a triangulation by at least two receiving antennas was needed. Each of the latter was supported by four wooden trestles 72 m high. Even though the project was covered by strict military secrecy, these tall towers (see Figs. 4.9, 4.10 and 4.11) could not go unnoticed.

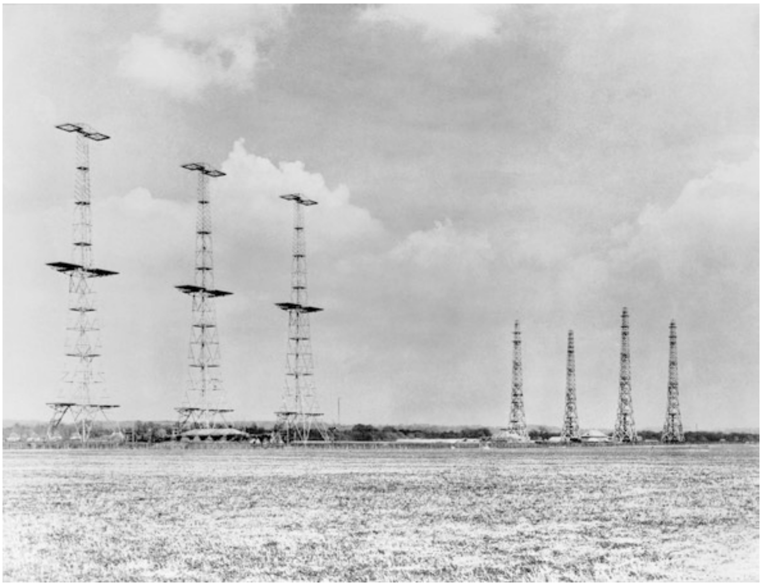

Fig. 4.9 AMES type 1 CH east coast radar installation at Poling, Sussex. On the *left* are three (originally four) in-line 360 ft. steel transmitter towers, between which the transmitter aerials were slung, with the heavily protected transmitter building in front. On the right are four 240 ft. wooden receiver towers placed in rhombic formation, with the receiver building in the middle

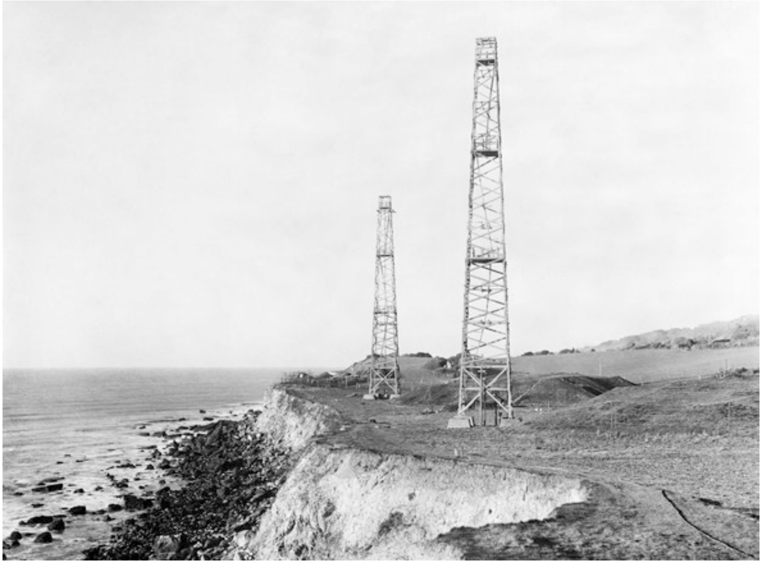

Fig. 4.10 Radar receiver towers and bunkers at Woody Bay near St Lawrence, Isle of Wight, England. This installation was a ‘remote reserve’ station to Ventnor CH

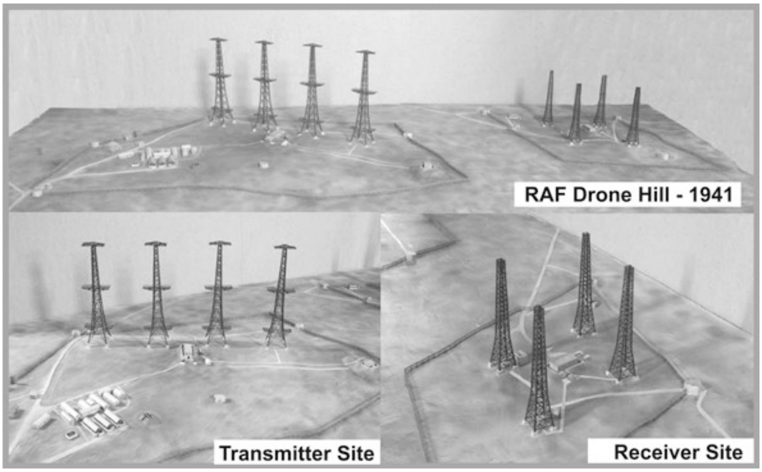

Fig. 4.11 1:500 scale mock-up of the Drone Hill site of the Chain Home (at the *National Museum of Flight*, located in East Lothian, Scotland, a group of very active volunteers operates organized in the *Aviation Preservation Society of Scotland* (APSS), see http://www.apss.org.uk. In one of the projects of the APSS, the volunteers have built—on the basis of some rare photographs of the wartime period—a 1:500 scale mock-up of a site (Drone Hill) of the Chain Home, with transmitting and receiving antennas, buildings, fences and roads)

In 1941 a celebrated inventor, Lee De Forest[21] was interviewed by the magazine *Popular Mechanics*; the related short paper can be found on page 26 of its September 1941 issue. In it, although the existence of transmitting towers different from the receiving ones is not present, there are remarkable insights by De Forest of the operation of the Chain Home for both the sensors and for the command and control. Furthermore, this is one of the very few publications relating to the radar appeared in the period 1939–45[22]; an associated drawing deserves to be shown, see Fig. 4.12, as in its apparent naïveté it seems to anticipate the microwave radar.

The Chain Home was, basically, a system suitable to coastal air defense but not to ground air defense. Moreover, the radar techniques of this system, mostly derived from HF radio communications, had no really new elements[23] and was suffering from the limitations due to the used frequencies, too low to obtain a reasonable

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[21] Lee De Forest (1873–1961), scientist, as well as director and producer of movies, invented the triode (initially called Audion), a vacuum tube with three electrodes that allowed for the amplification of weak radio signals, for which he got the US patent No. 879532 in February 1908. De Forest, who never liked Marconi's word *wireless*, first introduced the term *radio*. He carried out the first radio broadcasts, among which that of *Tosca* in 1910, followed by that of Enrico Caruso, from the Metropolitan Theatre in New York.

[22] The other publications in this set, to the best of the author's knowledge, are only in Italian language: [Tib 39], [Taz 39], [Taz 41]).

[23] As already shown, earlier in 1934, at the Naval Research Laboratory in the USA, Robert M. Page implemented and tested some much more advanced pulse radars.

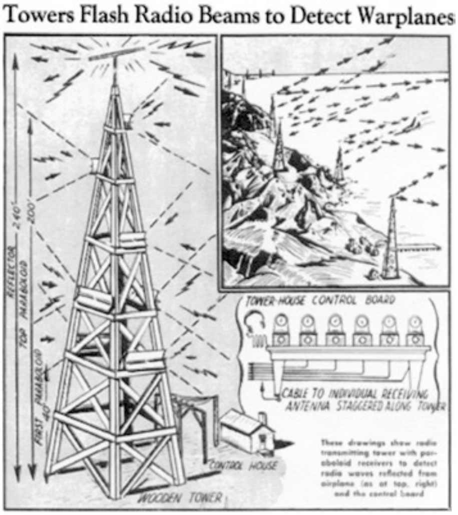

Fig. 4.12 Description of the chain home operation, from Popular Mechanics, Sept. 1941

angular resolution, and to the very long (20 μs) pulses, causing a poor range resolution. In such conditions, an operator could hardly distinguish between an attack by a single bomber and an attack by a formation of bombers (i.e. a *mass raid*). However, the well-trained British operators (probably they were the true strength of the Chain Home, constituting a valuable "*signal processor*" downstream a *poor sensor*) were able to detect the mass raid condition through the "beats" due to multiple targets in the resolution cell. In fact, the contributions of individual targets within the resolution cell add either constructively or destructively according to their mutual phase relation, which slowly changes according to the relative positions of the targets. By analyzing the frequency of the beats (today we refer to *RCS fluctuations of a complex target*) the well-trained operator could have an idea of the size of the mass raid. In addition, to try to resolve multiple targets, the operator could momentarily shorten the transmitted pulse by pressing a button, bringing it to 6 μs and improving the range resolution by about three times.

Despite the evidence, the brilliant and productive Watson-Watt has always claimed himself to be the *father of the radar*[3]. In the course of the meeting organized in 1954 by the German institute of navigation (DGON) to celebrate 50 years of radar, which was attended by Watson-Watt and by the elderly Christian Hülsmeyer, Watson-Watt stated that he did not intend to recognize Christian Hülsmeyer as the *father of radar*: as a maximum, he could accept him to be named the *grandfather* of radar!

Fig. 4.13 The control centre for the defense operations in the battle of England with the female staff consisting of the *WAAF* (Women's Auxiliary Air Force) operators

Therefore, in this chapter Watson-Watt is called the *alleged father of radar*, as the fact that the British (in particular Watson-Watt who really was Scottish, as J.C. Maxwell) have invented radar, is one of the many myths of our time.[24]

Conversely, the very important contribution by Watson-Watt was the idea to collect the detections of the many radar sets in a single room, the Filter Room, where an image of the air traffic was graphically created (Fig. 4.13).

The Chain Home is the ancestor of modern ground-based air defense systems and of the subsequent air traffic control systems. The requirement to integrate the surveillance centers (i.e. the radar stations) was well clear at the time of writing the system-level Chain Home specifications. As a matter of fact, it was not deemed sufficient that each Chain Home station would provide an alarm at the approach of

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[24] This myth is present in many sources, for example, in http://www.radarpages.co.uk/mob/ch/chainhome.htm, a Web site with an ample and detailed description of the Chain Home. The lack of paternity of Watson-Watt is well highlighted by Gregory C. Clark in [Cla 97]) and in http://spitfiresite.com/2010/04/deflating-british-radar-myths-of-world-war-ii.html/6.
The American G.C. Clark did not miss an opportunity to identify an American inventor of radar, i.e. Robert M. Page, who *inter alia* wrote a remarkable book [Pag 77]. Clark wrote:"…*in 1934 Page first developed practical monopulse*. *If there be an "inventor" and pioneer of radar, it is him.*

hostile aircraft. Conversely, it was required that "*the information of the different stations were coordinated so as to be able to decide which air squadron to activate to react to the attack and to precisely define the directions to be sent to fighter pilots*".

At each C.H. and C.H.L. station the radar operators derived the "raw" information, called "Report", i.e. the position and the IFF classification (in three classes: *friend*, *enemy*, and *unknown*, see below) of the detected targets. These *Reports*, together with the associated time, were transmitted through telephone lines, to the "RAF Fighters Command HQ" center in Stanmore (north to London). There, in seven "*Filter rooms*", the Reports due to adjacent radar were combined and the needed corrections were implemented, in order to obtain the most accurate and timely description of the air traffic. To this purpose, the Stanmore operators[25] called *Plotters* wrote position, IFF class, estimated number of aircraft and time on a gridded map showing the so-called *radar Plots*. Other operators called *Filterers* correlated subsequent *Plots* to build the *Tracks,* each of which included IFF class, position, direction and speed; physically, a Track was a metal arrow on a whiteboard. It was left to the Filterers the decision of how many Plots to wait to build a reliable enough Track. In fact, by increasing the number of Plots the quality and the reliability of the Track improved but the timeliness of surveillance degraded rapidly. The Tracks were used by the controllers of the Fighter Command Group that operated on the same premises, or on adjacent premises, to direct, via radio, the RAF fighters toward the targets.[26] Very soon, this approach proved to be more effective than the one used by the Germans, in which individual surveillance centers were rigidly connected to individual control centers of fighter interceptors, without a centralized synthesis.

Very little remains today of the many stations of Chain Home, and of the ensuing Chain Home Low and Chain Home Extra Low, that were necessary when the attackers Germans learned to fly under the height coverage of the C.H., even less of what remains of the Sound Mirrors. However the various sites are cataloged and shown on detailed maps in http://www.anti-aircraft.co.uk/index.html.

In addition to the design of this British radar system, Watson-Watt gave indications on the possibility of providing the British aircraft with an on board transmitter able to reply to an "interrogation" (or request) pulse by emitting a given signal that unfriendly aircraft, of course, could not radiate. In this way, the technique for the IFF—*Identification Friend or Foe*—of fundamental importance to reduce the "friendly fire" risks—was prefigured.

The former IFF, i.e. the Mk 1 produced by Ferranti, entered the service in November 1939. It used the signals from the radar of the Chain Home as an interrogator, and the following model Mk 2 responded also to the signals of the C.H.L.

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[25] Most operators were the girls of the WAAF as explained above.

[26] It is easily understood that the method of target tracking in the early 1940s is, in principle, the same as today. Of course, the introduction of automation has deeply changed the means of processing and transmission of information, as well as the human role.

While these IFF were based on a simple amplification and retransmission of the radar signal, in the Mk 3 model the ground-based interrogator transmitted on dedicated frequencies (i.e. wavelengths between 1.6 and 1.9 m) to which the airborne transponder replied with a pulse of an encoded length, that the pilot had to vary at predefined instants. In this way the radar operator could distinguish the echo signal from an aircraft not equipped with a transponder from the “reinforced” signal from a friend aircraft.

The German air attacks against central and south England began in September 1940, and the Chain Home (C.H. and C.H.L.) proved effective at the time of the first bombing of London, with a climax on September 15th, 1939, when the loss of German bombers reached the highest value of 56, more than a quarter of the used air force.[27] As described above, the lack of air supremacy of Germany—also due to the radar of the opponent—did definitely delay the operation of ground attack to England, which likely would have overturned in favor of Germany the fate of the conflict.

The Nazi Germany was more interested in the offensive actions (everybody knowns the concept of *blitzkrieg*) rather than in the defensive ones. Therefore the Germans development of their defense systems from aircraft attack was limited and late, as shown in the following chapter.

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[27] The problem of the Luftwaffe was not so much the loss of the aircraft (that the powerful German war system produced quickly in a large quantity), but, rather, the loss of the crews: the training of pilots, radio (radar) operators, bombing operators etc. required a too long, not compressible time. Therefore a loss of 25 % of the crews each raid was not acceptable.

Chapter 5
The Second World War and Radar Technologies—Developments of Air Defense and Air Traffic Control Radars

5.1 Antiaircraft Defense and Radar Systems in Germany

In Chap. 4 it was shown that the advancements of aeronautical technologies during and after the First World War have deeply changed the military strategies, making destructive bombing onto enemy territory possible. This new situation has stimulated the search for more and more effective means to detect and locate incoming hostile aircraft and to activate a defense by fighters/interceptors or by anti-aircraft artillery (AAA). After the Second World War the situation changed again with the “ballistic” weapons (AAA) flanked, and in some case, substituted, by missile weapons. In many cases missile systems become the preferred defense solution, as shown at the end of this chapter.

It is well known that the rise of the air threat in the period between both World Wars mostly resulted from the desire of revenge[1] by Germany and from its quick economic, technical and industrial development through the early 1930s.[2] From a technical point of view, at the beginning of the W.W.II (September 1939) and up to 1941 the Germans were superior, concerning air navigation and radar, as shown, among others, in [Pri 09], [Pri 89], [Roh 05], [Kro 00] and [Bla 14]. However, with the first defeats of German forces and—then—with the military crisis and the beginning of collapse of the German industrial system, the Anglo-Americans progressively gained superiority.[1] It has been shown that initially the Germans underestimated the air defense system developed by the British. However, for sure they did not underestimate the importance of the wireless (or radio). In fact, on August 2nd, 1939 (less than a month before the invasion of Poland) the airship Graf

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[1] In particular the Allies excelled in the field of airborne radar, a topic treated in the next chapter. The British produced through 1943 the H2S, first “ground mapping radar” of the world, operating on various bombers of the RAF, with the then top secret cavity magnetron operating at the wave length of 9.1 cm with ensuing versions at 3 cm.

G. Galati, *100 Years of Radar*, DOI 10.1007/978-3-319-00584-3_5

Zeppelin LZ 130 of the Luftwaffe started a two-days mission[2] aimed to analyze the signals used by British radio and radar systems. Probably, it was the first ELINT (Electronic Intelligence), mission, which, however, did not produce important results, as the British radar signals were searched above 100 MHz,[3] while, as already explained, the Chain Home was operating at lower frequencies.

Until 1941 the Allies knew very little about radar developments in Germany. An exception was the naval apparatus *Seetakt* (abbreviation of *Seetaktisch*, tactical naval), which, as already shown, entered into service in 1937 on ships such as the Graf Spee. The official name of this apparatus, operating on the wavelength of 81,5 cm and produced by the firm Gema, was FuMG 39 with subsequent releases FuMO 22, 26 and 27. The transmitted power of 1.5 kW for the first version was raised to 8 kW when Gema realized a version based on *TS6* triodes, and the range on naval targets reached 25 km. The heavy cruiser (also called *pocket battleship*) Admiral Graf Spee (class *Deutschland*) had on board, on the front surface of the main rangefinder tower, the *Seetakt—FuMO 22*. This ship was severely damaged by three British cruisers in the Battle of Rio of Plata, December 13th, 1939, and sheltered in the neutral port of Montevideo, Uruguay. Its captain Hans Langsdorff (1894–1939) sank the ship on December, 17th, but the low waters allowed the British observers to examine the wreck, to write a report (which was read with great interest by the British scientific intelligence expert Reginald Victor Jones, 1911–1997) and, in the ensuing months, to pick up parts of the radar (Fig. 5.1).

At the beginning of W.W.II, unlike the United Kingdom, Germany, because of the different structure and location of its territory and of the choice of an attack strategy rather than a defense one, did not implement an integrated air defense system with coverage of the whole nation. But Germans had a remarkable tradition in antiaircraft weapons, [Wes 01], and during the First World War developed three basic means of antiaircraft defense: (a) the artillery, or FLAK (*Flugabwehrkanone*[4]), assisted by fire control stations and by localization[5] means, (b) the barrage balloons and (c) the masking of high value objectives with various techniques, including the color camouflage and, in the case of night attacks, the dimming of buildings and of vehicles.

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[2] This mission was deemed so important by Germany, as on board the Zeppelin was the Chief for Signal Affairs of the Luftwaffe, general Wolfgang Martini (1891–1963), the main responsible for the development of radar in Germany before and during W.W.II.

[3] All German radars at that time operated above 100 MHz.

[4] The translation from German is easy when it is reminded that *Abwehr* means *defense*. The acronym FLAK (or FlaK) is normally declined as a noun: “the Flak”. These guns included the 20 mm Flak 30, capable of up to 280 rounds per minute (rpm) and effective against targets with an altitude up to 2000 m, the 128 mm Flak 40, capable of 12 rpm and effective up to the height of 10,675 m (and over 20 km in distance), and the well-known 88 mm Flak18/36/37 by Krupp, 15 rpm, effective up to 8000 m of altitude.

[5] Angular localization was obtained optically, and before the advent of radar the target distance was obtained by means of optical range finders with large baseline (up to ten meters—see Figs. 5.1 and 5.2), from which they derived the *rangefinders* used in the best cameras of the early 30s such as Leica II (by Leitz) and Contax I (by Zeiss).

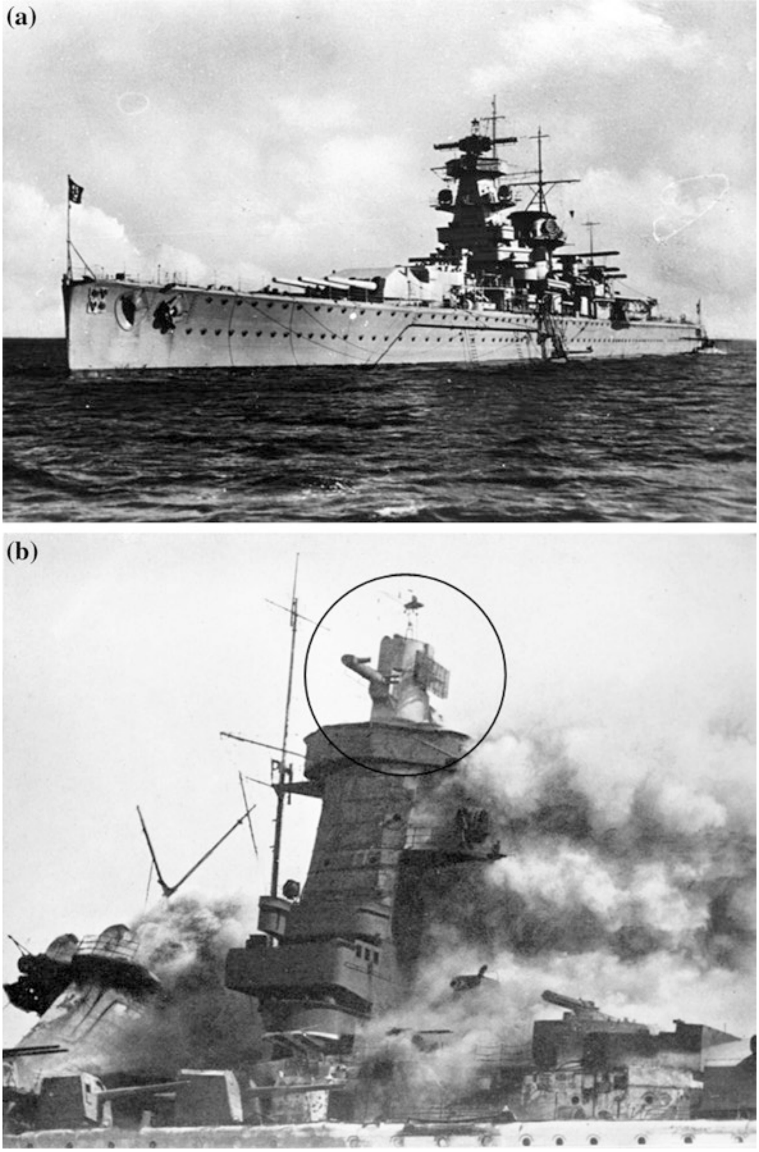

Fig. 5.1 The pocket battleship “Admiral Graf Spee—**a** in navigation, **b** in Montevideo, after the attack. In a circle: the *Seetakt*, on the telemetric tower

The fundamental problem of the antiaircraft fire is to find the point at which the trajectory of the projectile intercepts that of the aircraft. Such a computation requires a very accurate sensor (a specification of 1934 for the automatic fire calls for an angular error less than a sixteenth of a degree and an error in distance less than a dozen of meters) and means for forecasting the trajectories, or for "tracking"[3] the targets.

During the Second World War, Germany built large defensive infrastructures, such as the mighty fortifications described, for example, in [Kau 03] or [Foe 98]. The «Atlantic Wall» [Bla 14], built by the German forces along the occupied coasts of Western Europe as a rampart to protect them from allied landing attempts, included a powerful chain of anti-naval and anti-air radars. This counterpart to the British Chain Home, however, had a different command and control architecture and organization.[6] The «Atlantic Wall» was equipped with much more efficient radars, and worked on a different procedure, called *Himmelbett*. The data from one *Freya* and two *Würzburg* radar systems were used to control a fighter towards its target, i.e. an enemy bomber. This chain was progressively discovered by the Allies who conceived different counter-measures. At the beginning of the W.W.II a first system called *Air Defense-West* (with thickness between twenty and fifty km) was operational for the protection of the Ruhr region. Basically, it was a line of defense obtained by *integration of many point defense systems*, i.e. a very different philosophy than the British one. This German line of defense was made up by 197 sites with heavy artillery and 48 with light artillery, for a total of 788 heavy weapons (88 or 105 mm) and 576 small and light weapons (20 or 37 mm). More that to block the air attacks from the west, in such a zone it was intended to slow them (forcing them to climb) and make them vulnerable, due to high altitude, to the German fighters (which, in reality, only happened to a limited extent). Between September 1939 and May 1940 there were 410 Allied flights over the German-controlled land, 70 of which were night flights (many of them were for reconnaissance purposes and with a limited penetration beyond the border). Only fifteen of them were shot down, about fifty-fifty by the Flak and by fighters-interceptors, and none was shot down at night, [Wes 01]. Through spring 1940 the aircraft of the Royal Air Force (RAF) began to carry out missions of night bombing against Germany, mainly in the area of the Ruhr [Fri 04] and, in the nights of June 4th and 5th, on Munich. Finally, in the night between August 25th and 26th, 1940, twenty bombers of the RAF made the first raid on Berlin. Just after the raid Hitler ordered the construction of the "FLAK Towers" (see Fig. 5.2) to house the antiaircraft systems.[4] There were pairs of such buildings, one for the artillery and the other for the detection, localization and guns control by means of optical range finders, spotlights and radar.

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[6] While in the U.K. there is very little of the Chain Home today, remains of the *Atlantic Wall continental chain* can still be seen more than seventy years later in many places, especially in France. Their «archaeological» study may enlighten the war time archives and documents from both sides, to explain how it was built, how it worked, and what could be its supposed efficiency, see also [Bla 14].

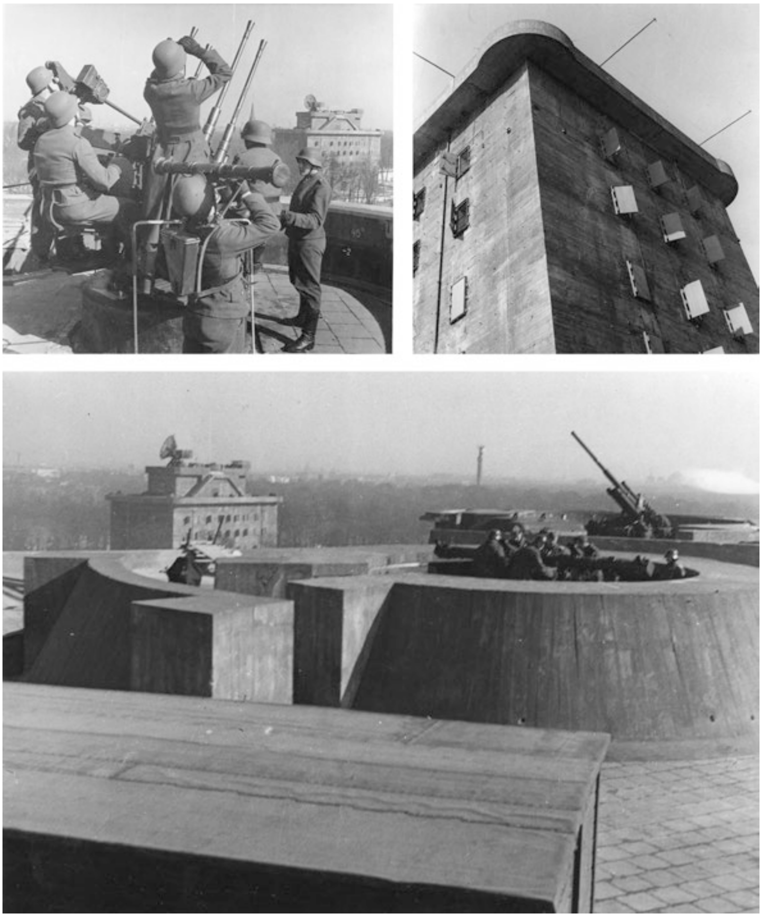

Fig. 5.2 Some “Flak Towers”, with Anti-Aircraft Artillery and tracking radar

From the organization point of view, the—somewhat late—decision by the Luftwaffe to constitute specific departments for the air defense against night attacks dates back to the summer of 1940. The pertaining organization was due to the colonel (later, general) Josef Kammhuber (1896–1986), appointed by Göring as head of the air defence. On July 20th, 1940, the first *Nachtjagdgeschwader* (Night Interception Squadron) entered officially the service for directing the fighters-interceptors (or, for targets in a useful position, the AAA) onto enemy’s bombers. Before the advent of airborne radar, as described in the ensuing chapter, it was necessary to enlighten the night bombers with powerful light curtains or with illuminating rockets launched from suitably equipped aircraft.

Early detection (early warning) before the radar era was mainly devoted to acoustic sensors or “aerophones”, as described in the previous chapter, present in thousands in the Flak batteries. In addition to the intrinsic limitations of the aerophones, their use resulted more and more difficult both for the environmental acoustic disturbances and for the strategy of the RAF pilots who, to confuse the aerophones, learnt how to change periodically the number of revolutions of the motors and, when close to the area of attack, to flight (glide) with idle engines.

Kammhuber understood that the solution was the embodiment of an advanced defensive network (toward the direction of the attacking aircraft), far away from anti-aircraft batteries, equipped with precision radar stations and capable of guiding the fighters onto the enemy aircraft in suited attack position.

It has been shown that Germany was one of the earliest countries involved in the implementation of operational radar systems. It is generally agreed that the first ideas in the early 1930s [Bla 14] are due to Rudolf Kühnhold from the NVA (*Nachrichtenmittel-Versuchsanstalt*—Naval Signal Research Office), which resulted in October 1934, in collaboration with the newly formed company GEMA, in the experimental detection of an airplane, and three years later in the air surveillance radar family *Freya* operating on the 2.4 m wavelength (Chap. 3).

At the beginning of the W.W.II, in Germany only eight surveillance radars of the *Freya* type were installed and operating along the north coast. Using them, in the early months of the war the Germans were able to detect the British aircraft attacks up to distances of the order of 120 km. However, the Freya radars could not measure the height of aircraft and their accuracy was too limited to direct any anti-aircraft fire. Hence, a new radar sensor with accuracy and resolution far in excess that of Freya was needed. On July 8th, 1940 Hermann Goering, as president of the Defense Council of the Reich, put in the highest priority a radar capable of guiding the AAA, [Mül 98], i.e. an AAA radar (also called gun-laying—*GL -radar* in the Anglo-American jargon). The firm Telefunken had developed, in 1939, the prototype of the *Würzburg*[7] AAA radar, which was presented to Hitler on July 1st, 1939 at the Luftwaffe test field in Rechlin (Mecklenburg-Vorpommern). In the operational tests carried on in summer 1940 they compared the *Würzburg Darmstadt* with the *Lorenz* radar model *FuMG 40L*, which showed a better accuracy (with a range error within plus or minus a dozen meters) but had less maximum range. At the end, they choose the Würzburg, model FuMG 39T (also called FuMG 62) for its quicker availability (Fig. 5.3). An order of as much as five thousand (5000) sets followed, establishing a remarkable success for the responsible of the program, Leo Wolfgang Brand (1908–1971), who was with

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[7] The name of the radar was chosen by pointing at random on a map of Germany: Würzburg was a masterpiece of baroque architecture on the Main river, about 250 km north-west of Munich. This small town surrounded by towers is also known as the place of birth of the Nobel Prize in Physics (1932) Werner Karl Heisenberg (1901–1976). This town is also related to one of the less known (well-known are those of Hamburg and Dresden) bombing campaigns [Fri 04] of the war: during the night of March 16th, 1945, 389 tons of cluster bombs and 572 tons of incendiary material were released over Würzburg. The British, who knew the abundance of wood in the baroque architecture of the city, succeeded once again to create a vast fire—the "storm of fire"—which destroyed a large part of the city with 5000 casualties out of 107,000 inhabitants. The bombing of Würzburg was one of the most tragic and unnecessary actions of W.W.II: only 20 days later the VII American Army would have conquered the zone.

Fig. 5.3 The German FuMG 62D "Würzburg" radar, the first radar with sufficient precision to allow batteries to hit an air a target in the absence of optical visibility

Telefunken through 1932 and became head of their radio laboratory. The series production by Telefunken began in 1940.

The Würzburg, operational in the summer of 1940, had a parabolic-shaped antenna with a the diameter about 3 m, which in some models could be folded in two halves for transport. It was capable of measuring the distance (the range resolution was 25 m), the azimuth and the elevation of the target. Initially this radar operated at a fixed frequency, then the frequency was made variable from 553 to 566 MHz as an interference suppression (ECCM) technique. After the former versions A and B of Würzburg, the "lobe-switching" technique was added to the "Würzburg C" to improve the angular accuracy, and the Würzburg D introduced the conical scan.[8] The angular measurement of Würzburg C was accurate within ±0.75°. The version FuMG 39T(D) entered the service in December 1941 and was the standard sensor for the Flak during most of the war period. However, when operational requirements called for improved resolution and angular accuracy, a new version was developed: the FuMG 65 *Würzburg Riese* (*Giant Würzburg*—Fig. 5.4) operating at the same frequencies as the Würzburg but equipped with a parabolic antenna whose diameter was 7.5 m. This radar, into operation in the second half of 1941, had an angular error as small as ±0.25°: obviously the large antenna permitted a superior angular accuracy. The maximum range of the Würzburg Riese was 60–80 km, i.e. approximately twice that of Würzburg. Doubling the range was obtained with the two-times larger antenna (quadruple gain), without any change of the peak transmitted power, set at 8 kW (according to others, at 10 kW), of the duration of the pulse, 2 μs, and of the carrier frequency, around 560 MHz. The pulse repetition frequency, PRF, was 1875 pulses/s, exactly half that of the Würzburg. The Würzburg was produced in thousands of sets (the

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[8] The conical scan used an the antenna feed rotating at 25 Hz and generating, for an "off boresight" target, a modulation with orthogonal components proportional, for small angular deviations, to the sine and cosine of these deviations. This simple and effective technique (although prone to electronic counter measures) was used in tracking radars for over 20 years, before the advent of "monopulse".

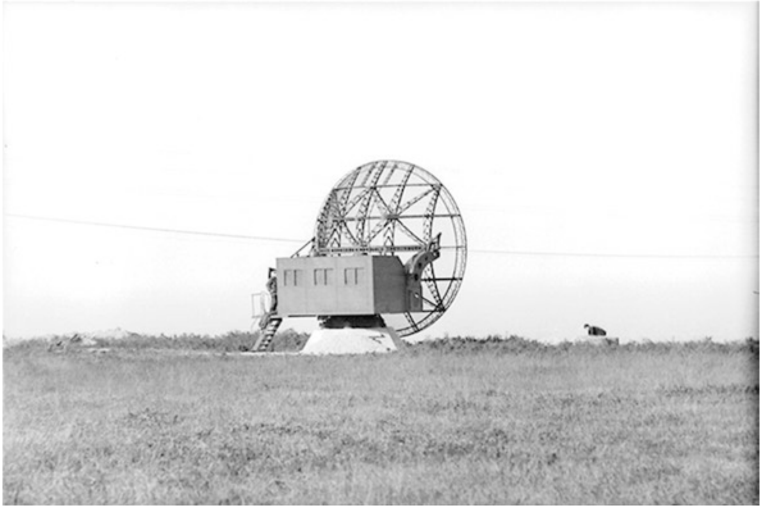

Fig. 5.4 The radar FuMG 65 “Würzburg-Riese“ (Giant Würzburg) with its parabolic reflector of 7.5 m in diameter

various sources cited figures between 3000 and 4000, plus 1500 sets of Würzburg Riese). An antenna of the Würzburg Riese weights nine and a half tons, and its parabolic surface has a diameter equal to seven and a half meters and a focal length of one meter and 70 cm. It was not easy to guarantee, for such a huge antenna, tolerances compatible with a pointing accurate up to a tenth of one degree: they were produced by the only German firm with the needed capacity, the Zeppelin.[5]

The Würzburg exceeded in performance all tracking radars of that time, at least until the advent of microwave radar SCR-584, developed by Bell Laboratories for the US army and produced in thousands of sets. The designated substitute of the Würzburg was the *Mannheim*, characterized by an extreme accuracy, and entered into service in the second half of 1943; it had only one display (thus making its use much simpler than the previous three-display tracking radars) and could automatically track the target.

As already mentioned, Kammhuber devised the Himmelbett system, which was operational since the summer of 1941 and through the end of the conflict. The Himmelbett stations were equipped with a Freya radar to acquire distant targets (up to 120 km), a first Würzburg Riese radar for the accurate tracking of enemy bombers and a second Würzburg Riese for the control of the night interceptors that were directed via radio toward the bombers[9] (Fig. 5.5). The poor resolution[6] of

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[9] These two radars, developed independently and with a very different appearance (a panel of dipoles for the 2.4 m *Freya* and a parabolic reflector for the 56 cm *Würzburg*), were complementary and cooperating all along the war, the former providing wide-area surveillance and the latter, tracking and fire (or interceptors) control.

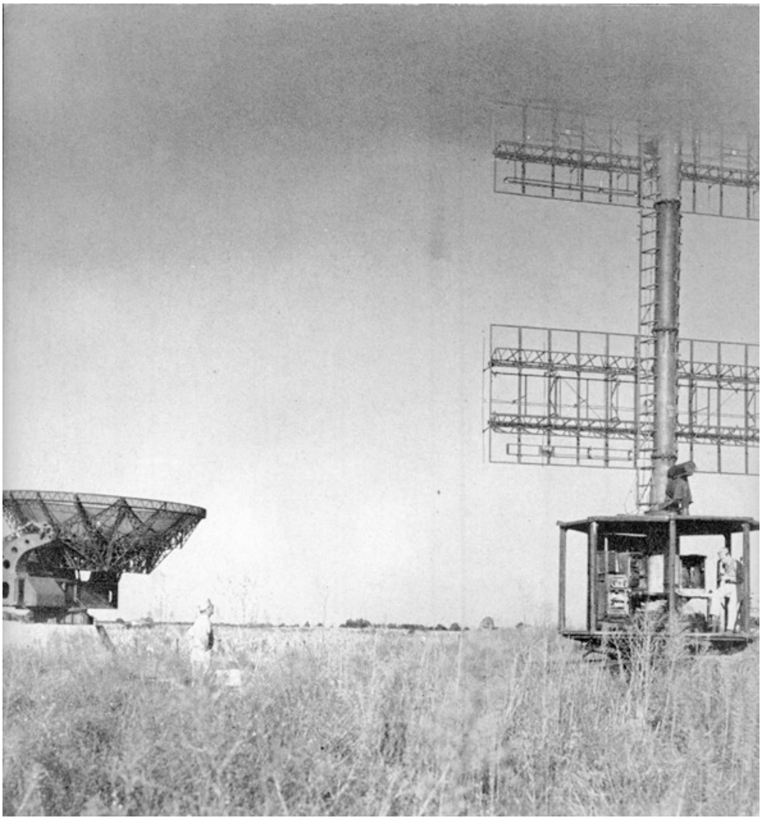

Fig. 5.5 "Würzburg Riese" and "Freya"

the Freya could not permit to distinguish the own fighter aircraft and the enemy bomber on the radar monitor before the fighter could see the bomber, while with the Würzburg one could distinguish both aircraft thanks to the excellent resolution due to its greater frequency, its large antenna size and its short pulse. The measured positions from both Würzburg were shown at the fighters coordination center on a horizontal table of frosted glass (*Table of Seeburg*), projecting from the bottom a red light spot for the bomber, and a blue spot for the fighter.

On February 22nd, 1941, the fortuitous discovery of *Freya* on an aerial photograph taken by the RAF was a total surprise, which finally certified the existence of the still disputed German radar. Some of the numerous installations of German radar were close to the coast. Among them, on the north coast of France, Le Havre area that, photographed by a British interceptor in 1941, revealed the German radar installations (see Figs. 5.6a, b) in Auderville and in Bruneval near Etretat. On February 1942, the Bruneval raid [Pri 89] by the RAF allowed the British to acquire most of the information about the Würzburg A (which was disassembled with several parts removed), installed in the same area as *Freya*.

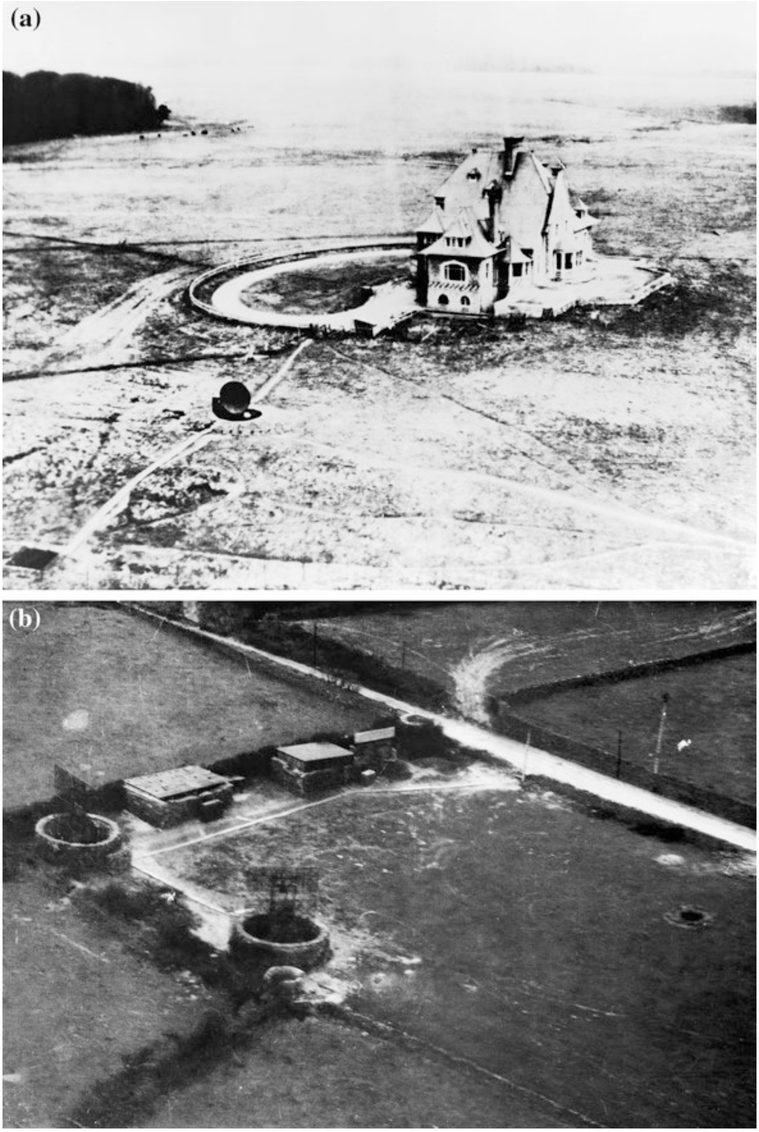

Fig. 5.6 Aerial photographs taken by a Spitfire of the RAF on 1941 at Auderville and Bruneval, with the demonstration of the existence of German radar: Würzburg (**a**) and Freya (**b**)

(a) Low level oblique photo of the "Würzburg" radar near Bruneval, taken by Sqn Ldr A E Hill on 5 December 1941. Professor Jones described these photos as classics of their kind, which enabled a raiding force to locate, and make off with, the radar's vital components in February 1942 for analysis in Britain.
(b) Low-level aerial reconnaissance photograph of the 'Freya' radar installations at Auderville, taken using an F.24 side-facing oblique aerial camera.

5.2 Anti-radar Systems—The Invention of “Chaff”

When radars (and in general radio systems) were used in war operations, electronic countermeasures born almost immediately [Pri 09], [DeA 81]. Both noise generators (jammers) and generators of false radar signals by retransmission of the radar pulses were developed. In this context, in Italy, 1943–45, a remarkable activity was carried out by Giorgio Barzilai (1911–1987), see [BLF 07]. During W.W.II a method was devise to confuse enemy radar which proved particularly effective from the strategic point of view. It was called *Window* by the British and *Düppel*[10] by the Germans; it is still used today and called *chaff*. As soon as in 1937, R.V. Jones[11] suggested that thin and lightweight metal strips thrown from an aircraft could create echoes able to disturb the enemy’s radar systems; the idea was then developed, through experiments, between the end of 1941 and March 1942 by Joan Currain, a researcher of Telecommunications Research Establishment (T.R.E.), who defined the embodiment based on packaging of thin and light strips made by aluminum sheets, see Figs. 5.7 and 5.8.

It was observed that a package of only 40 aluminum strips produced, on the *Type 11* radar operating at a wavelength close to that of the Würzburg, an echo similar to that of a twin-engine bomber. Moreover it was soon realized that the maximum effectiveness could be obtained with metallic strips with a length equal (or close) to half the wavelength of the victim radar, that the other dimension was not important and that the thin sheets of aluminum used in the manufacture of capacitors were an excellent raw material for the mass production (Fig. 5.8). Therefore, in order to disturb the Würzburg, thin strips long about 27 cm were adequate. When it was decided to use the *Window* against metric wave radars, like the Freya (with a wavelength around 2.4 m), the solution was to launch folded aluminum strips, equipped with a weight and, on the opposite end, a small parachute, that opened up after the launch.

Around 1940 the Germans had—independently—the same idea as the British, but Goering forbade any research in the “chaff” area and, even, to speak about it. Since there was no any known countermeasure, both parties in war were very reluctant to use the *Window*/Düppel: by examining the strips laid on land, the enemy would easily discover this new type of “invincible” radar countermeasure.

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[10] Also in this case, the Germans used the name of a town, precisely the German name of Dybbøl, a Danish city famous for a battle on 1864. On the other hand, the English name *Window* is entirely arbitrary. It was invented by A.P. Rowe, who happened to discuss this method near a window, and choose, to maintain maximum confidentiality, a name with no relationship with the object or function to be developed.

[11] Reginald Victor Jones (1911–1997), physicist and expert on military matters, in 1939 was assigned to the Intelligence Section of the Air Ministry; he studied the measures against the weaponry of the Germans, including the navigation and guidance system “Knickebein” which used two beams of radio waves intersecting each other on the target, the flying bomb V1 and others.

Fig. 5.7 Reel of aluminium foil

Fig. 5.8 A factory worker producing code-named “Window” (Chaff) foil which was dropped by allied aircraft to jam enemy radar

In reality the *Window* was not so new to anyone. The Japanese called them *Giman-chi* (deceiving paper) and first used them in 1942, on the Solomon Islands, to disturb the operation of American radars. On that occasion this method did not lead to success, probably due to the small amount of strips that the Japanese were able to produce. Anyway the use of *Gimanchi* in 1942 was the likely reason why Churchill decided to authorize the use of *Window*, considering that at that time it was not so much secret. The most reasonable decision was, therefore, to use

Window in a mass raid on an important target that justified the consequence of breaking the (residual) secrecy. However, the RAF was authorized from Churchill to use *Window* only from mid-1943,[12] with the immediate start of their mass production in England.

The first operational use of *Window* occurred in the night between July 24th and 25th, 1943, with the *Operation Gomorrah*, the well-known large scale attack by the RAF on Hamburg. Three minutes before the zero-time (01:00 GMT), twenty *Pathfinder* aircraft—based on the indications of their airborne radar, the H2S (see Chap. 6)—launched illuminating devices with white and yellow light markers on the targets to bomb; a minute after, eight crews had to visually acquire the illuminated targets and make them visible by red markers. 791 bombers, of which almost half of the *Lancaster* type, launched a pack of *Window* exactly every minute, starting from meridian 8°30′ East at the arrival, and from meridian 8°00′ at the return flight.

The attack was regularly detected by the early-warning (maximum range up to 300 km) radars *Wassermann* and *Mammut* shortly before 23:00.

The first launches of *Window* occurred at 00:25. The operators of the Himmelbett Air Defense stations saw, on their Würzburg monitors, a large amount of false targets, fixed or slowly moving, so that they could not identify the real threats nor guide the fighters. At the same time, the Freya radars, not very sensitive to the *Window* because of their greater wavelength, were disturbed by electronic jammers on board the attacking aircraft. Even the *Lichtenstein* radars mounted on the German fighters (Chap. 6) were confused by the *Window*,[7] making it extremely difficult for the crew to hit the RAF bombers (Fig. 5.9).

In these raids to Hamburg, the RAF lost only 12 aircraft, three of which during the first attack; the losses were 1.5 % of the used air force, versus the usual percentage of 5 or 6 %.[13] In the days immediately following the first night attack, July 25th–27th, there were two daytime attacks over Hamburg by the USAAF and three more night raids by the RAF, causing the many fires to join in a *storm of fire*, an event [Fri 04] whose destructive capacity was only exceeded by the nuclear bomb.

The Germans succeeded soon in inventing some counter-measures against *Window*/Düppel, to be applied to the Würzburg; today they would be called *anti-chaff* means. On July 28th, 1943, just 3 days after the first raid over Hamburg, they developed the prototype of *Würzlaus*, a system aimed to allow the radar operator to distinguish *Window* from aircraft. The Würzlaus used the Doppler effect, exploiting the lowest speed of the *Window* (the same as the wind) as compared to the one of the aircraft. In the Würzlaus system two pulses were transmitted with the same

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[12] It was estimated that if the *Window* had been used by early 1942, their usage would have saved over 300 bombers and their crews.

[13] Therefore one can claim that about 35 aircraft were saved by the launch of 50 tons of Window, i.e. of 92 million of aluminum strips.

Fig. 5.9 A Royal Air Force *Avro Lancaster* bomber over Essen dropping "Window" (the white cloud on the *left*) to interfere with ground gunners during a bombers raid on the city

phase to implement what today is called a MTI (moving targets indicator) filter. The stop-band of this filter was centered on the null radial velocity and extended up to 20 km/h. Therefore Würzlaus was not very effective in the case of strong winds with a significant velocity component in the direction of the radar. The first Würzlaus "kits" were delivered in September 1943. The ensuing system *Nürnberg K-Laus* introduced several improvements including the fine tuning of the speed response to the speed of the wind.[14] The suppression of the chaff disturbance, estimated by a figure 3:1 for the Würzlaus, reached 20:1 with the K-Laus which used, *inter alia*, the modulation of the echo signal due to propellers rotation, to be recognized by the radar operator in headphone and obviously absent in the *chaff* echo.

5.3 The "Passive Radar"

In addition to the concepts of Doppler radar and of spectral analysis of the echo, Germans scientists and engineers anticipated the one of *passive radar*.[8] At the beginning of 1940s the Germans devised a very ingenious system—called *Klein Heidelberg Parasit*—which exploited the "floodlight" nature of the transmission

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[14] Most anti-chaff techniques remained classified many years after W.W.II and one of the earlier publications in "open literature" is [Gal 78], which follows the invention and the patent of a novel *open loop adaptive MTI* called SACE/RALA.

by the Chain Home in order to covertly detect and track the British aircraft [Gri 10]. In 1942 the Germans installed near *Oostvoorne*, the Netherlands, a system able to receive both the direct signal from a Chain Home radar and the—much weaker—echo of the targets; the delay between direct signal and echo signal could be measured. In such a way the set of possible positions of the target defined an ellipse whose foci were the transmitting antenna (in the British territory, but in a position well known to the Germans) and the receiving antenna in Oostvoorne, respectively. The position of the target on the ellipse was obtained by the azimuth measurement with a large and very directional antenna, see Fig. 5.10.

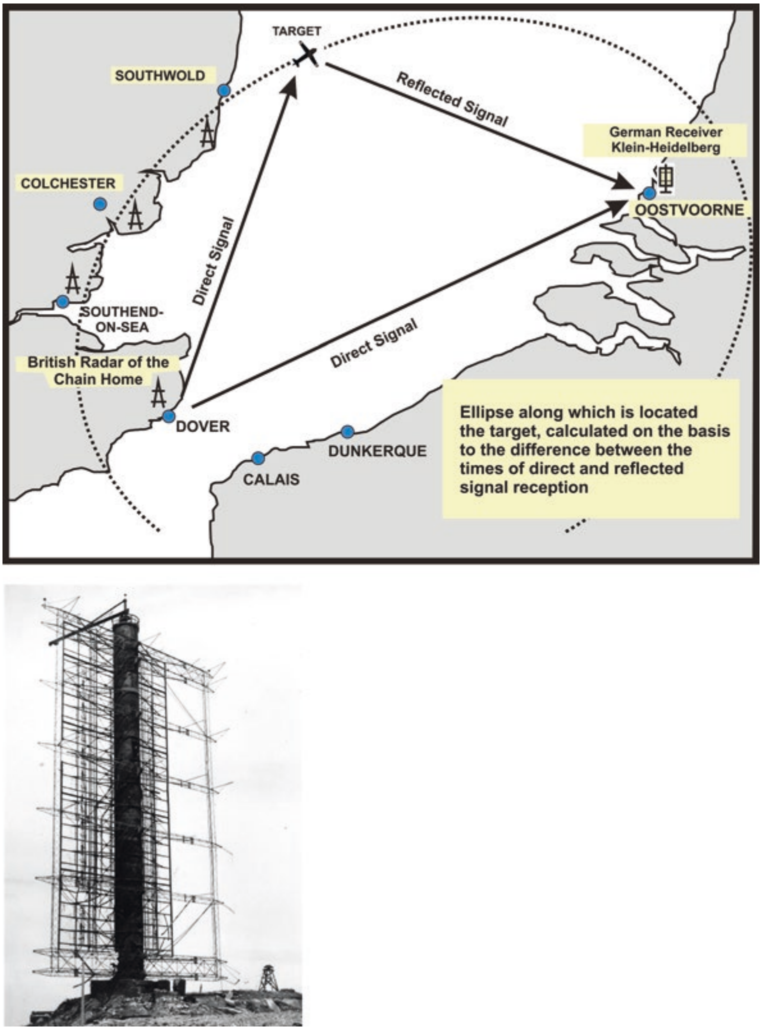

Fig. 5.10 The German passive radar Klein-Heidelberg Parasit—the operating scheme and the receiving antenna

The system was able to detect targets at a distance of 400 km, with a measurement accuracy in the order of one km in distance and of one degree in azimuth. Due to its passive operation, it was not detectable, and therefore could not be jammed by the British.

5.4 The Magnetron, the "Tizard Mission" and the Microwave Radar

From the early months of war, both enemies missed radar sets with limited size and weight—and at the same time with a reasonably fine spatial resolution—for airborne, naval and battlefield applications. It was clear to everybody that the only way to satisfy this need was to increase the operating frequency up to the microwave region. However the thermionic valves (triodes, tetrodes, pentodes) used for the radio transmission at these times generated decreasing power levels with the frequency increasing. It was soon understood that the solution to this problem was that of electronic tubes of different design, with the electrons flow controlled by a magnetic field. It was shown in Chap. 3 that the cavity magnetron is not, as many have claimed, a British invention [Bgvg 13], but, rather, as the radar itself, a simultaneous invention due to researchers from many nations (Britain, France, Japan, Germany, the United States, the Soviet Union) dating back to the 1920s. But it must be also recognized that the first, easily reproducible device of this type operating in the microwave region with high power was implemented in the laboratories of the University of Birmingham. The achievement was due to the enhancements introduced by John Randall and Harry Boot (Fig. 5.11), two researchers of the group led by prof. Mark Oliphant,[15] who had received from the British Admiralty a financing for the development of a radar operating at the wavelength of 10 cm.

In fact, the British government regularly financed research on the key elements of radar and electronic warfare, i.e. high power sources and sensitive receivers in the microwave region. In particular the Admiralty, concerning the 10 cm wavelength, had issued some contracts with the Department of Physics of the University of Birmingham for power tubes to be used in transmission and with the Clarendon Laboratories at the University of Oxford (prof. Cockroft) for the low-noise tubes to be used in reception. In fact, the need to improve the angular

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[15] Sir Marcus (Mark) Laurence Elwin Oliphant (1901–2000), an Australian physicist and politician, is known for his research in nuclear physics and for his participation in the program of uranium enrichment at the MIT Radiation Laboratory (1943–44). In 1937 he was called by the University of Birmingham as professor of physics, where he contributed to the implementation of the microwave radar. Back to Australia, in 1950 he resumed his academic activity, and from 1971 to 1976 was the Governor of South Australia.

Fig. 5.11 Sir John Turton Randall and dr. Henry Albert H. Boot (*left*) in laboratory after W.W.II. Boot has in his hands the anode block of a six-cavities magnetron

resolution[16] by increasing the operating frequency became vital in airborne radar (treated in the ensuing chapter), in which the size of the antenna is necessarily limited. The British found, for the wavelength, an optimum value around 10 cm[17] and for the peak power a minimum requirement of 1 kW.

It is common to indicate February 21st, 1940 as the date on which, with some amazement by Randall (at the time, 34 years old) and Boot (at that time, only 22 years old) their device, shown in Fig. 5.12, oscillated at a wavelength of 9.8 cm, producing the remarkable power of 400 W, a level two orders of magnitude higher than the values obtainable until then in the range of 10 cm (i.e. at frequencies around 3 GHz, or S-band).

The power was brought up to some kW in the ensuing weeks. The work at Birmingham proceeded quickly: in September Randall and Boot developed a fourteen cavity magnetron on the five cm wave and a six cavity magnetron on the three

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[16] The angular resolution (in radians) is roughly evaluated dividing the wavelength by the antenna dimension in the considered plane (azimuth or elevation).

[17] This was an order of magnitude less than the metric waves then in use in Britain, where there was a general trend to reduce the radar wavelength during the war, including the Chain Home, which went from the original wavelength of 50–26 m and finally to 10–13 m.

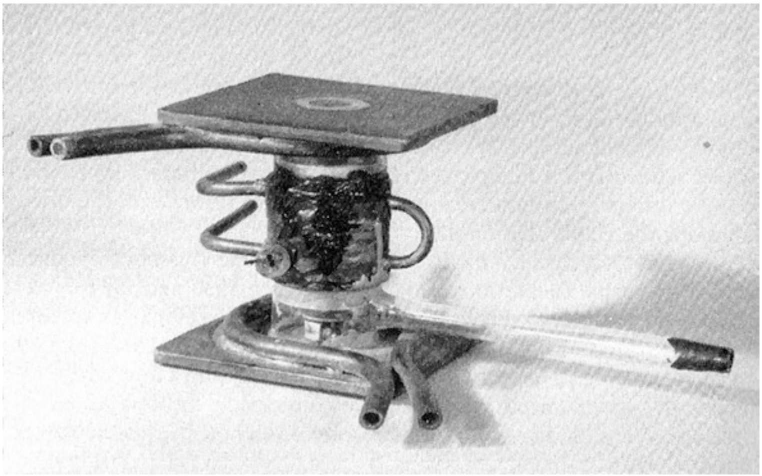

Fig. 5.12 The first laboratory magnetron by Randall and Boot, with six cavities. It was water-cooled, needed for a vacuum pump and has to be kept between the poles of an electromagnet

cm wave (X-band).[18] These early prototypes from a University laboratory were not suitable for use in any operating environment, but industrial products were quickly derived from them. In April 1940 the British Admiralty signed a contract with the Research Laboratories of the *General Electric Company Ltd*. (GEC) in Wembley with the aim to derive, from the design by Randall and Boot, a device usable in the field.[19] The resulting water-cooled device operated for the first time on June 29th providing 500 W at 9.8 cm. Subsequent devices were air-cooled. Shortly later, the design of this first prototype, called *E1188*, was modified using an oxide coated, indirectly heated cathode, originating the magnetron *E1189*. On July 17th a prototype of the E1189 supplied 12 KW pulses at the 9.5 cm wavelength. The early prototypes all had six resonating cavities, but in August 1940 the design of E1189 was modified with eight cavities and a larger cathode. The improvements of the original magnetron are mostly due to E.C.S. Megaw, team-leader of GEC laboratories. Very soon, on September 1940, peak power levels (again at the wavelength around 10 cm) as high as 100 kW were obtained, see [Red 01].

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[18] Centimetre waves were used in Germany in 1934 on the wavelength of 13.5 cm to detect ships by the continuous wave technique, and similarly in 1935 in France, on the wavelength of 16 cm, aboard the steamship Normandie for the detection of obstacles and, by pulsed technique, in 1938 during the experiments done by Maurice Ponte with the French Navy in Le Havre. However, the limited power restricted the detection range to a few miles. For the development of the early centimetre-wave tubes in various nations (France, Soviet Union, Japan, Netherlands) see [Red 01] and the Chap. 7 of [Bla 04].

[19] First of all, the tube had to be thoroughly sealed to operate without any vacuum pump.

On May 1940, with the fall of the weak Chamberlain government, Churchill became Prime Minister; on June 14th the German army was in Paris, and the armistice of France followed eight days later. It was clear that the industrial production capacity of Germany and of the occupied nations was so large as to defeat the British. In fact, without any external aid, in particular by the United States, the United Kingdom should succumb in that war becoming more and more technological, especially in the aerospace[9] and in the radio industry. To cope with such a situation, the British quickly took some wise actions. First, in February/March 1939 the British Air Ministry informed the governments (the so-called *Dominion Governments*) of the most industrially advanced nations of the Commonwealth about the radar developments in Great Britain, of course under the constraint of the military secret. This fact permitted significant radar developments in Canada, Australia, New Zealand and South Africa.[20]

The second, most important British action was to transfer to the Americans the new knowledge developed in the United Kingdom for military applications in exchange for the use of their technological, industrial and productive capacity. This challenging idea was conceived by an influential professor and British officer, Sir Henry Tizard[21] (see Fig. 5.13). This proposal was well considered by Churchill who, in the utmost secrecy, contacted the American president Franklin D. Roosevelt[22] and finally approved the plan on August 9th, 1940.

This decision paved the way to the Tizard Mission, more exactly "The British Technical and Scientific Mission to the United States and to Canada" [Phe 10] which took place between the end of August and October 1940.[10] The content of the exchange was divided in three main, broad topics: radar, jet engines for aviation and thermonuclear bomb.[11]

The cavity magnetron shown in Fig. 5.14 was brought to North America personally by one of the members of the Mission, E.G. Bowen[23]; the trip, with the train to Liverpool, then by sea, and the arrival on September 9th, 1940, is vividly narrated in Chap. 10 of [Bow 87]. The Tizard Mission members, when dealing

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[20] Such developments are normally ignored in the literature, with the notable exception of the last chapter of [Wat 09] and of a few other works such as [Red 01].

[21] Sir Henry Thomas Tizard (1885–1959) was member of the Royal Society in 1926, and rector of Imperial College, London, from 1929 until 1942. From 1933 he was the president of the Aeronautical Research Committee where he served during most of the war.

[22] Franklin Delano Roosevelt (1882–1945), who was elected President of the United States of America four times to (in 1933, 1936, 1941 and 1945), conducted the Nation during the W.W.II until his sudden death in April 16th, 1945, shortly before the end of the war and after having participated, with Churchill and Stalin, to the "Yalta agreements" (February 1945). In his first presidential mandate has created the "New Deal".

[23] Edward George "Taffy" Bowen (1911–1991), a Welsh physicist, in 1932–33 worked at the Radio Research Station—RRS, Slough, a laboratory directed by Watson-Watt, where he became Junior Research Officer once obtained his Ph.D. At RRS, since 1935, he contributed to the realization of the Chain Home and became team leader for airborne radars. After the war, in 1946, he became director of the Radio Physics Division of CSIRO (Commonwealth Scientific and Industrial Research Organization) in Sydney, Australia.

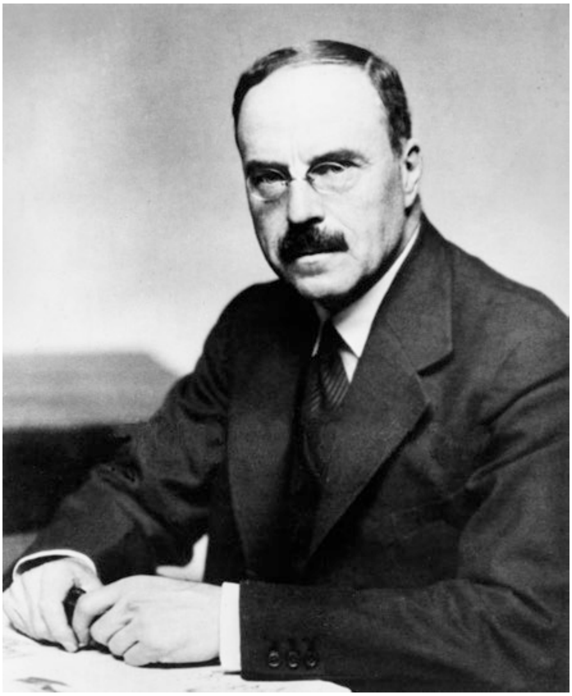

Fig. 5.13 Sir Henry Tizard. From 1933 Tizard, chairman of the Aeronautical Research Committee, was one of the pioneers in the development of the operational radar

with their American and Canadian partners, found it very difficult to create a two-ways, equal-level exchange of information (i.e., a secret versus a secret). Therefore, the Mission quickly became an open exchange of results, especially from the Great Britain side, in the form of reports, manuals, schematics, and, mainly, of objects, the most important of which was of course the resonant cavities magnetron, model 1189, serial number 12, capable of providing 10 kW on the wave of 10 cm (Fig. 5.14). This precious item was presented to the US counterpart in the meetings held in Washington from September 12th, 1940, in the frame of a complete description of the developments of British radar (land, sea and airborne).

On the other hand, the British could directly see the progress of the Americans both in the field of naval radar, at the Naval Research Laboratory in Washington, and of ground-based radar, at the Signal Corps.[24] With the exception of the magnetron, and therefore of the microwave radar, the delegations discovered that the two countries were at a comparable level in the technical-scientific frame. However the situation was very different from the operations and applications

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[24] With the reorganization of the Ministry of War in March 1942, the Signal Corps became one of the technical services of the U.S. Army, both for the land forces (army's Ground Forces) and for the air ones (army's Air Forces). In the Signal Corps laboratories in Fort Monmouth, New Jersey, they developed some of the most used early American radars such as the SCR-268 and the SCR-270. The designation *Signal Corps Radio* (*SCR*) concealed the real nature of these equipments.

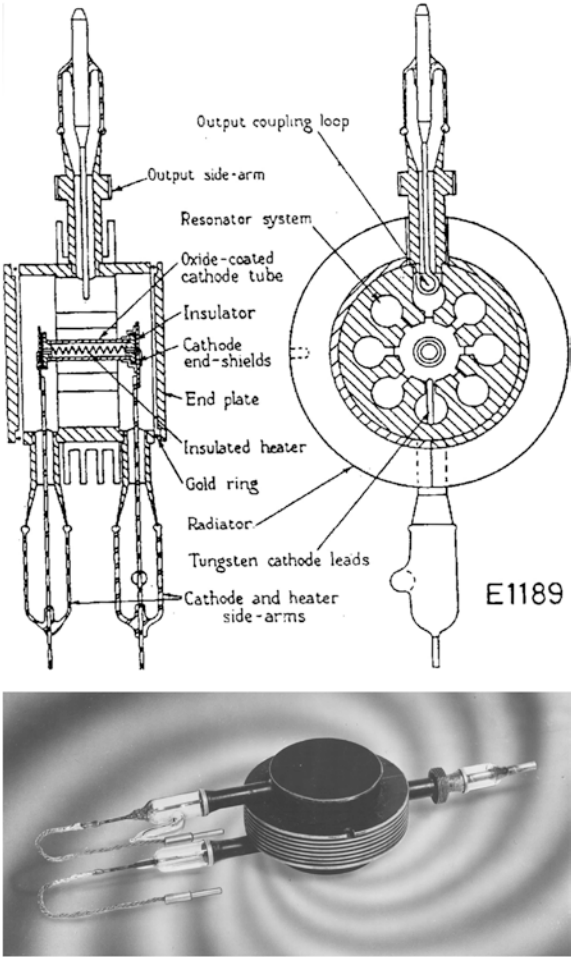

Fig. 5.14 The first S-band power magnetron (type E1189) produced by GEC. On the bottom, a picture of the E1189 brought to North America by the Tizard mission in 1940

point of view. Not directly threatened by attacks from air or from sea, the Americans had made a few sets of each type of radar, and many types of radar. On the other hand, as previously shown, the British since 1935 had financed with about a million pounds the first group of radar stations (basically, of a single type) to cover the estuary of the River Thames, and had then (1938) invested ten times as much for the radar coverage of the whole England borders. The results on the military side were clear: just when the Tizard Mission was in North America, the Chain Home was a precious help against German air attacks in the so-called Battle of England. The British strongly pursued their own development of cavity magnetrons during W.W.II and beyond, mainly at GEC in Wembley [Pat 91], see for instance Fig. 5.15.

The new cavity magnetron technology was quickly acquired by the Americans. Their advanced manufacturing processes made it possible to form precise anode

Fig. 5.15 British Magnetron *CV1481* (improved version of *CV76C*). Nominal frequency 2993 MHz, peak output 450 kW at PRF = 500 Hz, pulse length from 0.7 to 2 µs

blocks in a single operation, starting from a cylinder of oxygen-free copper. Western Electric developed its celebrated *725A*, a double-ring-strapped X-band magnetron, which soon became the most popular magnetron ever made[25] and the basic reference for many new developments.

The American developments in the radar field were mostly due to remarkable people such as Alfred Loomis, the multi-millionaire who had constructed, at the end of the 1930s, a modern private electronic laboratory in Tuxedo Park, New York, [Con 03] and Vannevar Bush, counselor to the Secretary of War Henry Stimson, who allocated for the first year of the microwave radar projects funds for almost half a million dollars. In autumn 1940, the Massachusetts Institute of Technology created the Radiation Laboratory (usually called briefly “Rad Lab”).[12] The *Rad Lab* supplied the Allies with the ability to design microwave radars with (a) smaller antennas, fundamental to airborne and naval applications, (b) better spatial resolution and (c) lower sensitivity to natural or man-made interference coming from different directions, thanks to the reduced angular extension of the main lobe of the antenna. In 1940–45 the Radiation Laboratory supplied to the Allied forces new radars based on the microwave technology, for applications including air search, coastal and marine defense, anti-aircraft and anti-ship radars

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[25] The 725A was capable of delivering about 60 kW peak power at 9375 MHz (which remains one of the standard frequencies in the X band for magnetron radar even today), had a glass boot on the filament seals and a rugged flange to be easily handled even in field service operations. As much as 89.480 units of 725A were delivered during W.W.II to the British under the *Lend-Lease Law* enacted by F.D. Roosevelt on March 11th, 1941 to provide military support by means of material and services to Great Britain, Free France, China and other nations, thus de facto ending the neutral status of the USA, who entered the war in December.

and finally airborne radars (subject of the ensuing chapter), for a total of about 100 radar types.

A notable implementation of the *Rad Lab* was the creation of the large long-range radar called Microwave Early-Warning (MEW)[13] which was effective against the V-1 attacks on London, see Fig. 5.16. In 1945, the Rad Lab arrived to employ 3500 people with a monthly expenditure of the order of four million dollars.

The technical and operational advantages resulting from the use of microwave with respect to the German radars were huge for two or three years, and the gap was never filled up by the Germans for the situation of crisis of their factories after the first defeats. Figure 5.17 shows the Germanic effort, between the end of the 1942 and 1943, to fill the great difference between the available power levels in

Fig. 5.16 The *AN/CPS-1 microwave early warning* (MEW) radar, deployed in time for D-Day on the south coast of England. *On the left* the British *AMES Type 13 Mk III* height seeking radar

Fig. 5.17 Comparison of effective power levels (*Leistung*) between the British and German microwave radars during the W.W.II

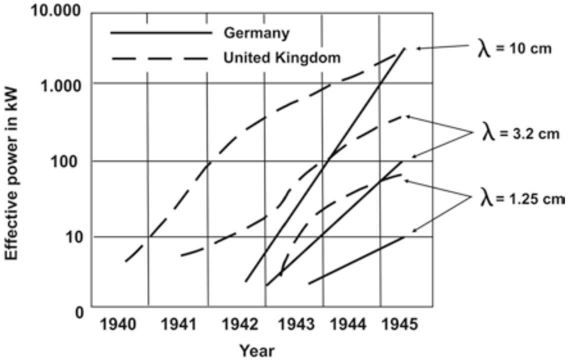
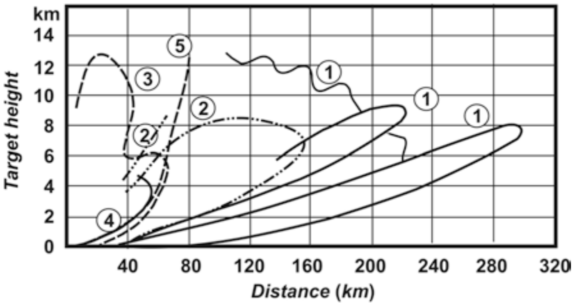


Fig. 5.18 Measured coverage of some German radars



the microwave region,[26] with the technical results arriving too late to have a significant impact at the military level. However the German radar technology went to remarkable results, as shown in the coverage diagrams in Fig. 5.18.

In addition to the airborne radar, the magnetron became the preferred power device for other mobile applications. In 1941 the British started the implementation of fire-control radars (tracking radars) with a magnetron transmitter, with functionalities similar to the Würzburg. The British battlefield radar *No. 3 Mk 2* operated at 10 cm with a peak power of 140 to 290 kW depending on the model of magnetron.[14] The production started in 1942 and continued for nearly all the wartime. Overall, 876 sets (of which 50 were delivered to the Soviet Union) were produced when (April 1945) the production ended.[27]

5.5 The Italian Situation

Italy was necessarily off the impetuous development of the microwave radar which started in the autumn of 1940. In fact, on May 22th, 1939 the Foreign Ministers Galeazzo Ciano and Joachim von Ribbentrop signed the “patto d’acciaio” (*steel agreement*) between Italy and Germany, and on June 10th, 1940 Italy went into war. Germany, owing to its strong industrial and technological superiority, had not any interest in letting its allies to know too much about their developments in the field of radar and radio navigation, but allowed them to use their equipment, often with German personnel for technical operation and maintenance. Italian armed forces used for air defense, until the armistice, the German radars Freya and

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[26] The microwave era started with the Randall and Boot’s magnetron at wavelengths around 10 cm, i.e. S band, and during W.W.II the wavelengths quickly arrived to 5, 3 and 1.25 cm, i.e. to C, X and K band respectively.

[27] After the war some sets were adapted to meteorological applications (tracking of balloons to measure the speed of the wind, model No. 3 Mk2/4), while others have been demolished in 1957/1958.

Würzburg curiously renamed *Felino* and *Volpe,*[28] while, as already shown, in some vessels they installed the *Gufo*, in others, the German *Seetakt*.

With the notable exception of the *Gufo*, of which fifty sets were ordered to the firm SAFAR[29] but only eighteen were delivered, no radar of Italian design—as far as it is known—arrived at the stage of a real industrial production. Likely, not even these partial implementation results of the Italian radar would have been achieved without the impetus due to the famous defeat known as Cape Matapan, on March 28th, 1941, by the British fleet. According to Bowen, the Battle of Cape Matapan[15] began with the detection of the Italian fleet, first visually and, later, by the radar of the *Swordfish* (this was an ASV: *airborne-surface vessel*, radar on board a maritime patrol aircraft), which took off from the air carrier *Formidable* [Bow 87]. In this battle, the Italian navy lost three 10,000 tons cruisers of two destroyers and 2300 persons. A previous action of the Royal Navy damaged some of the important units of the Italian fleet in Taranto.[16] However, only after the defeat of Cape Matapan—and therefore, very late as compared to other nations—the attention of the Navy for the naval radar exploded and they started the development of the only national radar which would be produced in series, the *Gufo* E.C.3. This radar—as described in detail in Chap. 2—suffered from the technical limitations of that time, as well as from the scarcity of resources of the Italian armed forces. As a result, the Gufo had to be multifunction, not specialized for either surveillance or fire control, nor for the type of targets, ships or aircraft, and had two antennas for transmission and reception. It has been shown that, after the operational trials in 1942, a few of these radars were supplied to the Italian naval units only near to the end of the war, or—more precisely—the war on the same side as Germany.

Summing up, after Cape Matapan Italy better considered the importance of operational radar equipment for the needs of its three armed forces, first of all the navy, in the shortest possible time. So, quickly (see also Chap. 2) the two prototypes of the E.C.3 system kept in the laboratories were refurbished and enhanced, and the "*Folaga*" radar, operating in the band between 150 and 300 MHz, was implemented for the coastal surveillance[30] in addition to the above described "*Gufo*" operating in the band between 400 and 750 MHz. The "*RaRi Committee*"[31] was formed with qualified representatives of the three armed forces, in order to coordinate the entire panorama of radar, radio-navigation and electronic warfare, and adding, to operational experts from the forces, technical experts such as Ugo Tiberio and Nello

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[28] The Italian forces used the first letter of German radar names to attributed to each radar type the name of an animal (e.g. *Volpe*–Fox, *Felino*–Cat), maybe to conceal the nature of the apparatus, as in *Gufo*-Owl, *Folaga*-Coot, *Veltro*-Dog, *Lepre*-Hare, *Lince*-Linx, *Vespa*-Wasp….

[29] See also Fig. 5.18 in [Gal 12].

[30] The Navy did later request to the Italian industry the construction of 150 sets of this radar under the supervision of R.I.E.C., but the request resulted too late with respect to the developments of the war.

[31] This—rather strange-looking—name was derived from *RadiotelemetRi*, Radio-rangefinders. In Italian, *Rari* is the plural of *Raro*, i.e. of rare.

Carrara. With the establishment of the *RaRi* committee, the task of completing the development of *Gufo* and *Folaga* and of adapting it to the production of many sets from the prototypes made in Livorno was entrusted to the industry. Unfortunately, the Italian industry was not technologically ready to the development of this new equipment, and was still lacking an adequate number of human resources. Also because of the events of the war, of the damage suffered by the Italian industries due to the bombing and in some cases (SAFAR and others) of their transfer to safer areas, the "*RaRi* Mobilization" got only partial and limited results.[17]

During the war and until the armistice of September 8th, 1943, in addition to the activities mainly due to Tiberio and Carrara, described in Chap. 2, we must remember the ones by Giorgio Barzilai and Gaetano Latmiral (1909–1995) [Fra 05]. Moreover, in addition to the Navy, the Italian Army has to be mentioned, with its Direzione Superiore Studi ed Esperienze—DSSE (Direction for High Studies and Experimentations) in Guidonia[18] (near Rome) where Barzilai worked in 1941–43. Thanks to the "RaRi mobilization", the SAFAR Company in Milan allegedly implemented, based on the design by ing. Castellani, the *radiotelemetri* (radars) *Lince* (1939) and *Veltro/RDT4* (to which the giant version *RDT4 bis* followed) for long range surveillance and guidance of fighters. At the DSSE, in Guidonia, they studied and experimented prototypes of national radar: the long-range *Argo* (see later), the airborne radar for naval search *Arghetto* (also called *Vespa*, tested on a SM-79 and a CANT Z-1018) and the reduced-size *Lepre*[32] derived from the *Vespa* for night fighters.[19] It should be remembered the valuable contributions to radar techniques by the Italian radio industries in 1936–1941 and its original ideas and patents, due to persons such as the aforementioned (Chap. 2) ing. Arturo Castellani as well as ing. Ernesto Montu,[20] ing. Augusto del Vecchio,[21] and prof. Francesco Vecchiacchi.[22] Some rather vague documents refer to the "*Lince*" radar which was allegedly developed and implemented as a prototype for the *Regia Aeronautica*.[23] From the SAFAR/Castioni archives in the *Museo Nazionale della Scienza e della Tecnologia "Leonardo da Vinci"* in Milan, Italy it results that the implementation of the "Gufo" and "Folaga" radars was mainly entrusted to the firm SAFAR. The Italian industries which worked, before and during the Second World War, in radio and radar, were SAFAR, Allocchio Bacchini, Magneti Marelli, IMCA Radio, Italian Philips, Officine Marconi, the components makers FIVRE and FARET, and from 1942, also the Italian Telefunken. Finally, a consortium, called BGS, was constituted by Borletti in Milan, Galileo[33] in Florence and San Giorgio in Genova (with a factory in Pistoia)

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[32] The airborne radar *Lepre* is mentioned in the Minutes of the Technical-Scientific committee of the Italian Armed Forces on December 23rd, 1942; two sets, built by SAFAR, were tested in Cameri, near Novara, on April 29th, 1943.

[33] The celebrated Florentine Company "Officine Galileo", whose legacy is currently at the Finmeccanica firm Selex ES (previously, called Galileo Avionica and Selex Galileo) in Campi Bisenzio (Florence), has been known for a century and a half for precision optical (and, subsequently, electro-optical) instrumentation; for those interested in the history of this firm, in Campi Bisenzio there is the Museum of Technology "Adolfo Tiezzi", see http://associazioni.comune.firenze.it/exiti/anno-2012/selex-galileo/museo-selex-galileo.pdf.

Fig. 5.19 General Algeri Marino

for the production of an anti-aircraft fire control system based on the *Breda* 90/53 gun, an equivalent of the celebrated German 88 mm series of guns; through 1942 the BGS pointing system used the Würzburg D radar. Thirteen *Gufo* sets [Zep 08] added to four coastal radar model *Folaga*[34]; a set was entrusted to gen. Algeri Marino[35] (see Fig. 5.19), DSSE, Guidonia, to obtain a terrestrial version for the air defense, called *Argo*. According to some sources, at the end of 1942 the prototype of the *Argo* (which allegedly reached the remarkable range of 250 km) was used for the airport surveillance in Pratica di Mare (Roma), and was taken by the Germans in September, 1943.[36]

According to some sources still to be carefully checked, Magneti Marelli realized its own version of the *Folaga* with an antenna array and in 1943, SAFAR (according to other sources, Magneti Marelli) realized a fire control radar, the *Lince*, operating on the 70 cm wave (such as the Gufo) with a range exceeding 150 km. Finally in 1941 SAFAR presented the patent application for an airborne radar, from which the *Veltro* radar design was derived for the Flak. Due to the paralysis that underwent all industrial activities after the armistice, it is very likely that these radar sets with imaginative names: “Argo”, “Vespa”, “Veltro”, “Lepre”, “Folaga” and “Lince” (in the versions “Near Lince “ and “Far Lince”) did not arrive beyond the prototype stage, or in some case, beyond the design stage, see Fig. 5.20.

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[34] As already mentioned, a version of the *Gufo* operating at twice wavelength, i.e., about 1.5 m, was designed for the coastal defense and called *Folaga*. It is reminded that during the tests of “Folaga” in May 1943 on the terrace of the EC Institute (*Mariteleradar*) it was possible to detect at over 200 km a mass raid of American aircraft arriving to bomb Livorno (Leghorn).

[35] Algeri Marino (Càsoli, 1894–Rome, 1967) pioneered the use of radio in aviation, was a general of aeronautical engineering, and research director of the Ministry of Aeronautics; in 1948 he became professor of electrical communications at the University of Rome “La Sapienza”.

[36] Also on the *Argo* clear and reliable source documents are missing. The first operational Italian air defense radar was a Freya supplied to the Italian armed forces on July 1st, 1942 by the Germans to operate in Benghazi, and later transferred to Sicily.

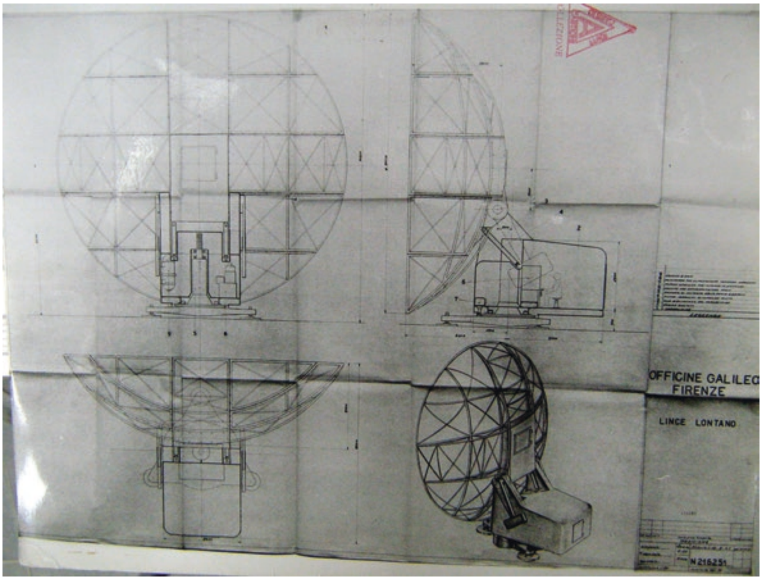

Fig. 5.20 Drawings of the antenna (diameter: 10 m) of the "Lince Lontano", by Officine Galileo—Florence, September 1942

Summing up, the story of the Italian industrial radars of the W.W.II period unfortunately remains unclear with a very poor documentation and with the few available sources being not always in agreement. For sure, the operational use of these Italian *Radiotelementi*, some of advanced design but all coming too late (to confirm the lesson by Watson-Watt on "third best") was practically zero, especially for airborne and air defense applications. In fact, Italian air defense until the September 8th, 1943 used the *Freya* German radar network, christened "*Felino*", positioned at a distance from one another, slightly less than their range of 150 km, to covered the borders of the national land and the islands (i.e. Sicily and Sardinia, see Figs. 5.21 and 5.22). Every "Felino" was associated with one or two "Volpe" (Würzburg) or "Volpe Gigante"(Würzburg Riese); a team of 11 units was assigned to the operation of each Volpe, while the "Felino" team was made up by 8 people.

Excluding a mention in [Fra 05], there are no documents relating to real and effective technology exchanges between Germany and Italy. Only in June, 1940, after Italy's entrance into the war, the Italian Navy did receive some technical information on the various equipment built in Germany. In fact, a committee made up by three officers of the Italian Naval Weapons was invited to Germany from 14th to 28th June, 1940 to get knowledge of technological innovations in the war at sea. The topics discussed and the material shown ranged from magnetic mines, torpedoes (without wake), systems for the protection of ships from torpedoes and mines and many other, among which a "Freya", not of the last generation, not usable on board vessels, but with technical details interesting a lot the Italian researchers of the E.C. Institute. On the other hand, nothing was said or shown on

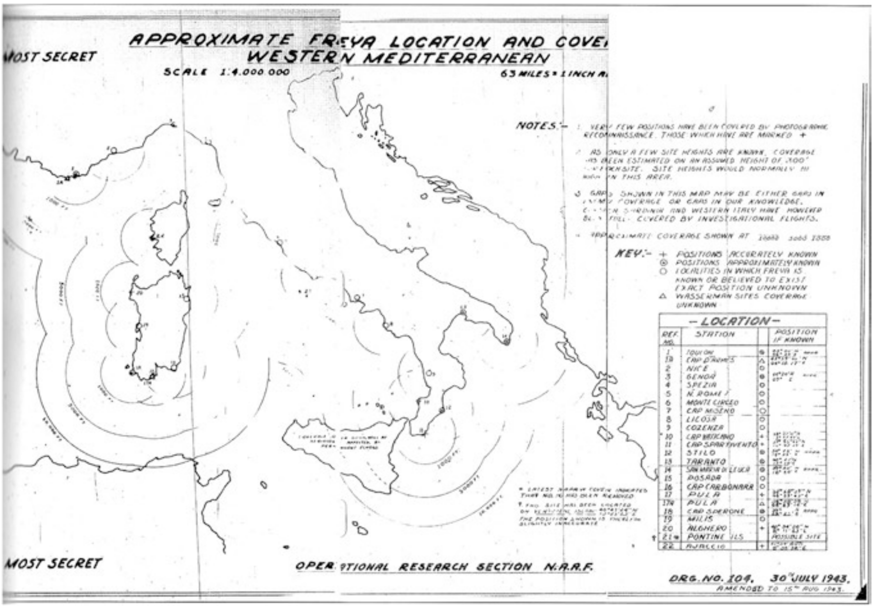

Fig. 5.21 Positioning of Freya radars on the Tyrrhenian coasts and in Sardinia, July 30th, 1943 (amended August 15th) as reconstructed by the Allies

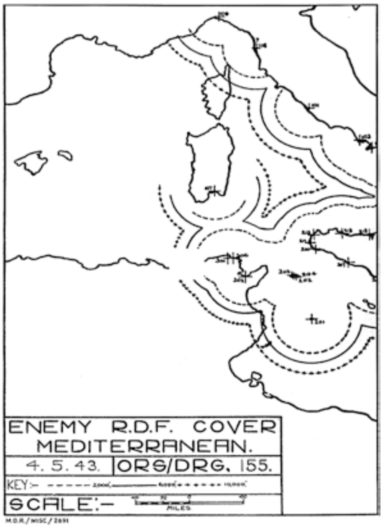

Fig. 5.22 Coverage of the Italian-German radars, Tyrrhenian and low Mediterranean Sea, May 4th, 1943 (as reconstructed by the Allies for air targets at 2000, 6000 and 10,000 feet a.s.l.)

the “Seetakt”, that for over a year was embarked on the Graf Spee, on new battleships and on two brand new cruisers. Summing up, some Italian-German exchange of knowledge on radar technique took place, but ultimately the Germanic contribution to the development of the Italian radar was very limited. The delivery of some sets (as the DeTe—FuMO models 24 and 21G which were installed on some Italian ships) was mainly a contribution to the conduct of the war, not a contribution to the technological development of the Italian *radiotelemetri*.[24]

Overall, Italy invested a total of about sixty thousand dollars of that time for the development of the radar, with teams consisting of a very few researchers and technicians. This is a derisory amount, orders of magnitude lower than the billions of dollars and the thousands of researchers and technicians (including those employed in the production) committed by the USA.

5.6 The US Contribution

During the war the US researchers contributed to two essential elements of the development of the radar, i.e. “Phased Array” antennas and “Monopulse”. The former, treated in more detail later, were also developed in Germany[37]; however the first microwave phased-array is due to the *Radiation Laboratory* and to *Bell Laboratories*. It is the X-band fire control radar *Mark 8* or *FH*.[38] The antenna of the Mk 8/FH, with its unusual appearance, was constituted by 42 elements of the “polyrod” type, organised in fourteen rows and three columns. The phase of the signal of each column was mechanically controlled by inserting the triple appropriate delay elements, which created a horizontal scanning. The width of the beam was 2° with the possibility of azimuthal scanning within 30°. The limited length of the transmitted pulse, only 0.4 μs, allowed an excellent resolution (and accuracy) in range. The transmitted power was 20 kW. The Mk 8 radar was put into production by Western Electric in 1942, after the tests of the prototype called CXBA. Then the version *Mark 14* was developed with an ancillary height finder.

The second element, the Monopulse, is an ingenious technique that permits to improve by an order of magnitude the angular accuracy of a tracking radar—and to reduce the effects of some disturbances on the angular measurement. The angle

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[37] German radar engineers had to design large radar equipment for long range surveillance such as the *Mammut*, whose enormous size required a non-rotating antenna with the beam moving in an electronic way.

[38] The U.S. Navy used the following naming rules for his radar sets. Search (or surveillance) radars were identified with a two letters sequence, i.e. the “S” (from “search”) followed by a second letter in chronological order (the radar type “SG”, for example, was designed before the “SJ”, the latter before the “SK” and so on). Similarly, fire control radars were identified by a “Mark number” which—in turn—gave a chronological order to the various types of set.

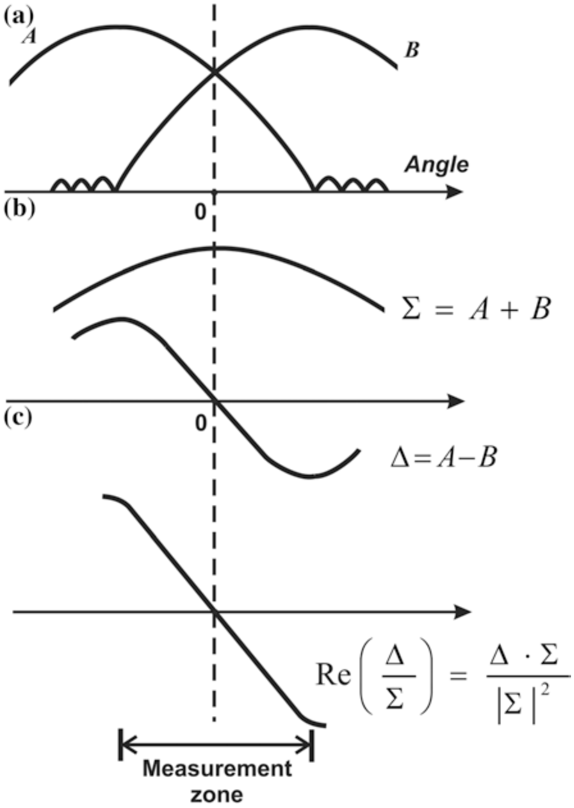

Fig. 5.23 Operating principle of the Monopulse technique

measurement is made on a single pulse basis (hence, the name), unlike the previous methods using beam switching and conical scan. The Monopulse (see Fig. 5.23) uses two antenna beams, called Σ (sum) and Δ (difference), in each of the two measurement planes (azimuth and elevation); the first American radar set of this type[39] was developed at the Naval Research Laboratory in 1943, and although it is clear that monopulse radar have been developed in secret and in an independent manner by various nations, R.M. Page[40] is generally recognized as the inventor of the Monopulse, also because of his US patent No. 2929056 “Simultaneous Lobing Tracking Radar”.

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[39] On the history of monopulse radar in the USA see [Bar 10], and concerning the development of the Monopulse in USSR, [Leo 98].

[40] Robert Morris Page (1903–1992), was intended for the role of protestant pastor when a professor of physics addressed him toward the scientific career. He entered, very young, the NRL in the group headed by A.H. Taylor in 1927, and was with the NRL for 39 years becoming, in 1957, its Research Director. In the 1930s has was one of the pioneers of the pulsed radar, inventor, along with Young, of the duplexer, see [Pag 55], [Pag 62a], [Pag 62b], [Pag 77].

(a) pair of antenna beams
(b) their coherent sum and difference
(c) the Monopulse measurement (the dashed line shows the “boresight”)

The conclusion of W.W.II, with the launch of atomic bombs on Hiroshima and Nagasaki (August 6th and 9th, 1945) saw once again the use of the radar, which was installed on board of each bomb as an altimeter[41] and to make it detonate at the “optimum” height of 580 m (the one that would have maximized casualties and damages).

5.7 Developments and Applications of War-Time Studies

The end of the Second World War also concluded the phase of rapid and convulsive studies with the quick growth of radar technologies and systems as described before. In addition to France, Germany, Italy, the United Kingdom the United States, Japan, the Netherlands and Russia, radar developments took place in Hungary,[42] where in 1946 they concluded, as explained in [Bay 47], a scientific project proposed at the beginning of 1944 by dr. Zoltán Lajos Bay consisting in transmitting a signal on the Moon and receiving its echo,[25] with a mean delay of about 2.6 s due to the mean distance of 384,000 km.

During W.W.II, the design and experimentation effort concerning radar techniques in Europe and in the USA was never equaled, with the commitment of thousands of researchers and technicians and a huge spending, estimated—only in the United States—as 2.7 billion dollars (about twice the spending for the atomic bomb). They developed with the greatest speed, even in the absence of means for automatic computing and simulation, techniques such as: microwave,[43] target recognition and early forms of radar imaging,[44] active jamming (ECM: *Electronic countermeasures*) and radar countermeasures (ECCM: *Electronic Counter Counter Measures* including frequency agility and anti-chaff), tracking, first by sequential lobing, then by conical scan, and finally by the already mentioned Monopulse.

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[41] This altimeter was derived from the surveillance radar APS-13, operating at 410–420 MHz; this frequency band was continuously monitored by the APR-4 receiver on board of the B 29 to avoid any premature triggering by possible Japanese radars, with a serious risk to the B 29.

[42] In this nation operated the Tungsram, the third European producer—after Philips and Osram—of lamps and thermionic tubes.

[43] In 1943 new airborne radars operated at 9–10 GHz, and during the last years of the war the wavelength of some new radar sets went down to 3 cm and even to 1.5 cm in an experimental German radar of 1945, capable of providing radar images of the targets.

[44] At the end of the war the Germans implemented the high-resolution experimental radar system *Barbara* which associated the microwave wavelength of 9 cm with the huge antenna of the Würzburg Riese and performed a scan of the target by rows for imaging purposes.

At the system level, just after the naval and terrestrial applications, the radar became also airborne and was embarked even on submarines.[45]

During and after the war they developed the former "instrumental radars" characterized by highly accurate tracking and dedicated to the precise reconstruction of the trajectory of cooperating targets such as balloons, rockets, missiles and launchers. The U.S. Air Force and NASA "single object tracking radar" AN/FPS-16, the first radar designed for the tracking of rockets and missiles, is one of the better known of those radars. It was a result of the work by NRL during the wartime period on the Monopulse techniques. The AN/FPS-16 was used at Cape Canaveral in 1958 to guide the space launches Explorer 1 and Vanguard 1.[46]

The main aspects of the radar applications emphasized in the post-war period, very little (or not at all) developed until W.W.II, are related to (i) civil purposes (including remote sensing and traffic control), and (ii) defense from the potential new threats from the Soviet bloc, that will be discussed later on.

Among the civil applications of radar technology, the most natural and promising resulted the Air Traffic Control (ATC). In fact, with the post-war development and the growth of the civil aviation, the skies become more and more crowded, and in the 1960s and 1970s it was necessary to reduce separations between aircraft. In the most crowded volumes of airspace, the ATC separations passed from the large values typical of the *procedural control*, based on "position reports" in radiotelephony by the pilots, to those of *radar control* permitting much smaller separations with a real time picture of the traffic being available to the ATC controllers. Within the radar control, different types of requirements emerged soon, depending on the portion of air space and the segment of aircraft route to be monitored. Thus they developed different types of ATC radar, i.e. for the *en route* control (*En Route* Radar), for the control of the *terminal manoeuver* and *approach area* (TMA Radar) and for the airport surface control (*Surface Movement Radar*, SMR, also called ASMI or ASDE). The requirements for those different applications are variable and related to the maximum surveillance distance (the so-called radar range), to the resolution in range and azimuth, and finally to the data updating period, varying from 8 to 12 s for *en route* control, 4 or 6 s in the TMA control and finally one second for airport control.

Perhaps the first ATC-related use of radar was as a landing aid, to locate in a very precise way the approaching aircraft during landing (from about 30 km) and

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[45] The periscope radar "Funkmess Berlin U 2" allowed the U-Boot at periscopic depth to see convoys of vessels up to 20 km, as well as the coastline and the buoys.

[46] The measurement errors of this radar (when the signal power is two orders of magnitude above that of the noise) are: in angles, less than a tenth of a milli-radian, i.e. approximately six thousandths of a degree, and in range, less than five meters. Its main technical data are:

- Interval of operating frequencies: 5400–5900 MHz
- Peak Power: 1.3 MW
- Diameter of the antenna: 3.9 m
- Antenna Gain: 47 dB
- Receiver noise figure: 6.5 dB.

to guide it in the vicinity of the runway threshold, hence the name Ground Controlled Approach (GCA).[47] The first GCA system was the AN/MPN 1 by *Gilfillan Brothers*, then *ITT Gilfillan*; the Heathrow airport was equipped with a GCA in 1947. The GCA was used in 1948–49 during the well-known "Airlift" in Berlin, with a peak of 1398 landings (over all the Berlin airports) in the single day April 15th, 1949. The GCA is still used for landing (or decking) of military aircraft. The modern name is Precision Approach Radar (PAR), see Fig. 5.24.

The entry into force of the Chicago Convention (signed on December 7th, 1944 and effective, after the formalization by the different States, through April 4th, 1947) started the operation of the *International Civil Aviation Organization*, ICAO[48] with the issue of standards to ensure the uniformity at the global level of the procedures and facilities for flight assistance. The standardization gave a strong impetus to their development. For example, the war-time Identification Friend of Foe system (IFF)[49] has originated a standard ATC surveillance mean i.e. the secondary surveillance radar (SSR), currently in its "Mode S" (Selective mode) version. The air traffic control radar, called "primary" to distinguish them from the secondary radar (i.e., the SSR), initially derived from military long range surveillance radars. For instance, the 50 cm–500 kW primary radar Marconi S 264 (derived from the wartime English radar Type 11) for about thirty years has provided the long-range surveillance in the Italian airspace areas centered on the airports of Linate and Fiumicino, where two sets were installed. The antenna had a cylindrical reflector and a linear feed, skimming the ground, hence the name "lawn mower", see Fig. 5.25; the elevation beam was created by the help of the reflection from the ground, which had to be continuously maintained wet enough. The S 264 operated on the 50 cm wavelength (i.e. at UHF around 600 MHz); the

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[47] In the USA, between 1943–46, they decided to use the GCA, with two radars whose antennas would move on small angles covering horizontally and vertically the volume around the expected path of the landing aircraft. This method was very flexible: the aircraft needed only to be equipped with radio and the controller was guiding the pilot to stay on its final three-dimensional path to the runway by advising for altitude and direction corrections with commands via radiotelephony. A GCA equipment could be carried on a truck and positioned near any runway in use. This tool was very useful especially in poor visibility conditions. Its major disadvantage is that it can handle only one aircraft at a time. Its main advantage *versus* air-derived navigation and landing systems—such as ILS and MLS—in the military field (for example, for decking on aircraft carriers) is the lack of any potential help to incoming threats, e.g. anti-ship missiles.

[48] The ICAO is the ONU agency specialized for Civil Aviation and has about 190 member states. Its main organization comprises: the *Council* (with eight Committees), the *House of the Representatives of the Member States* and finally the *Secretariat.* The most important decisions of the ICAO are contained in the 18 documents called *Annex* 1… *Annex* 18 and containing the Standards and the Recommended Practices—in short, the SARPs—for Air Navigation. The Annex 10, for example, is related to communications, surveillance and navigation.

[49] The IFF is still in use with the name SIF (Selective Identification Feature) and has various "Modes" of operation: Mode 1, Mode 2… Mode 5, some of which are compatible with the SSR, e.g. Mode 3 of IFF is compatible with Mode A of SSR, and Mode 5 provides a secure version of Mode S. For the history of IFF see: [Bow 85].

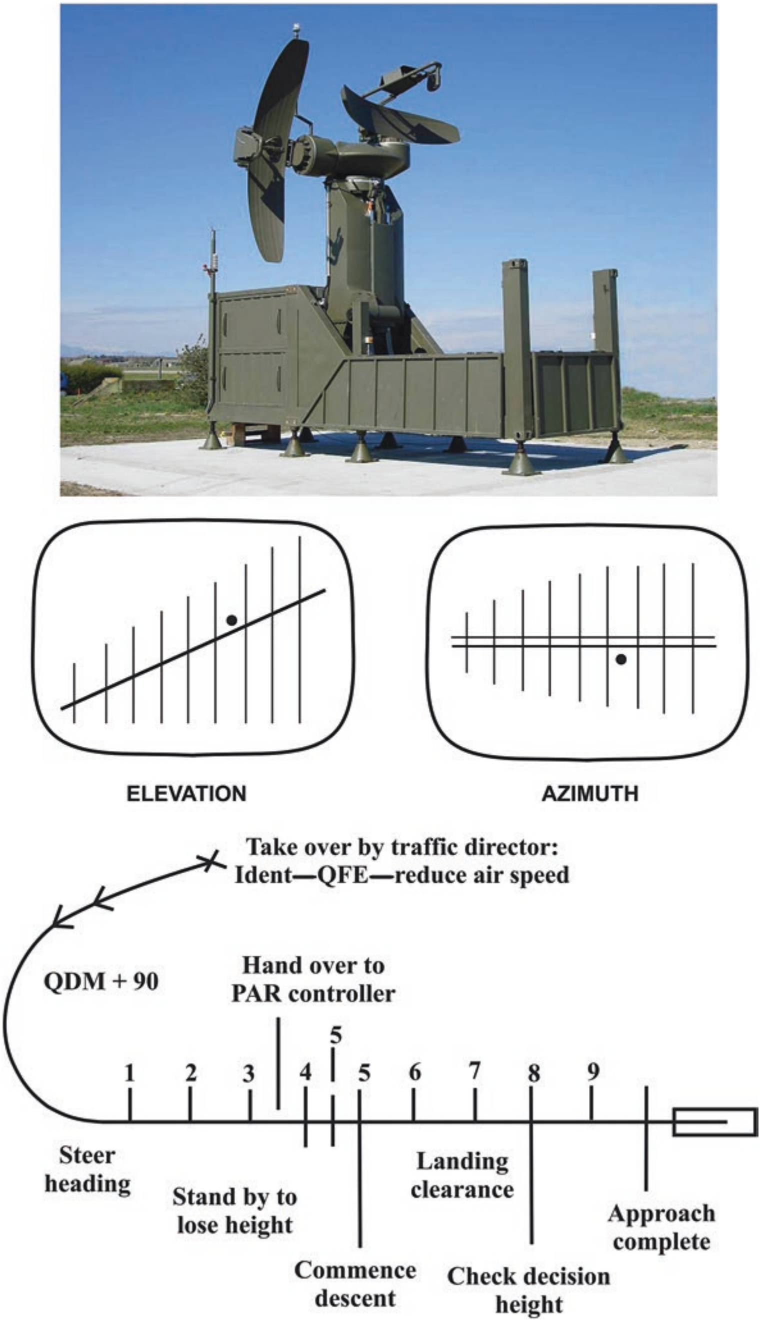

Fig. 5.24 A precision approach radar (*PAR 2090 CF* by Selex Galileo) and the schemes for display and operation

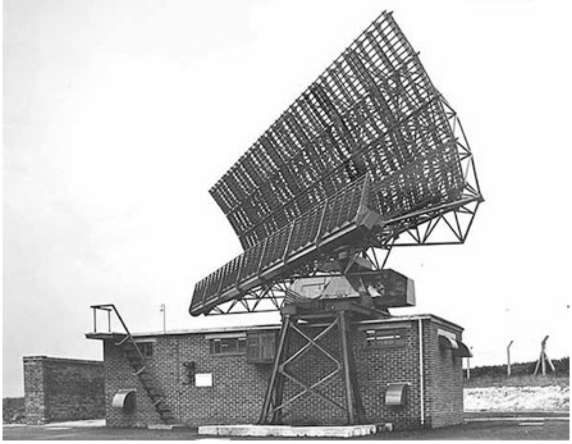

Fig. 5.25 The 50-cm air traffic control radar S 264

designer of the S 264, Eric Eastwood, succeeded to show that it was suited to provide radar coverage at a very large distance (400 km) and was also no prone to weather disturbances (rain and other phenomena), hence better suited to the surveillance *en route* than other radars operating at L and S band frequencies according to the American school.[50]

Figure 5.26 depicts the progress of the equipment used by air traffic controllers (referred to the Italian situation), covering a period of about thirty years, in which the radar control was introduced.

The dream of Hülsmeyer wishing an all-weather collision avoidance system for vessels was finally realized at the end of the Second World War. In May 1945, in fact, a first prototype of navigation radar for ships, the Type 268 (working around 9 GHz), was installed on *HMS Pollux*.[51]

However the diffusion of this technology, essential for the safety of the maritime traffic, has been somewhat slow and with some failures. The most serious of them happened on July 25th, 1956 shortly after 23:00, when the collision between the *Stockholm* and the *Andrea Doria* took place, also due to wrong understanding of the radar information.

Since then, radar processing, filtering, and display have seen considerable progress, so much so that today the navigation radar is mandatory on all boats exceeding three hundred tons of gross tonnage. The largest vessels must have more than one radar, at least one in the S-band, less sensitive to the rain, and another one in

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[50] In 1954 the Marconi radar S 264 entered the service in the airport of London Heathrow; Italy then purchased from the GEC Marconi Company two sets of the S 264, installed at Milano Linate and Fiumicino Coccia di Morto, respectively. This radar, connected with the control centre in Roma Ciampino, remained in service, flanked gradually with more modern systems, until 1990, when its frequencies were attributed to a channel of the UHF TV broadcasting.

[51] The English Marconi civil system called "RADIOLOCATOR 1" was fitted on SS *Duke of Lancaster* and then moved to SS *Argyll*, on the Heysham—Belfast route.

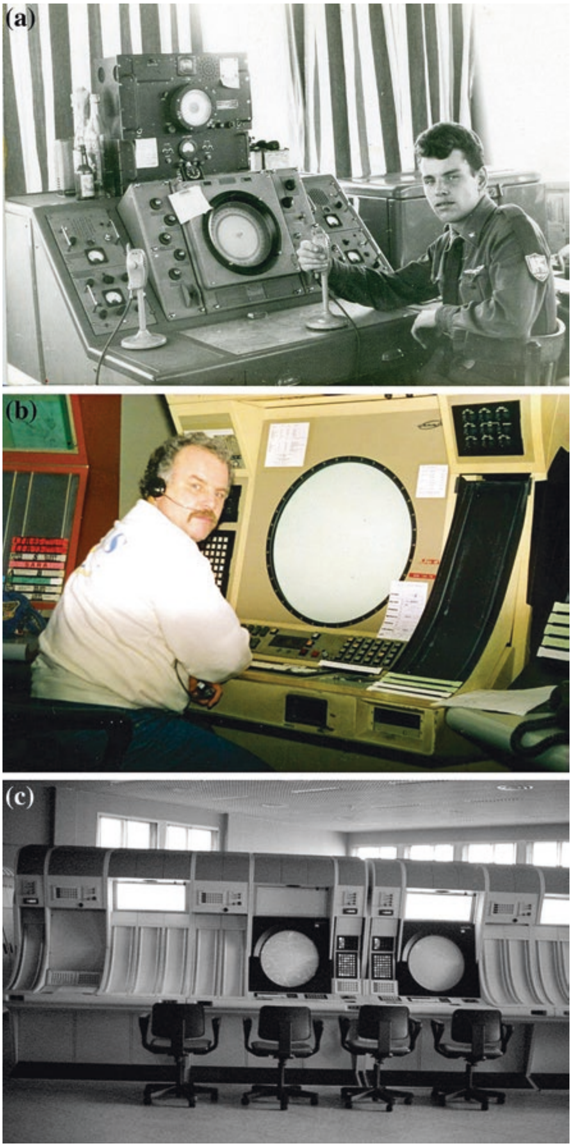

Fig. 5.26 **a** August 1963: the 18-years-old Franco Iosa, Tower Controller of the Italian Air Force, in the control tower of the military airport in Istrana (Treviso, Italy, ICAO code LIPS), with two radio goniometers, in UHF and (bottom) in VHF. **b** End of 1980s: the radar controller Franco Iosa in front of a Selenia DDS 80 console in the Area Control Centre (ACC) in Abano/Padova (Italy). **c** Beginning of 1990s: partial view of the renewed radar room in the Abano/Padova ACC just before the official opening

the X-band, with better resolution. Within the field of civil and consumer products, the widespread use of radar on boats (even small) for transport, fishing and leisure is well known; also known is its use by the police for the control of speed limits, realized, since the 1960s, via the Doppler effect.

Table 5.1 Names of the frequency bands (IEEE Std. 521, 1984)

Band	Frequencies
HF	3–30 MHz
VHF	30–300 MHz
UHF	300–1000 MHz
L	1–2 GHz
S	2–4 GHz
C	4–8 GHz
X	8–12 GHz
Ku	12–18 GHz
K	18–27 GHz
Ka	27–40 GHz
V	40–75 GHz
W	75–110 GHz
mm	110–300 GHz

The radar frequency bands (and also those for of telecommunications and navigation) are named still today with the letters—intentionally meaningless—dating back to the Second World War: L, S, C, X, K…and incorporated by the IEEE as a standard. The corresponding frequency intervals are reported in Table 5.1.[52]

The allocation of frequency bands used by radar, as well as the management of the entire electromagnetic spectrum, is a task of the *International Telecommunications Union* (ITU/ITU) through a series of regular conferences named WARC (World Administrative Radio Conference). The frequency ranges (below the millimeter-band) for radar use are essentially those of the WARC-79.

Among the post-war technological steps one must remember in the 1950s the *klystron* power microwave amplifier tube,[53] and then the *traveling wave tube* (TWT), characterized by a wider bandwidth; in more recent times, the tubes were replaced by solid-state devices for the applications not requiring a very large peak power.

The effect of noise in Telecommunications was masterfully analyzed by Claude Shannon immediately after the Second World War [Sha 49]. After the end of the conflict, in particular in 1955–1960, the basic radar theories were systematized. To a large extent, they derived from studies carried on in the wartime period. In particular one must mention: the theory for the detection of non-fluctuating targets in noise [Mar 60], then extended to fluctuating targets by P. Swerling [Swe 57],

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[52] It should be remarked that other letters (progressive: D, E, F…J, K…) designate the bands of the apparatuses of electronic warfare and at the same time, to make things more difficult, the radar bands: in this way, the L band is also denoted by the letter D, the X-band by I/J etc. according to a NATO standard.

[53] The klystron, being an amplifier, is suitable for the use of coded waveforms—unlike the magnetron oscillator. Another advantage over the magnetron is the very clean emission spectrum.

the estimation of the target parameters [Man 55], the matched filter and the "pulse compression" [Tur 60], [Kla 60].

In this context we should also remember the 28 volumes of the Radiation Laboratory[54] Series, covering the main radar technologies, in particular at microwave (transmitters, receivers, antennas).

These volumes, edited by Dr. L.N. Ridenour, were published by Mc Graw-Hill, New York in the early post-war years, and after sixty years they retain a large part of their value. The "Zero Volume" with the Preface and the Contents of the whole series, is available on http://www.scribd.com/doc/37137209/MIT-Radiaton-Lab-Series-V28-Index.

In addition to the volumes of the Rad Lab Series, in the postwar years the MIT produced other notable books on radar, including the almost 1000 pages long [Rei 53], and other scientific organizations played a role in the advancement of knowledge related to radar and communications during the war, such as the *Radio Research Laboratory* of the University of Harvard, which also carried out extensive basic studies on radar. One of these was, aimed at identifying the factors that defined the effectiveness of electronic interference (jamming) on radar and communications systems, and was carried on by J.H. van Vleck[55] assisted by David Middleton,[56] originating the celebrated work [Vle 66].[57]

For obvious reasons the technical and scientific contributions to radar from the nations that did not win the war (in particular Germany, France, the Netherlands, Japan and, as already shown, Italy) are less known, and worse documented than those of the Allies; the Soviet Union developments will be treated separately in the following. Radar developments in France and in The Netherlands, nations invaded by Germany in the first half of 1940,[58] was abruptly stopped [Bla 04], [RDN 04]. Documents and prototypes were destroyed, to avoid them falling into German hands, or secretly transferred to the United Kingdom. In [RDN 04] is narrated the story of the Dutch radar "Electrisch Luistertoestel" (electric listening device), which, as the *Gufo*, operated at 70 cm wavelength; the 1 kW power (on a pulse

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[54] The Radiation Laboratory of MIT (Massachusetts Institute of Technology), located in Cambridge, Massachusetts, worked from October 1940 until the end of 1945 under the coordination and funding of the National Defense Research Committee, established by the American president F.D. Roosevelt (1882–1945).

[55] John Hasbrouck van Vleck (1899–1980), an American physicist, after the W.W.II, during which he contributed to various studies of military interest, including the Manhattan Project, returned to basic physics and in 1977 obtained the Nobel prize for his contributions to the knowledge of the behavior of electrons in magnetic solids.

[56] About fifteen years later, Middleton wrote the popular textbook [Mid 60].

[57] The topic of this study, i.e. the spectral characterization of the noise after amplitude limitation, aroused, and raises, such an interest that the original technical report by van Vleck of 1943, hardly accessible, was published in the *Proceedings of the IEEE* in January 1966, [Vle 66], with a very few additions, i.e. the References after 1943 and some footnotes.

[58] The conflict began on September 1st, 1939; Denmark surrended in April 1940, Belgium, Holland and Luxembourg in May and France in June, with a German occupation of more than half of its land.

duration of about 3 μs) allowed ranges, demonstrated to the military authorities on March 1939, between 15 and 20 km on a typical aircraft target such as a Fokker C3.[26] During the German invasion of May 1940, just before the capitulation on 16 May, two “Electrisch Luistertoestel” sets were sent in haste to the Great Britain, while the other two, together with the documents of the project, were destroyed so as not to let them fall into the hands of the enemy. Out of the two sets that arrived in England, one was studied by British engineers, who were very surprised at the use of only one antenna, and the other was embarked on the destroyer *Hr. Ms. Isaac Sweers* (launched on September 13th, 1941 and sunk by a U-Boot in 1942) and called “Type 289 of Dutch origin”.

Although Hitler, with his strategy of military aggression by the “blitzkrieg”, did not encourage the development of defensive weapons, German researchers and engineers worked on radar with great professionalism, providing [Bla 04] the best apparatus until the first half of the war period. In addition to the electronic scanning of the beam, they feared (but we do not know whether and to what extent realized) techniques normally attributed to the post-war period. Among them is the *pulse compression*: this method, which dramatically improves the resolution ability of the radar as far as the measurement of the range is concerned, is effectively set forth in the Patent 768-068 by Erich Hüttman whose application was filed in Germany on 22 March, 1940 (but the patent was only published on 5 May 1955!). Its first page is shown in Fig. 5.27a the and two explanatory drawings in Fig. 5.27b.

The drawings are very clear and amazingly modern for that time (the first public works about pulse compression will appear in the technical literature around 1960). The pulse, transmitted every T seconds and with duration τ, is linearly modulated in frequency with a span Δf; in reception, a special network[59] applies a greater delay to at the lower frequencies, and a smaller one to the higher ones. Therefore, in the received pulse, the higher frequency components go to superimpose to the lower ones, thereby providing a pulse significantly narrower than the transmitted one.

5.8 Overview of the Developments in the Soviet Union—The Soviet Threat

The analysis of the relevant contribution by former Soviet Union (and later Russian/Ukrainian) engineers and scientists to the radar technology (for which the reader is referred to Chap. 3 of [Roh 05]) is somewhat complicated by the confidentiality with which these military-related topics were and are treated, up to absolute secrecy in the period of existence of the Soviet Union. From [Roh 05] it

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[59] This is a network (an “all-pass” filter) that applies to the input signals a delay proportional to their frequency.

(a)

Erteilt auf Grund des inzwischen aufgehobenen § 30 Abs. 5 Pat.-Ges.

AUSGEGEBEN AM
10. JUNI 1955

REICHSPATENTAMT

PATENTSCHRIFT

№ 768 068
KLASSE 21 a^4 GRUPPE [illegible]
P 80533 VIIIa/21a^4

Nachträglich gedruckt durch das Deutsche Patentamt in München
(§ 20 des Ersten Gesetzes zur Änderung und Überleitung von Vorschriften
auf dem Gebiet des gewerblichen Rechtsschutzes vom 8. Juli 1949)

Erich Hüttmann, Berlin-Köpenick
ist als Erfinder genannt worden

Julius Pintsch Kommanditgesellschaft, Berlin

Verfahren zur Entfernungsmessung

Patentiert im Deutschen Reich vom 22. März 1940 an
Patenterteilung bekanntgemacht am 5. Mai 1955

(b)

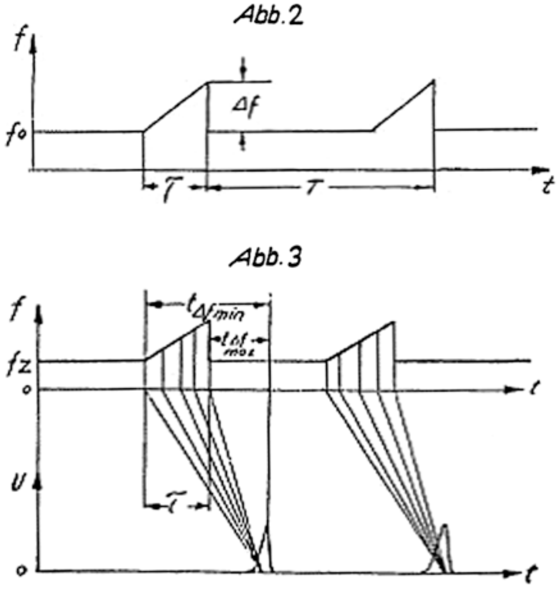

Fig. 5.27 **a** Patent by E. Hüttman, **b** Some drawings from the patent

results that as early as in July–August 1934, one or two months after the first tests of electromagnetic barriers by Pierre David, and eleven months prior to the tests by Watson-Watt in Orfordness, the first demonstrations of radar detection in Soviet Union took place with success. On October 26th, 1934 the first industrial contract for the production of five radar sets followed. These radar were *bistatic continuous wave*, the only known type at that time. In 1939 the Red Army accepted the first operational radar, the RUS-1 (*Radio Ulavlivatel Samaletov*-1), an apparatus operating in the metric wave (4 m) and of the bistatic type (transmitter and receiver were typically separated by 35 km). In 1940 the Red Army accepted the *Redut*, or RUS-2. Among the Soviet (and then Russian and Ukrainian) pioneers of radar, starting from the post-war years, one should remind Yakov D. Shirman.[60]

In the postwar years the Soviet Union developed their former antiaircraft defense and missile defense systems, i.e. the terrestrial *SA-10* and the naval *SAN-6*, well before the United States. The huge Soviet territory favored the choice of radar frequencies in the cheaper VHF interval rather than, as happened in the West, in the more costly microwave. As a matter of fact, it was necessary to produce and to install a large number of radars to cover that territory (some sources refer to the production of twenty thousand VHF radars during the years). Moreover, in the USSR the compatibility issues with other users of the VHF band such as FM radio, television, and some navigation aids were less serious than in the western world.

Between the military post-war applications of radar in the western world and particularly in the USA there are those related to the Soviet threat: since 1949 the USSR was equipped with bombers capable of reaching the territory of the United States by passing on the Arctic and possibly carrying thermonuclear bombs.[27]

In the United Kingdom, at the beginning of the post-W.W.II era, the threat of Soviet bombers imposed the rearrangement of that, then obsolete, Chain Home air defense system that had produced so many benefits during the war. The *Cherry Report* in 1949 recommended the urgent modernization and enlargement of the British air defense, with consolidation of the many radar sites (as much as 170) in 66 sites, and the replacement of the old radars with modern equipment.[61] Despite a very difficult economic situation (for example, many goods were still rationed),

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[60] Yakov Davidovich Shirman (1919–2010) was a celebrated radar scientist from the former Soviet Union. In 1959 he was awarded from the *Institute of Radio Engineering* at the Academy of Sciences of the USSR, Moscow, the “Doctor of Science” degree for his thesis “Improvement of resolution in distance without shortening the duration of the pulse”. The principles are also described in Shirman’s 1963 book “Fundamentals of the Theory of Detection of Radar Signals and Measurement of their Parameters”. In addition to pulse compression and ultra-wide band radar signals, between the end of the 1950s and the 1960s Shirman studied the adaptive filtering of the interferences (clutter and *jammer)* and patented several novel solutions. In 2009 Y. Shirman received, from the IEEE- Aerospace and Electronic System (AES) Society, the *Society Pioneer Award* “for his independent discovery of matched filter, adaptive filtering and high-resolution pulse compression, used in an entire generation of Russian and Ukrainian radars” (IEEE Trans on AES—Vol. 46, No. 4, October 2010).

[61] The technological advancement at the end of the W.W.II from the times of the design of the Chain Home was, as seen, huge.

the successor of the Chain Home was born. The contract for the construction of the new system, code: *Rotor system*, was assigned to the Marconi Wireless and Telegraph Company. In the new system the functional structure of the Watson-Watt system (command and control hierarchy, distinct areas etc.) was kept, but by renewing technology altogether.[28]

On the other side of the Atlantic, the Americans from February, 1945 started to design a surface-to-air missile (SAM) system capable of intercepting, with a good degree of effectiveness, a raid of enemy bombers and of exploding in front of it thus creating a wall of fragments, or of metallic spheres, that would have broken down the aircraft. This system reinterpreted some studies made by the Germans at the end of the W.W.II on weapons exploding on the group of aircraft rather than on a single aircraft. The study was assigned to a pool of forty companies and in 1948 the anti-aircraft missile *Nike* system was born in order to replace the 90 and 120 mm anti-aircraft guns of the wartime. Initially the system was fixed, used the *Ajax* missile and became operational in 1951/52.[62] In 1957 the Ajax was replaced by the SAM-A8 *Hercules* missile with liquid propellant, and with solid propellant since 1958. Quickly the Nike Hercules batteries reached the number of two hundred, and the system went into service in the armed forces of France, West Germany, Holland, Norway, Denmark, Japan, Italy and Turkey. The fear of an attack by strategic bombers from the Warsaw Pact was so strong as to push the installation of anti-aircraft missiles with nuclear warheads that, if used, would blast on its own territory.[63] From the 1980s, the Nike Hercules was phased out, as it could not fulfill its original role any longer.[64] In addition to the Hercules missiles and their launchers, the system was made up by radar, computers, command and control centers and communication facilities. A typical installation has one or more of the following transportable elements: Launcher, Launcher Control Trailer, Computer Trailer, Launching Section Panel, Low-power acquisition radar (LoPAR), Target Tracking Radar (TTR), Target Ranging Radar (TRR), Missile Tracking Radar (MTR); some installation have also

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[62] The "SAM-A7 Nike Ajax" system was operational through December 1953 in sixty batteries of the U.S. Army for the air defense of some major American cities. Seven batteries protected Baltimore, its airport, the Aberdeen ordnance and the Edgewood chemical facilities. Various Air Force and Navy's air-warning net systems would alert the Army's Nike Ajax to hostile approaching aircraft.

[63] As a matter of fact, the solid state, two stages, Mach 3, Hercules had a maximum range of the order of 60–100 km with a ceiling of 25–30 km and was the first SAM with anti-ballistic missile capability. It could have different warheads: conventional, 280 kg, able to project 20,000 metallic spheres on the targets after the blast, and nuclear, from 2 to 40 kilotons. However the nuclear option was not used by some nations, including Italy, were, luckily, the nuclear warheads were never installed.

[64] In fact:

1. It was designed to hit high altitude targets while the modern war scenarios have moved to low level the attack profiles;
2. the guidance system could track only one target at a time and the system mobility was insufficient to survive in a modern war scenario;
3. most important, today the main threat is by ballistic and tactical missiles and not by strategic bombers any more.

the fixed, large High Power Acquisition radar (HiPAR). The two-stages Hercules missile was radio-guided to the target in order to avoid its evasive maneuvers.[29] Some Nike-Hercules sites, abandoned, are now in ruin, others have been reconfigured to host the following generation *Patriot PAC-3* missiles as a part of the NATO *Medium, Extended Air-Defense System* (MEADS). In Italy, during its career, the Nike Hercules equipped 12 Italian Air Force Groups (*Gruppi Intercettori Teleguidati*, created in May 1959) whose duty was to protect the North East of Italy (Lombardia, Veneto and Friuli Venezia Giulia) from a Warsaw Pact attack, by means of 96 launchers and some 600–700 missiles.[65] One of the Italian Air Force Nike Hercules sites has been transformed into an open-air museum. This is *Base Tuono* (operational from 1966 to 1977) in Passo Coe, 1600 m a.s.l., near Folgaria (Trentino), open to public through October 2010 and shown in Fig. 5.28, adapted from a set of color photos taken by Ing. Giancarlo Chinino on August, 2013.

The Nike HIPAR transmitter used a powerful klystron[66] with 10.4 MW peak pulse power and average power 26 kW; frequencies: 1350–1450 MHz (10 channels). The antenna, at 6.6 and 10 revolutions per minute, had a big reflector with 6.3 m height and 13.11 m width, granting a 34.8 dB maximum gain in the Cosec^2 operation, with 1.2° azimuth beam width. The resulting coverage was: 0° to 60° in elevation, up to 46 km in height, up to 425 km in range. The LOPAR operated in the 3.1–3.4 GHz band with a lower power (average 650 W, peak 1 MW) and with a smaller antenna (height 1.32 m, width 4.57 m) and about the same azimuth beam width as HIPAR, rotating at 5, 10 and 15 r.p.m.

The Soviet threat in the Cold War led the USA to develop and install the first very long range radar, capable of tracking ballistic missiles and intercontinental satellites in low Earth orbit. The first of these giant sets is the AN/FPS-17 which has worked in a remote area of Turkey, i.e. Diyarbakir, from 1955 up to the 1990s, see Fig. 5.29.

The project was born at the beginning of the autumn of 1954, when the Pentagon was worried about the tests of Soviet ballistic missiles launched from the base of KapustinYar in Russia, a hundred kilometers to the east of Volgograd. After a few preliminary calculations they asked General Electric to develop a radar

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[65] They were located as defence of Northern Italy at Montichiari, Monte Calvarina, Bovolone, Zelo, Bagnoli di Sopra, Chioggia, Ceggia and Cordovado, plus four mountain locations from the old Ajax batteries. Likely, Patriot PAC-3 batteries are now located in Bovolone, Bagnoli di Sopra, and Cordovado. More details about the history of the Hercules within the Italian Air Force and their sites worldwide can be found in: http://www.nikemissile.altervista.org/index.html, http://ed-thelen.org/loc.html.

[66] During World War II, klystrons, mainly of the reflex type, were most used as low power oscillators. By the 1950s there was a considerable demand for high power (order of kilowatt average power, megawatt peak power) microwave sources; klystrons could deliver these higher power levels and could amplify low level precise signals with a gain of the order of 40 dB while maintaining coherence and spectral purity. Soon klystrons with average power levels up to 50 kW and peaks up to 50 MW were available. To achieve the high electron beam current densities at these power levels, powerful magnets (usually electromagnets) surround the tube and very high (tens of kV) voltages were used.

Fig. 5.28 Some views of the open air museum in *Base Tuono* (Folgaria)—Hercules launcher, TTR/TRR's and LoPAR

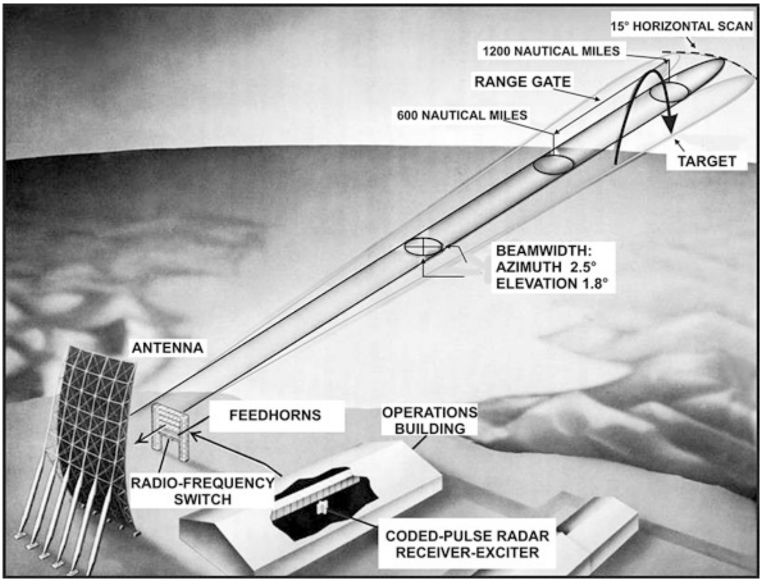

Fig. 5.29 The AN/FPS-17 radar—scheme of the operation of the system installed in Turkey

capable of detecting and tracking those missiles. Hence, maximum radar ranges in the order of 1500 km were required, four times those of the most powerful long-range radar of that time. In a few months[67] they implemented the first radar for space surveillance and probably the first (in the western world) to use the pulse compression (thanks to the work by MIT/Lincoln Laboratory[68]). The AN/FPS-17 became operational in Diyarbakir on June 1st, 1955, followed by a second installation at the air base of Pirinçlik, in south-east of Turkey; the entire program was kept strictly secret for many years. It was soon realized that radar data permitted features of considerable interest, such as the determination of the trajectories of missiles and of the ephemeris of satellites. The huge antenna, with a parabolic reflector 53 m high and 33 m wide, generated six beams above the area of Kapustin Yar. The transmitters, derived from the TV ones by General Electric,

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[67] The limited time available to render operational the AN/FPS-17 system required an air lift to carry the equipment parts, for a total weight over 400 tons—an effort only inferior to the 1948 airlift.

[68] The Radiation Laboratory, which exhausted its mission with the end of the war, was closed on December 31st, 1945 and the majority of the staff came back to the University. However, a few years later, the United States perceived the new threat from the USSR, and the Department of Defence asked the MIT to play a key role in the Air Defence, hence originating the Lincoln Laboratory, whose first mission was to design the former integrated Air Defence system, the SAGE (Semi-Automatic Ground Environment), which operated from 1963 till 1983.

operated in VHF range.[30] In 1958 a second antenna was added, 46 m high and 90 m wide, with 12 MW transmitters, to generate more three horizontal beams as well as a series of seven beams arranged vertically in a fan shape.

From the requirement of the exo-atmospheric surveillance, new radars with huge antennas of the "Phased Array" type have been developed. They are treated in the following.

Chapter 6
The Radar Flies: Birth and Development of Airborne and of Anti-submarine Warfare Systems

As early as in 1936, in his "Rediscovered Document" (Chap. 2) Ugo Tiberio indicated seven applications of radar techniques to military operations. The latter are:

(5) to *see* enemy aircraft;
(6) to measure, from an airplane, its height from the ground;
(7) to locate a ship from an airplane for torpedoing.

These are exactly the purposes for which the industrially advanced European nations, immediately prior to and during the Second World War, began the developments of airborne radars, installed on fighter/interceptors, on bombers and on maritime patrol aircraft in the relevant configurations:

- Airborne intercept (AI), i.e., an aid to the fighting in flight, both for the attacks onto enemy aircraft (especially, bombers), and for the defence, particularly in night operations (as well as in other low-visibility conditions).
- Radio-altimeter, i.e. a nadir-pointing radar for the precise measurement of the height over ground or over sea.
- Air-to-Surface Vessel (ASV), i.e., for detection and attack of ships (and submarines in emersion) by aircraft.

In the early 1940s, they added a fourth item to the above list:

- The aid to the night bombing with the Ground Mapping function, namely the creation of radar maps on a monitor in the cockpit, with the possibility of recognizing coastlines, lakes, estuaries and cities to bomb at night.[1]

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[1] Radar as a long-range navigation system—for example for night bombing—and as a sensor for *ground mapping* was quickly replaced by long-range radio aids to navigation such as the wartime LORAN by Alfred Lee Loomis, see [Con 03], and, through the 1970s, by the subsequent satellite systems are (TRANSIT, NAVSTAR—GPS, GLONASS, Beidou, Galileo).

G. Galati, *100 Years of Radar*, DOI 10.1007/978-3-319-00584-3_6

The development of airborne radars in Britain took place in parallel to that of the surveillance chain of air defence radars. While the Chain Home was developed with its high towers, it was clear that quite different technologies were required to reach the requirements of limited mass and small size in the airborne context.

The transmitted power level by electron tubes[2] as well as the size of the antenna was (and is) decreasing with the frequency increasing. The initial choice, compatible with the available technology, was the one of the metric wavelengths of and simple and readily available Yagi-Uda antennas,[3] or even of dipoles or folded dipoles. These radiating elements were eventually grouped in arrays to increase their directivity, which remained, however, small, with a limited angular accuracy. Due to the very wide and large side lobes of the antenna diagram, the ground below the aircraft created a strong echo which added to that of any useful target. Hence, it was virtually impossible to detect targets at a distance greater than the height of the own aircraft above ground. Another important element of airborne radars was the requirement of minimum range, or more exactly of detection of close-by targets.[4] In fact, the radar should allow the pilot of the attacking aircraft to move closer to the target until its visual acquisition. At night, a minimum range well below one km was therefore required, calling for then the transmission of relatively short pulses (with respect to ground or ship—based radars).

In 1936 Henry Tizard wrote to Dowding (see Chap. 4) a letter in which he noted that the accuracy of the radar by Watson-Watt, sufficient to provide the position of the enemy aircraft to the British fighter/interceptors during the day (when the pilots could visually acquire the targets at a few km), was totally insufficient to guide the interceptors onto the enemy bombers at night when these bombers were visible only at a few hundred meters. With some prophetic spirit, Tizard added that, in the case of an air attack to England, the aircraft losses of the enemy—the counter-actions by British interceptors being made more effective by the Chain Home—would soon have pushed the Germans to move to night bombings, which really and promptly happened in 1940.

So, the need was clear to put in service fleets of aircraft equipped with a special radar for night operations. Watson-Watt received a copy of the Tizard's letter and, with the usual promptness, decided to divide into two parts his radar design and development group. Hence, he attributed the responsibility of the Chain Home to

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[2] The "valves" such as the triodes and tetrodes were the only practically used devices before the industrialization of the cavity magnetron.

[3] This type of antenna was invented in 1926 by Shintaro Uda from the Imperial University of Tohoku, Japan, in collaboration with Hidetsugu Yagi. As recalled in [APS 01], and supported by a witness to the 1977, the *Searchlight Control* (SLC) Radar, a type of radar that contributed to the downing of Japanese aircraft in the Battle of Singapore (1942), used these antennas.

[4] During the transmission of the pulse, and the following "recovery time", the radar receiver is blind.

Wilkins and the one of the night interception to Eddie ("Taffy") Bowen.[5] The latter, after a few exchanges of ideas with the RAF, wrote the general specifications for an airborne radar, characterized by precise limitations in terms of mass (90 kg), volume (0.22 m^3) and power consumption (500 W). Additional requirements were the limited size of the antennas (to restrict as much as possible the aerodynamic "drag" effect and the consequent reduction of the maximum speed) and the fact that the radar set had to be manageable by a single person, the observer/navigator or, in the absence of him, the pilot.

With some luck, Bowen was aware of the new receiver[6] developed by the firm EMI[1] for the fledgling television service of the BBC. Bowen, thinking to use the EMI receiver, built a radar transmitter on the wave of 6.7 m (45 MHz), which, not being suited to an installation on an airplane, was installed on ground for testing purposes, while the receiver was mounted on a *Heyford* bomber.[7] The resulting (bistatic) system, called RDF 1R, was tested with the Heyford, in the autumn of 1936, detecting aircraft up to 19 km. However, the concept of bistatic airborne radar with a network of earth transmitting stations was considered not appropriate by Watson-Watt and therefore was abandoned after the latest tests in 1940. In 1937 the Western Electric's "Giant Acorn" 316 valves were available; with them it was possible to generate on board the needed power with a pulse duration of 2 (or 3) μs, a repetition period of 1 ms, and a peak power of a few hundred Watt. On March 1937 such a system was tested on the *Heyford*, with the detection of vessels and infrastructures in the port of Harwich.

For the purposes of maritime surveillance (i.e. ASV), considered at least as important as the interception (AI), a more suitable aircraft was the twin-engine *Avro Anson*, which operated over sea with two pilots and two observers. With this aircraft, on August 17th, 1937,[8] they demonstrated the ASV capabilities with ranges from 3 to 5 km on ships.

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[5] Bowen has been presented before; here it is useful to remember that he is the author of [Bow 87], a rigorous and well-documented book, with a pleasant reading starting from its nice title "Radar Days". With another high quality volume, [Whi 07], [Bow 87] is a main reference text for the history of airborne radar.

[6] That receiver—the best one available in Great Britain—operated at 45 MHz with a bandwidth of about 1 MHz and was very compact. In the subsequent development of British airborne radar, operating at higher frequencies, in all the war period—and beyond—they used an intermediate frequency (IF) of 45 MHz (today, in the most common radars, the IF is typically either 30 or 60 MHz, except when it is reduced to a submultiple of 30 MHz for the direct sampling of the signal and digital down-conversion).

[7] The ignition system of spark plugs for the Rolls-Royce engine of *Heyford* was particularly well designed as compared to the standards of the era and produced little radio frequency (RF) noise; in other aircraft with radial engine pistons the produced RF noise was incompatible with a radar on board.

[8] Bowen, in recalling the event [Bow 87], cannot avoid mentioning the "utmost regret" for his own absence in that day, due to "a short leave to go home, in South Wales" because he had not seen his parents for two years.

An aero-naval exercise was done on September 4th and 5th, 1937 with the participation of the *Avro Anson* K6260 equipped with the radar by Bowen. Strong echoes were noticed from the involved vessels (a battleship, an aircraft carrier, a cruiser and several destroyers). Moreover the radar "saw" all the aircraft that took off from aircraft carriers during the exercise. On October 18th Tizard was on board a trial flight of the new airborne radar. Later, very soon, new researchers and technicians from universities and industries were added to the group of Bowen. However, the Bowen complained of scarce resources and the administrative problems that made the transition from experimental radar of 1937 to real operating radar sets somewhat complex and not so fast as it would have been necessary. The internal situation, with stages highly conflicting that saw the dissolution of the first working group and its replacement with a completely new one, is described in [Fis 88]. Anyway, at the beginning of the war four sets of a new radar (called ASV Mk. I) were installed on nearly fifty aircraft (24 *Hudson* and 25 *Sunderland*); the production was of 200 sets. The radar by Bowen, with the wavelength brought to a meter and a half (200 MHz), became the British standard ASV set until it was overtaken by a microwave radar.

It was a rather unreliable radar, with major problems of maintenance and training. In addition, the minimum detection distance, which was well above the theoretical value of 150 m, needed to be reduced.[9] Until 1939, the radar by Bowen did not provide the necessary indication of the azimuth and elevation of the targets, that was obtained with an ingenious system of antennas. The transmission antenna, with a wide main beam toward the bow of the aircraft, was a folded dipole with reflector (essentially, a *Yagi*); the reception system used two pairs of antennae that created two partly overlapped beams, in azimuth and in elevation. Their amplitudes comparison gave an indication of the angles of azimuth and elevation, while the delay (the same for the four signals) indicated the distance. This information was displayed on two cathode ray displays (in essence, two oscilloscopes) whose input was cyclically switched on the outputs of the four receivers, two for each antenna, see Fig. 6.1.

One of the first uses of the AI radar to was on the night fighter *Bristol Blenheim* $I f$, on which it was installed through autumn 1939, see Figs. 6.2 and 6.3.

To install the radar on the Blenheim it was necessary in some cases to make the plane about 300 kg lighter by suppressing the upper turret; the result is shown in Fig. 6.4, and a detail of the antennas is shown in Figs. 6.5, 6.6 and 6.7.

Summing up, given the threat to the British and Allies ships by German ships and submarines, initially the ASV was considered of high priority by the British (and by the Americans). However, in practice, from a technical point of view, there

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[9] This was obtained by desensitizing the receiver—that was saturated during the transmission of the pulse—with a *quenching* circuit synchronized with the transmitted, 1 μs long pulse: a minimum distance of 800 m was obtained without significant detection losses. Of course, the maximum range was slightly less than the height of the aircraft.

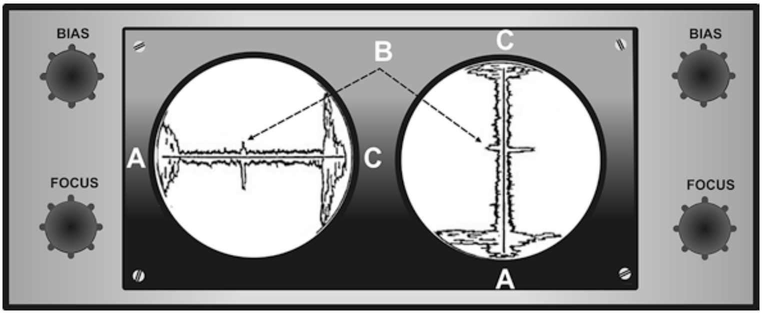

Fig. 6.1 Display system used in the first British airborne radars in the metric wave, such as the AI Mk. IV installed on *Beaufighter* fighters in the spring of 1941. The cathode ray tube on the *left* shows the amplitude of the echo versus the delay with respect to the transmission of the pulse: the double track refers to the two lobes of the elevation antenna (*upper and lower lobe*), and shows, at a distance proportional to the segment *AB*, a target at an altitude lower than the radar. Similarly, on the cathode ray tube on the *right* it is shown that the target is located to the right of the Beaufighter. The pulses *A*, *B* and *C* show the transmitted pulse, the echo of the target and the echoes of the ground, respectively

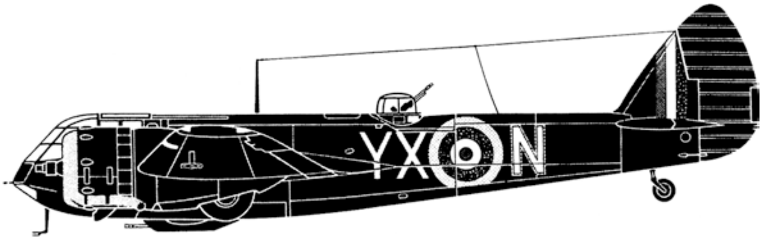

Fig. 6.2 Drawing of the *Blenheim I f* “YX-N”, September 1939

is little difference between the ASV and AI radar. While the radar AI was an important element to the conclusion of the Battle of England, an even more important contribution of the airborne radar to the victory of the Allies was that of the ASV, used in the Battle of the Atlantic against the deadly U-boat[10] of the powerful *Unterseewaffe* of Karl Dönitz,[2] see for example [Val 11].

In the summer of 1940, with the German attack of May–June, the fall of Paris and the capitulation of France (June, 22th), to the German sub-marines it was possible to use the bases along the French Atlantic coast, in Lorient (the main), in Brest and in La Rochelle. With these bases, the German submarines had direct access to

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[10] On October 14th, 1939, the German submarine U-47 reached the British naval base in Scapa Flow, Western Isles (Scotland), and with two launches of torpedoes sank the 33,500 ton battleship *Royal Oak*, causing 833 casualties in addition to the complete loss of the ship. The web site http://uboat.net/index.html is rich of information on U-Boots.

Fig. 6.3 The *Blenheim I f* “YX-N” with the radar on board

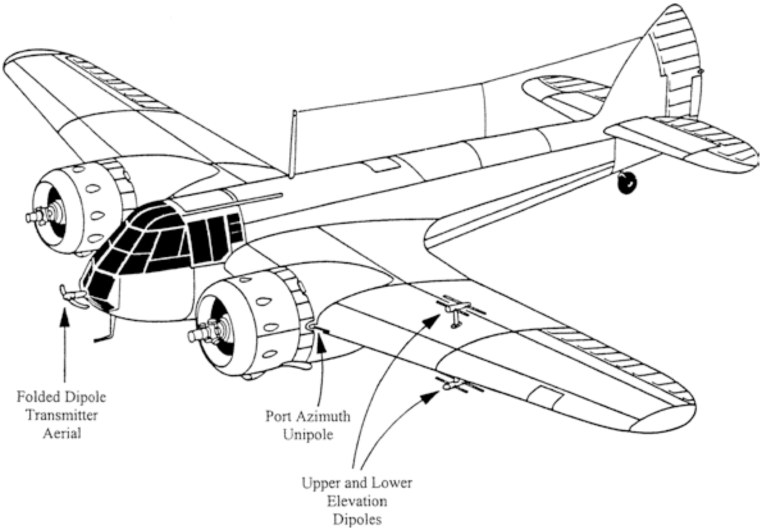

Fig. 6.4 Drawing of the fighter *Blenheim I f*, version with two crew members (pilot and radio operator/observer). The antennas the radar AI Mk. III are visible

Fig. 6.5 Transmitting antenna of the Blenheim fighter I f

Fig. 6.6 Azimuth monopole of the Blenheim fighter I f

the ocean with a considerable increase in their operating range.[11] From June to October 1940 they sunk 270 allied ships.[3] The declaration of war to the United States on December 11th, 1941[12] opened an huge area of ocean to the U-Boot operations and pushed the production of these submarines above twenty units per month, with the *Unterseewaffe* in a continuous expansion. Until March 1941 the

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[11] Previously, due to the low depth and the presence of mines in the English channel, the U-Boot that departed from German bases in the North Sea were obliged to sail to the north of the British isles to reach the ocean.

[12] Shortly before, on October 31th, 1941, the American destroyer *Reuben James*, engaged in escorting a convoy to England, was torpedoed and sunk by the U 552 (first USA ship sunk in W.W.II).

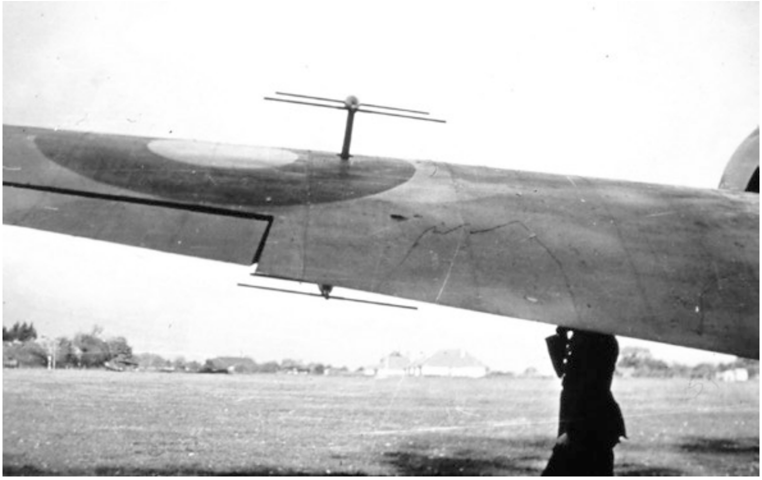

Fig. 6.7 Elevation dipoles of the Blenheim fighter I f

U-Boot were the winners in the Battle of the Atlantic.[4] The situation changed soon also thanks to three instruments of the Allies: the ASDIC,[13] the deciphering[5] of radio messages between the U-Boots and their command (which were essential for organizing the attacks to the allied ships) and, of course, the radar.[14] It was soon clear to the Allies that aviation was the only suitable tool to react to a situation that could lead to the block of vital supplies to the United Kingdom.

While a ship, in order to reach the vertical position above a submarine that has spotted the ship itself with its periscope, requires a time that for the submarine is sufficient to a deep immersion to escape, an airplane is able to reach the vertical in a much shorter time, and may attack the submarine when it is still close to the water's surface. In fact, a naval radar, with its antenna at some 20 m above sea level, could detect the U-Boot a few (e.g., a dozen) km away because of the limit due to the horizon. Conversely, while the same type of radar on board, an aircraft at a few hundred meters above the sea could detect it at much greater distances. In some cases the radar could detect the periscope and the schnorchel[6] of a submarine at periscopic depth. Until the summer of 1942, the air attacks against the U-Boot took mostly place in the Bay of Biscay[15] or not far from the English coast. But, later, the

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[13] This acronym means *Allied Submarine Detection Investigation Committee.* The apparatus is today known as Sonar (*Sound Navigation and Ranging*).

[14] On March 17th, 1941 the British destroyer *Vanoc*, same class as the *Walker*, sank the U-100; [Val 11] cites this battle as the first one in which the British navy used the radar.

[15] The bay, or gulf, of Biscay (the name comes from the Castilian *Golfo de Vizcaya*; the French use the term *Golfe de Gascogne*) is delimited from the west coast of France and from the north one of Spain; it was a forced passage for the U-Boots which from their bases located on the French coast of the Gulf, from Brest to La Chapelle, had to reach the Atlantic routes of the convoys they had to attack.

Allies created bases of aircraft patrol aircraft of the VLR (very long range) type in Iceland, in Greenland and in the Azores islands. Therefore they greatly restricted the area of the Atlantic where the submarines could operate free from any air threat, and forced them to travel immersed, at low speed, during the day.

The first British ASV radar was, as explained before, the ASV Mk. I by Bowen, which during the flight tests at the height of 1800 m demonstrated the ability to detect an emerged submarine up to ranges of 10 km and a 1000 tons ship of up to 18 km. However, this radar, which operated on the wave of the one meter and a half and was installed on twelve *Hudson* aircraft of the Coastal Command in January 1940, got poor operational results being an unreliable set. The ensuing ASV Mk. II, again in the metric wave (i.e. 70–176 MHz) had a much better quality and was produced in the United Kingdom in about four thousand sets, to be installed on aircraft of Coastal Command: *Hudson*, *Sunderland*, *Wellington*, *Beaufort*, *Warwick*, *Whitley*, *Liberator*, and more. However, the air crews were frustrated by the minimum radar distance: in night attacks to German submarines, just when the plane had arrived at about 1 km away from the target, its echo was superimposed with the disturbance due to the transmitted pulse (as shown in Fig. 6.1) and the crew could hardly visually acquire the target.[7] To overcome this drawback, the Allies used a light projector with a diameter as large as 50 cm installed in a turret under the fuselage of the antisubmarine aircraft in order to put on the U-Boot, in the final phase of the attack, a powerful light aligned with the radar on board. This system, called *Leigh light*, was used for the first time in January 1941 on a *Wellington* equipped with an ASV Mark II. The inventor of the Leigh light, the *Squadron Leader* Humphrey de Verd Leigh, was on board the *Wellington*. The Germans reacted to the threat of ASV radars by developing what today would be called a Radar Warning Receiver (in German, *Radarwarngerät*).[16] The first of these sets, in the metric wave, effective against the ASV Mk. II, was known as FuMB1-*Metox*,[8] and had a wooden antenna in the form of a cross, said *cross of Biscay*, which was placed on the emerged submarine and withdrawn before immersion. Thanks to the Metox, in the last months of 1942 the losses of the allies' ships increased again. The transition of the ASVs from metric waves to microwaves forced the U-Boot to acquire new *Radarwarngeräte*.[9]

As a further countermeasure, the Germans developed quite sophisticated techniques to reduce the radar visibility of the parts above the water's surface, anticipating the modern *stealth* techniques.[17] The small naval targets, such as the periscope and the more bulky *schnorchel*, were very difficult to detect by metric-wave radars; the subsequent microwave radars operating at 10 cm and, later,

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[16] This set, installed in the U-Boot for the interception of radar signals, was designated FuMB—*Funkmess-Beobachtungs-Gerät*: when a radar pointed on the U-Boot, the FuMB alarmed the crew, which executed a fast dive.

[17] The reader interested in the self-defence of the U-Boots may see: http://www.ibiblio.org/hyperwar/USN/rep/ASW-51/ASW-14.html.

at 3 cm,[18] were much more effective in a calm sea. The reduction of the *radar cross section* (i.e., the *radar camouflage problem*) was studied in Germany by June 1943, and the decision to apply to *schnorchel* coatings capable of absorbing the microwave dates back to the autumn of 1944. About 100–150 U-Boot had the *schnorchel* with anti-radar coatings at the end of March 1945. Two types of coating were used, the *Jaumann* one and the *Wesch* one. The former used suitedly spaced layers of partially conducting paper, the latter, rubber containing a high percentage of iron powder. The absorber of Jaumann resulted the most effective, permitting a strong reduction of the detection range of the submarine as compared to the absence of coating.

Finally, U-Boot also used (with limited success) radars for their defence against air attacks. The first U-boot radar, the FuMO-29, a conversion of a shipborne set,[19] was installed at the beginning of 1942; its antenna was mounted on the U-Boot's conning tower as a fixed cylindrical array, consisting of two horizontal rows of six dipoles each. The transmit antennas were divided into port and starboard groups of three each and were energized in turn, in a very early form of phase-shifting. This gave a coverage of about 10° on each side, which could be increased by turning the U-Boot.

The next radar installation, FuMO-30, had a new rotatable antenna (by a mechanical linkage from a hand wheel in the radio room), which was mounted on the port side of the bridge and retracted into an oblong housing. The antenna array consisted of a tubular steel rectangle covered with a wire mesh and with four pairs of dipoles on the front face and 8-shaped elements on the rear face, see Fig. 6.8.

On March 1944, the new set FuMO-61 *Hohentwiel-U* began to be installed on Type VIIs and IXs U-Boots. This set was adapted for U-Boot use from the Luftwaffe's *FuMG-200 Hohentwiel* radar which was fitted on the Focke-Wulf FW 200 *Condor* aircraft. The *Hohentwiel-U* had a mattress-type antenna 1.5 m wide and 1 m high, with four rows of six dipoles each. The version FuMO 65 *Hohentwiel U1* replaced the traditional radar display, which had separate oscilloscopes indicating range and azimuth, by a PPI (Plan Position Indicator) screen, known to the Germans as *Drauf*. The FuMO-65 was installed in only a few Type XXI submarines.

The FuMO-391 *Lessing* was designed specifically to indicate the presence of aircraft and was intended to be installed on the Type XXI. With its omnidirectional antenna located on the schnorchel head, the *Lessing* could detect an aircraft up to

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[18] The development of X-band (3-cm) ASV radars was further stimulated by presence of the Naxos intercept receiver allowing German submarines and other ship to detect aircraft carrying an S-band radar. An H2X blind-bombing aircraft was downed over Berlin in January 1944, and from the damaged wreck the Germans learned of the new frequency band. They assumed that X-band would also be applied to ASV radar, and the development of the *Tunis* X-band intercept receiver was started.

[19] These naval sets were called *Funkmessortungsgerät* (radio localization apparatus), or simply Funkmess-Ortung, abbreviated to FuMO. The FuMO 29 was derived from the *Seetakt*.

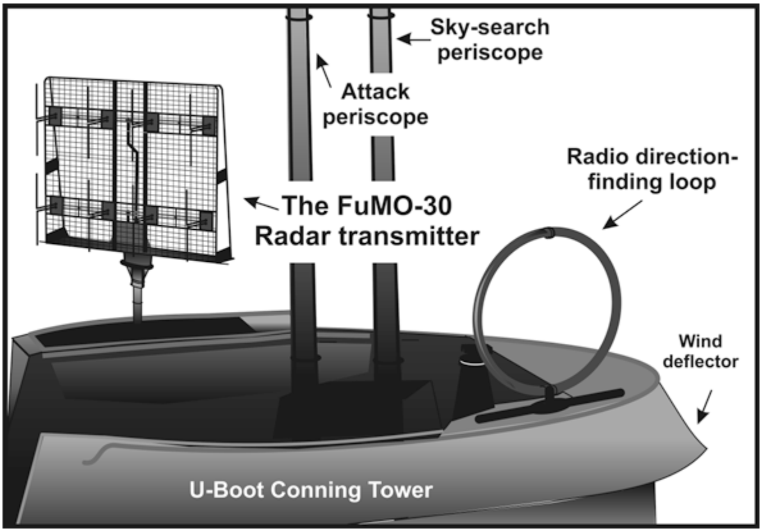

Fig. 6.8 FuMO 30 antenna

a 30 km range, but could not indicate either its height or its azimuth. A unique feature of this set was the ability to operate with the U-Boot at periscope depth (but with reduced performance). It was a warning device used to detect aircraft early in order to dive below periscope depth to escape a possible air attack.

FuMO 83 *Berlin UI* and FuMO 84 *Berlin U II*, by Telefunken, were enhanced, lighter and smaller copies of the British 9 cm radar named ASV Mk. III, found in a British bomber shot down near Rotterdam on February 1943. FuMO 83 had four watertight ceramic stub antennas in a plastic sphere, which was installed on top of a rotating mast. It could be used for panoramic scanning or for direction finding, at periscope depth. FuMO 84 was the final version (which, however, never went into production) not using a retractable mast. The microwave FuMO 84 "Berlin II" U1 (by Telefunken) and FuMO 391 "Lessing" (by GEMA) radars were developed near the end of the war for the type XXI U-Boot and able to operate when submerged at periscope depth. The war ended before FuMO 84 and FuMO 391 radars could be used in combat. In general, U-Boot crews were reluctant to use the radar (and super-het devices like the Metox) as they feared to be "listened" to by the enemy, and by 1944 preferred passive intercept systems in order to keep as low a profile as possible.[10]

With the advent of the cavity magnetron, as described in Chap. 5, and the production, by the GEC, of the first sealed devices suitable for airborne operations,[20]

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[20] This production started in summer 1940; during the same period, as is known, a sample of the cavity magnetron was brought from the *Tizard Mission* to the USA, where the production of this device started in a few weeks. Rather surprisingly, the English magnetron had six cavities, the one of the United States, eight.

detection and discrimination of both air and naval targets improved dramatically. Before the end of the war the Allies produced the remarkable figure of about one million magnetrons. The use of the magnetron in ASV radar came with a certain delay due to internal problems, the first of which, in the United Kingdom, was the rivalry between the Bomber Command and the Coastal Command. Finally, the new *ASV Mk. III* equipped with an S-band magnetron (wavelength between 9 and 10 cm) was installed on the twin-engine *Wellington* in 1943. On March 1st, 1943 a *Wellington* of the *aviation team 172* made the first patrol on the Bay of Biscay; on the 17th of the same month the new radar detected for the first time a U-Boot and 13 sightings were made by the end of this month. It was a remarkable technological step, with an antenna reflector of about 85 cm that covered a cone of 60° in front of the aircraft, and a planimetric display (plan position indicator—PPI) of the type widely used today. The ensuing model, called *ASV Mk. VI* (with a more powerful transmitter than the *Mk. III*) had in addition a deception device (against the German *Radarwarngerät*) called *Vixen*. The principle of the *Vixen* was to reduce the transmitted power from the radar after the detection of the U-Boot, so as to simulate that the aircraft was going away. Other improvements were added to the *ASV Mk.* VIA, capable of aiming the *Leigh light* on the target, and to the *ASV Mk. VIB*, suitable for night bombing. The production of these S-band ASV's was entrusted to the Company Ferranti.[11]

It is well known that by the summer of 1940 the Luftwaffe began a series of raids, both in daytime and at night, against the airports of the RAF, and against coastal defences, ports and British industries of aircraft and weapons (not cities, in this early phase). This strategic bombing, known as the Battle of Britain, showed some success until the end of August, albeit with growing losses of German bombers (15 % in August, 37 % in September) mainly due to the British air defence system, based on the Chain Home.[21] In September the Germans started to bomb the British cities, in particular London (whose first bombing took place on September 7th). In fact, Hitler attempted to force the British to seek peace by striking the civilian population to demoralise the nation. It is well known how the British bombing of German cities for retaliation had a tragic escalation in the course of the war. These operations in their initial stages were, however, of poor strategic effectiveness: the bombs struck half of the times the country areas, and only a bomb out of ten reached its target. Of course, the difficulty of low-visibility bombing was related to the lack of a precise and reliable navigation system. First, the British introduced the radio navigation systems *Gee* and *Oboe* [Pri 09] to guide the bombers on the target in the absence of optical visibility; but being based on radio transmitters located in England, they suffered from the horizon limit. The research of an "all-weather" bomber guidance system independent of the ground infrastructures had a turning point with a remark made by Taffy Bowen during the first tests of the airborne microwave radar. Bowen noticed that the radar echoes were very

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[21] The first downing of a German aircraft intercepted by radar is alleged in the night of July 22th–23th, 1940.

different if obtained by different surfaces such as sea, countryside, mountains, cities. In March 1941, the British AI radar using the new magnetron technology and called AIS (perhaps the letter S was added to recall the S-band on 3 GHz i.e. with wavelengths from 9 to 10 cm) was tested on a *Blenheim*. The group of Philip Dee noticed, as Bowen did two years before, the different radar response of the different types of environment. The bombing at night was discussed again in a meeting of the Bomber Command in October 1941, with Dee present. On November 1st, Dee tested the AIS as a BN (Blind Navigation) system and from his Blenheim managed to detect the profiles of cities up to a 55 km distance. From the beginning of 1942, the group of designers from the Telecommunications Research Establishment (TRE) led by Bernard Lovell (1913–2012) went to work to provide a radar in the S-band based on the AIS with an antenna located on the ventral part of the bomber under a protective shell said "radome", and able to scan the surrounding area on 360°, producing a kind of dynamic radar map on the PPI display. A difficulty in the design and development of this magnetron-based radar was due to the opposition by the scientific adviser of Churchill, Lord Cherwell, who insisted on the solution based on the less powerful klystron as alternative to the magnetron. As Cherwell was often saying, the magnetron, with its super rugged cavity anode made by a metallic block, was in substance indestructible: if a plane had crashed in the hands of the Germans (as it really happened—see after), they could get this top secret device.[22]

The new radar took the name H2S[12] and made its maiden flight on April 23rd, 1942. The H2S anticipated many modern radar solutions. Among them, the *radome* and the suitably shaped antenna reflector able to implement the "cosecant square" radiation pattern (which maintains a constant intensity level of the echoes of the ground at different distances from the radar). The H2S program had great strategic importance and highest priority for the *TRE*. Fearing a German raid on *Swanage* (in fact, the Germans had placed a company of paratroopers in Cherbourg, just across the English channel), on May 25th, 1942 the establishment moved 160 km to the north, in *Malvern*, Worcestershire, at the naval college site. The TRE remained in Malvern—at St. Andrews Road—at the end of the war with a remarkable staff, which in 1945 was as large as 3500 people. At the end of hostilities, and unlike Canada, and, to some extent, the USA, the British decided to keep in life their structure of research and development in radio systems and radar, although born for war purposes.

In 1953, the TRE merged with the *Radar Research and Development Establishment* to set up the *Radar Research Establishment*, then called *Royal*

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[22] In this regard the British made various tests with increasing amounts of an explosive charge to destroy the magnetron in the case of downing of the aircraft, but the fragments of the transmitter were always such as to make the magnetron operation quite clear and reproducible. The proposal to use explosives in two batches, one for launching the magnetron away from the wreckage of the plane, the second to destroy it, was not successful: finally self-destruction was deemed too much complicated.

Radar Establishment (1957) and later (1976) *Royal Signals and Radar Establishment*, or RSRE.[23] The legacy of the English radar school before and during the Second World War was thus preserved. This strict continuity in every aspect (even in the location of plants, which are still in historical places: Malvern, Farnborough and Boscombe Down) is probably a unique case in the technological world.

The development of the H2S had a difficult time with the disaster of June 7th, 1942 when the Halifax V9977, with which the operational tests were carried out, fell down, causing the complete loss of the crew and of the investigators, including Alan Blumlein, perhaps the best technician working on the H2S program. Despite this, in the meeting on July 3rd, 1942 Churchill asked two hundred H2S sets to be ready for usage by the Bomber Command on 15 October.[24] It is interesting to notice that in those years the British did not plan to use the new microwave techniques, and in particular the magnetron, to improve their air defence, which was based, as shown before, on the Chain Home[25] and they did not implement any particularly significant radar system for tracking and anti-aircraft artillery: it seems that the bombing of German factories and cities was the main nail fixed in the mind of Churchill and his counselors.

The first combat trial of the H2S held in the bombing of Hamburg,[26] which took place on the night of January 30th, 1943, when thirteen *Pathfinder* aircraft, following the typical tactics of the night bombings by the Allies, released illuminating flares and incendiary devices on the city, to "show the way" the bombers (on that occasion, one hundred *Lancaster*). This type of radar was widely used by Anglo-Americans even during the landing in Normandy, see Fig. 6.9.

The Germans, somewhat aware of microwave techniques, considered them, however, not suitable for operational use in radar. Although there was in Germany an ancient tradition related to various types of magnetron [Bgvg 13], Germans knew nothing about the British cavity magnetron. However, shortly after the attack

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[23] Through April 1991, the RSRE was a part of the *Defence Research Agency* (DRA), then (April 1995) *Defence Evaluation and Research Agency* (DERA). In 2000/2001 the DERA was divided into two branches, i.e. a private law firm, holding the curious name of ***QinetiQ***, at present rich of more than five thousand employees (only a small part of them, anyway, is working on radar), and a government agency, the *Defence Science and Technology Laboratory* (DSTL).

[24] However, at the beginning of 1943 only twelve *Stirling* and twelve *Halifax* were equipped with the H2S.

[25] As already explained, the Chain Home was a type (and a concept) of radar "born old" and with a poor accuracy, not allowing the automatic tracking nor the guidance of antiaircraft artillery. Apart from the *Gun-Laying* (GL) systems such as the AA no. 3 Mk2 (GL III), during the war the British never developed something similar to the German Würzburg or the American SCR 584.

[26] The authorisation to use the H2S over territory controlled by the enemies was given by Churchill not without some hesitation, due to the fear that the Germans would have discovered *the indestructible* magnetron among the wreckage of a possible plane crash, which in fact happened after only three days. The H2S was also used in the subsequent bombing of Hamburg with the dramatic and well-known *Operation Gomorrah*, started on July 24th, 1943.

Fig. 6.9 Photo of the display of a H2S radar. The APSS (Aviation Preservation Society of Scotland) has supplied this remarkable photo—taken on June 6th, 1944, day of the landing of the Allies in Normandy—from the U.S. Army Magazine "Radar", No. 3, June 30th, 1944. The bright dot at "7:00" is the city of Caen. At sea, between "9:00" and "11:00", the arriving vessels and landing means are readily seen

to Hamburg, what Lord Cherwell feared become true: on February 2nd, 1943 a Pathfinder was downed in the skies of Rotterdam, and immediately the Germans noticed the strange device between the wreckage of the airplane. The engineers went quickly to work on what was called the "Rotterdam Gerät", managed to reproduce the magnetron and engineered the new "centimetre-wave" radar better than the British. However, the Germans had neither the time, nor the needed industrial resources to produce an adequate amount of microwave radars: according to Leo Brandt, they produced about 500 cm-wave radar, of which, by the end of hostilities, only approximately one hundred became operational. We will come back shortly to this "German copy" of the S-band radar.

In parallel to the development of the H2S,[27] but with lower priority, the British developed the air–air (*airborne intercept* or AI) radar. Similar to Germans, they started

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[27] The H2S had two releases, i.e. TR3159 (H2S Mk. I/ASV VI B) and TR3191 (H2S Mk. II).

with VHF sets (one meter and a half wavelength) including the noticeable AI Mk. IV, installed on the *Beaufighter*. From January to May, 1941 this radar set permitted an effective contrast of the night bombings on London and on other British cities.[28] Following such encouraging results, centimetre-wave radar sets were developed, i.e. the Mk. VII (in service since March 1942) and the Mk. VIII (August 1942). Of course, in the framework of the cooperation started with the Tizard mission, also the United States realized airborne radar using the centimetre-wave magnetron brought to them by the British. The Radiation Laboratory soon implemented an ASV radar at 10 cm wavelength that was installed in the *Liberator* aircraft and operationally used from January 1943. The *Liberators* create many problems to the increasingly aggressive and effective *U-Boote*,[29] that the *Liberator* could detect at any point of the Atlantic. Churchill wrote to Roosevelt to ask him to put into service over the Atlantic thirty *Liberator* aircraft with on board the ASV in S-band (USA designation: SCR-517).

In the USA the development of microwave radar led to subsequent developments—in addition those operating in the S-band (about 9 cm wavelength)—in the X-band (around 3.2 cm). The X-band radar set developed by the Americans was called H2X or AN/APS-15, and sometimes *Mickey set*. Thanks to the plan position indicator of the land echoes, this radar, which provided better images of the environment around the aircraft than those in the S-band, permitted navigation and bombing with cloud coverage and at night. The B-17 of the *United States Army Air Forces* with the H2X on board operated in Europe, with the "Pathfinder missions", from February 1944. Having evaluated the results obtained in the X-band, the British adopted this band for the Airborne Intercept Radar Mk. III which entered service on November 18th, 1943 in the "Battle of Berlin".

In the area of the ASV radar, the need arose to improve the resolution in order to detect the *schnorchel* of the new class of U-Boot (introduced in October 1944). Moreover, the Germans had the Metox apparatus, with which the crews of the U-Boot could intercept the emissions of the S-band radar. For both reasons, the Allies increased the ASV radar frequency, going to the X-band like the AI radar. The decision to develop the X-band was taken on November 22nd, 1944. At that date experiments were on-going in the K band, i.e. at a wavelength of 1.2 cm, but finally the band X was chosen. The X-band model of the ASV was called ASV Mk. VII by the British. The next model, ASV Mk. XI, again in the X-band (also called ASVX), with the antenna under a ventral radome, was installed on the *Fairey Swordfish* and then on the *Fairey Barracuda Mk. III*, both equipped with rocket launchers under the wings; the rockets could damage an emerged submarine up to a distance of 500 m. The range of the ASV Mk. XI was 60 km on ships and, with the airplane in flight at low altitude (600 m), up to 20 km on emerged submarines and, in a very calm sea, 8 km on a *schnorchel*.

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[28] The end of the Battle of England was strictly related to the too high losses of German bombers, mostly due to interception by British fighters.

[29] In the former 20 days of March, 1943, the German submarines were able to sink 95 ships with the loss of only 12 *U-Boote*.

In addition to active countermeasures (jammer), the Germans used different passive means for disturbance and deception against enemy radars. One of them, called *Aphrodite*, was positioned in the sea—in a quite complicated manner—by the crew of the submarine. It was a balloon inflated with hydrogen and attached to a floating buoy with a cable about 50 m long. Three strips of aluminium—about 85 cm long, half the wavelength of ASV radar Mk. II—were connected, like flags, to the balloon. A subsequent "decoy" of the buoy type, called *Thetis*, could be launched from the torpedoes pipes and could remain on the sea for months. The advent of the ASV Mark III, with wave on 10 cm and better resolution, made these means of deception not very effective, and new ones were developed with limited success. As described above, in the first high-intensity nightly bombings by the RAF (Hamburg, January 1943), the H2S radar allowed to identify—even with cloudy skies and in moonless nights—the cities at distances up to 40 km[30] and the Germans ignored this revolutionary apparatus—equipped with the cavity magnetron—for three days only, until the said *Pathfinder Stirling* crashed in the night between February 2nd and 3rd, 1943 near Rotterdam. At the beginning of March, a second H2S was in German hands and in the middle of March it was clear that the apparatus was working on 9.1 cm, showing the greater advancement of the Allies with respect to the German radar technology. In just four months the Germans assembled an operational "*Rotterdam*" radar. When it was installed on the high *Humboldthain flak* tower in Berlin, clear images of the city and the surrounding landscape appeared on the display, with great astonishment by Goering. As a countermeasure against this new threat—in addition to the Naxos receiver—the Germans, studied—and in some cases, applied—new means to confuse the H2S. They were groups of corner reflectors[31] put in large quantities in non-residential areas, and often, on rafts in the lakes, to simulate the echoes of the cities or at least to modify the radar image which was a rough but effective map of the territory available on board the attacking aircraft (see Fig. 6.10).

The Germans were also active, albeit with varying strategies at different times, in the field of airborne radar. During the war they tried—however, too late—to recover their technological *gap* in the field of microwave and magnetron.

Many historians attribute this scientific and technical *gap* to the prohibition of engagements of the German military research into areas not supplying usable results in a short, defined time (some indicate six months, and others one year). However, it is well known that the Germans (and also the Soviets) knew about the principle of the magnetron with resonant cavities: they identified it immediately in the wreck of the aircraft crashed near Rotterdam and in the relationship describing

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[30] The on-board display, with the azimuthal scan of the antenna, showed a kind of map of the land below, with the possibility of guiding the plane over the targets after recognizing the peculiar characteristics of the territory: lakes, rivers, estuaries, and the cities themselves.

[31] In order to be effective, the *corner reflectors* faces had to be strictly flat and perpendicular to each another with errors less than a small fraction of a degree. It proved quite problematic to construct them in large quantities necessary to simulate the radar echoes of a city.

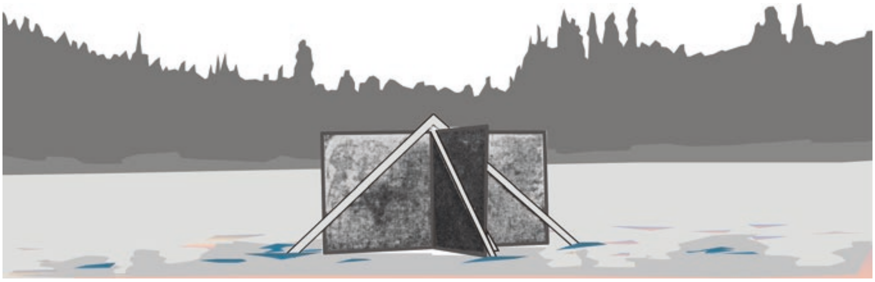

Fig. 6.10 One of the metallic Corner Reflector installed on wooden rafts in the lakes around Berlin to modify the image obtained by the H2S and H2X radars of the Allies

it[32] it is written: "*The efficiency of the magnetron is approximately 10 %—it should be remembered that this is an embodiment of the known Russian patent*".

The two main applications being firstly pursued by Germans were of course related to both attack and defence operations, i.e. (i) guidance of the bombers to naval targets and (ii) guidance of fighters/interceptors against enemy aircraft, in particular, bombers. The latter became of vital importance through 1943 with the strategic bombing on Germany.

The German airborne radar can be attributed to Dr. Wilhelm T. Runge (1895–1987) from Telefunken, who between 1939 and 1940 realized a prototype of radar-altimeter for the bombers. This set was never industrialized, but drew the attention of general Martini who asked Telefunken to study a search apparatus for the night fighters, in practice, the type of radar owned by the British since 1939. It was necessary to develop an antenna not disturbing too much the aerodynamics of the aircraft. To this aim the Germans chose a solution with sixteen dipoles on the muzzle of the airplane, making it similar to a sawfish and accepting a speed reduction of 10 km/h. In such a way, the family of *Lichtenstein* radars was born, which entered the service on April 1941. The radar Lichtenstein B/C[13]—FuG[33] 202—see Figs. 6.11 and 6.12—was used in night missions from autumn 1941 until 1943. Remarkable was the measurement and display of the angular signal, see Fig. 6.13.[34]

The ensuing German airborne radar set was the *Lichtenstein SN-2*, or *FuG 220*. In this further development the German designers went against the general

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[32] The relation is reported by B. Lovell in the paper [Lov 04] "The cavity magnetron in World War II: Was the Secrecy Justified?".

[33] FuG meant *Funk Gerät*, or *Funkgeräte*, radio equipment.

[34] On May 9th, 1943 the Junker 88-R—mark D5 + EV—driven by H. Schmitt, after having informed the base of a failure of an engine, headed to Scotland where, accompanied by two *Spitfire*, landed on the airport of Dyce. This desertion allowed the British to thoroughly study the *Lichtenstein B/C*.

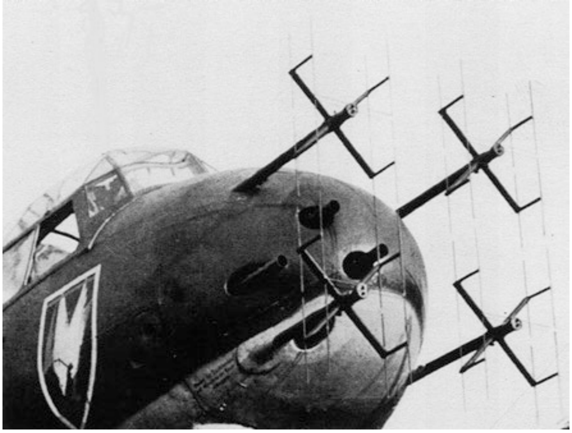

Fig. 6.11 The FuG 202 radar on a *Ju 88R*. Operating since 1942 with a transmission frequency around 490 MHz, had a *Matratze* (mattress) antenna system with four groups of four dipoles each

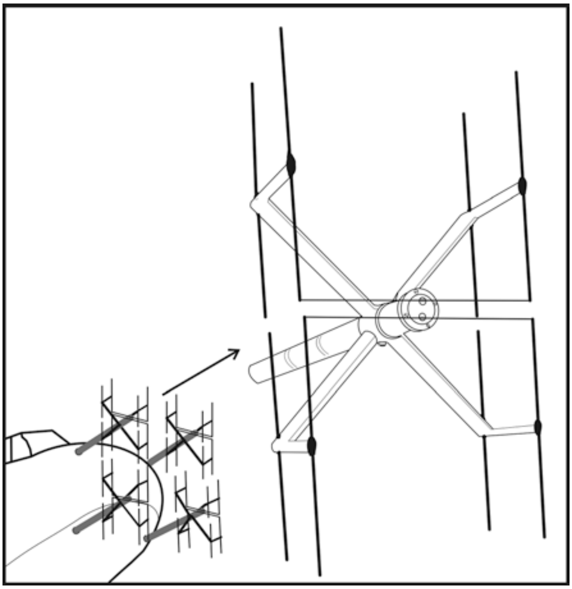

Fig. 6.12 Drawing of the antenna system of the FuG 202

trend toward higher and higher frequencies, and increased the wavelength that was adjustable between 3.2 and 4.2 m, i.e. much larger than the 60 cm of the B/C,[14] see Fig. 6.14.

The British probably could examine the particular technical solutions of the SN-2 only after the landing (which, according to the most common hypothesis, was due to a pilot error) of a *Ju 88 G1* at the English airport of Woodbridge.

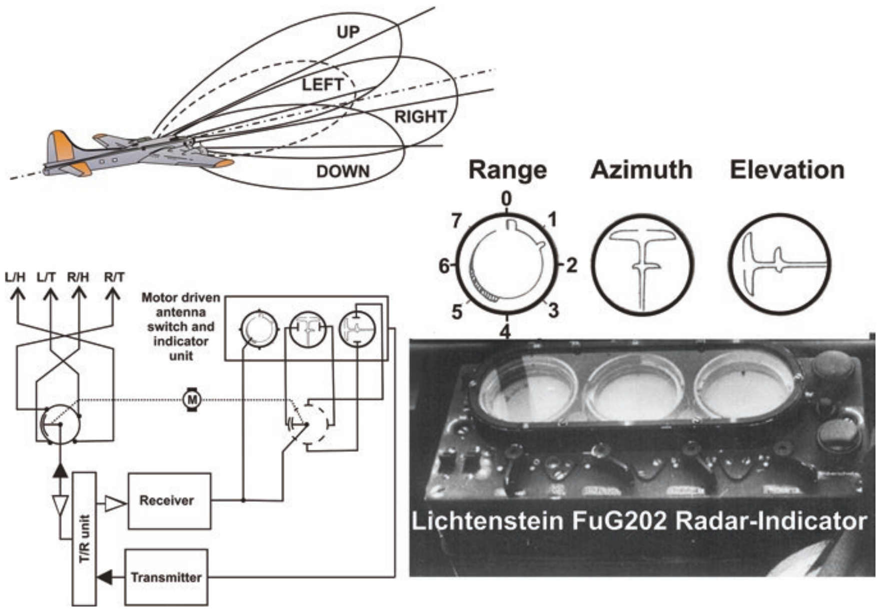

Fig. 6.13 The operation of the antenna system FuG 202—The four lobes were switched around 25 times per second, creating three images that appeared simultaneously on three displays

In addition the SN-2, the Ju 88G-1 had on board the radar emissions interceptor *FuG 350 Naxos* and the passive system *FuG 227 Flensburg*[35] (see Fig. 6.15) with which the fighters of the Luftwaffe could aim toward the bombers of the RAF following the emissions of their range-only radar system *Monica* (whose American version was called AN/APS-13) in the VHF range around 300 MHz. "*Monica*" was designed to provide the crew of the bombers an audible alarm when a threatening fighter approached from the back; however, the alarm generated by *Monica* was triggered by the other (friendly) bombers of a raid, and, even worse, the emitted pulses, received by passive systems as the *Flensburg*, allowed German fighters to best approach their target. Of course, the RAF ceased to use *Monica* in the summer of 1944 after having analysed the *Flensburg* on board the Ju 88 G1. Moreover, ten days after the landing of the Ju 88 G1, the British developed the countermeasures for the Lichtenstein SN-2, but, until then, this radar worked virtually undisturbed for nine months.

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[35] The "passive radar" FuG 227 *Flensburg*, built (by Siemens and Halske) with commercial components and, therefore, heavy and bulky, was much appreciated by the German crews, anyway. Receiving the emissions from the *range-only radar Monica*—which was possible up to a distance around 200 km—the FuG 227 permitted an angular accuracy of about 2° in a sector of about ±180° in azimuth and over 180° in elevation. The Flensburg could operate up to a height of 9000 m, had a consumption of 170 W and weighed 42 kg.

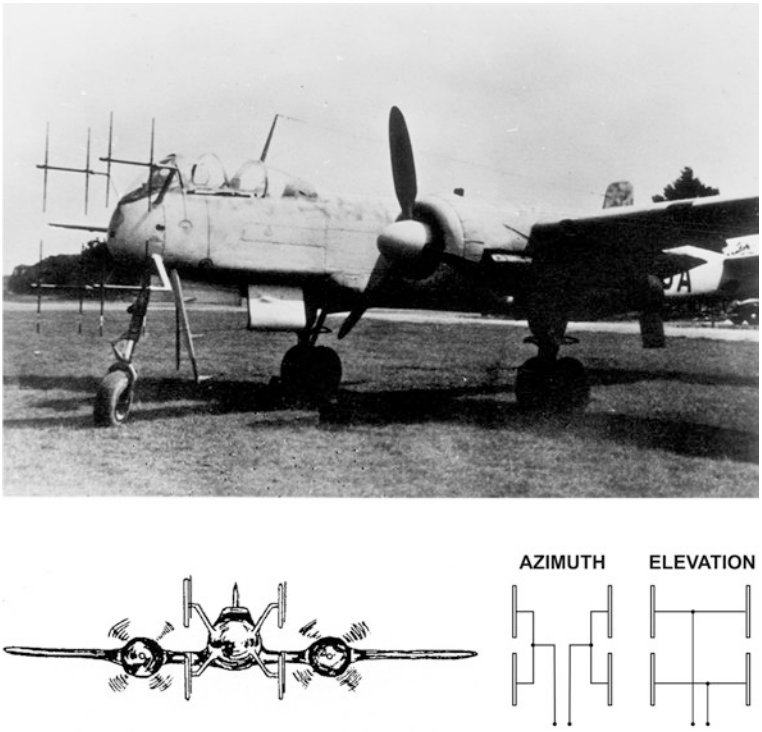

Fig. 6.14 The system of four antennas of the Lichtenstein SN-2 and their connections to implement the azimuth channel and the elevation channel (Heinkel He 219)

Fig. 6.15 Block diagram of the "passive radar" FuG 227 *Flensburg*

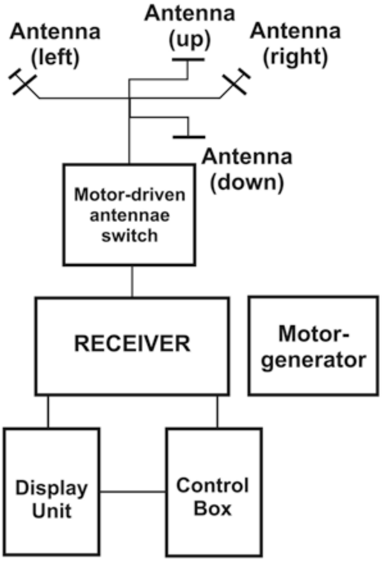

Fig. 6.16 The SN2 airborne interception radar on board a *Messerschmitt Bf 110G* night fighter at Grove, Denmark, August 1945

After the entry into service of the Lichtenstein SN-2, it was observed that the minimum distance was more than the approximately 200 m specified at the design stage. In fact, the receiver, in saturation during the transmission, took some time to return to normal operation. The only found solution to this problem, very serious for the night operations, was that of keeping on board also the previous Lichtenstein B/C in a simplified version, i.e. with the azimuthal measurement only.[36] It should also be mentioned that the much smaller antennas of the *B/C* did not significantly worsen the heavy aerodynamic effect of those of the *SN-2*. This particular radar configuration was also present on the Martin Drewes's[37] night fighter BF 110 G of the group III—*Nachtjagdgeschwader* 1 (see Fig. 6.16).

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[36] In fact, once the height of its target has been reached, the fighter had just to maintain the correct aiming for the visual acquisition before shooting.

[37] The Major of the Luftwaffe Martin Drewes (1918–2013) got as well as 52 victories (including the downing of 43 night bombers of the RAF, almost all of the model Lancaster) during the war and was decorated with the *knight's cross of the iron cross with oak leaves*. After the war, although he had not committed any crime, suffered for some months the inevitable harassment by the Allies who had captured him. In 1949 he emigrated to Brazil starting an activity first as a civil pilot and then as a business man and a farmer.

In addition to these air-to-air radar sets, the Germans developed some ASV sets. The FuG 200 *Hohentwiel* by Lorenz (see Figs. 6.17 and 6.18) was designed to detect vessels from aerial platforms. The first operating set dates back to September 1942, and from August 1943 this radar was installed on maritime patrol aircraft such as the FW 200 *Condor* and the He 177. It operated on the wavelength of about half a meter (about 550 MHz) like the *Würzburg*; a version for submarines was derived from it. In ensuing versions the frequency was adjustable between 525 and 575 MHz, as an anti-jammer technique.

The Germans also developed the *Neptun—FuG 218* that was produced in large quantities by Siemens/FFO; this airborne radar set operated on six selectable frequencies in the range of 158 to 187 MHz and had different versions, the J3 for single-engine night fighters, the V/R that included rear surveillance and was suitable to twin-engine aircraft, and finally the R3 that provided only rear surveillance. The coverage of the *Neptun* was 120° in angle and from 120 m to 5 km in Range.

The Germans, as it is well known, began the development of microwave radar with a magnetron transmitter only after the examination of the wreck of the English

Fig. 6.17 A Junkers Ju 88G with the "*Hohentwiel*" radar

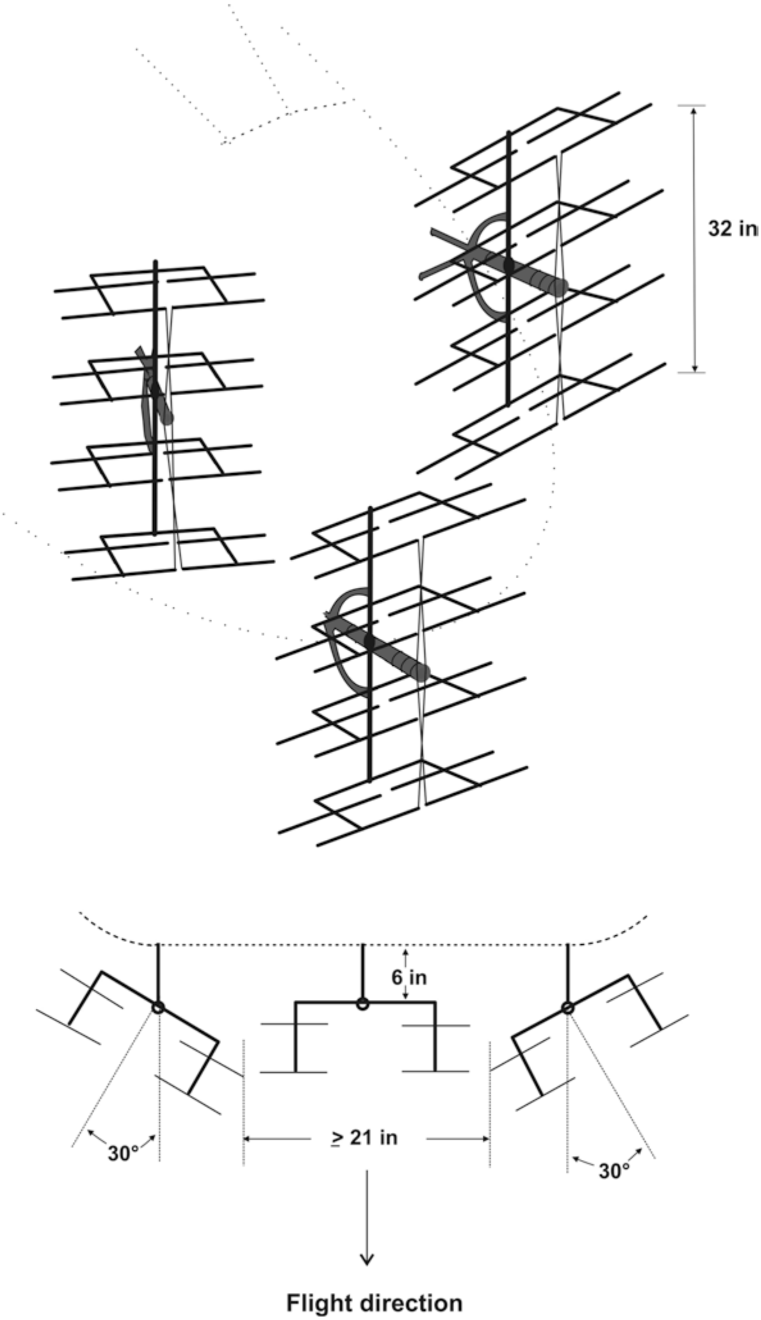

Fig. 6.18 The FuG 200 "*Hohentwiel*" radar had a complicated system of antennas, with groups of eight dipoles, each one with a reflector. The central group transmitted, the side one, with two elements pointing to +30° and −30° from the previous one, received

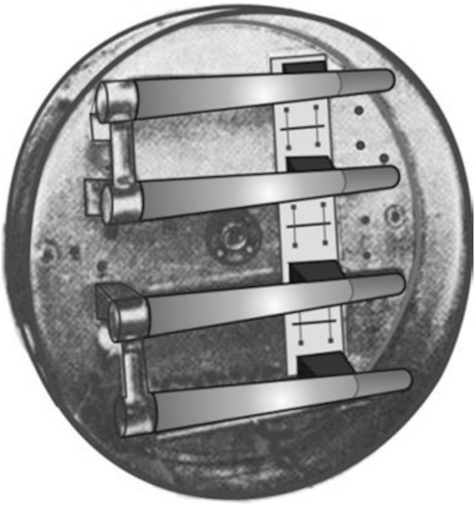

Fig. 6.19 The *polyrod* antenna of FuG 224 *Berlin A*, *top*

bomber Stirling—equipped with the H2S—downed in Hardinxveld-Giesendam (south-east of Rotterdam) on February 3rd, 1943, after a squadron of British bombers had attacked Cologne the night between February 2nd and 3rd, 1943.[38] After the initial shock, the German command answered promptly: on February 22th the coordination committee of technical-scientific "Arbeitsgemeinschaft Rotterdam" (AGR) was constituted in order to coordinate the needed efforts to overcome the technological gap with respect to the Anglo-American magnetron radars, called Rotterdam Gerät.[39] The copy of the cavity magnetron English CV64, which operated on 9 cm wave length, was called by the Germans LMS10 (the number indicates the power of 10 kW). On the basis of the operation of the Rotterdam Gerät, they also developed the (already mentioned) *Naxos* interception system for 10 cm wave length radar. In a few months at Telefunken they developed the FuG 240 Berlin N1[15] radar.

The next German microwave radar, the FuG 224 *Berlin* A, was developed by Telefunken on the basis of the H2S and of the American AN/TPS-13 and entered the service at the beginning of 1944. Particularly new was the antenna (see Figs. 6.19 and 6.20), made with radiating elements of the dielectric type, called *Stiehl-strahler* or *Dielektrische Strahler* (the English name was *Polyrod*).[16]

From the *Berlin* they derived two S-band radars for submarines, the *FuMO 83 Berlin U I* and the *FuMO 84 Berlin U II*; the FuMO 83 had a rotating antenna on top of a retractable mast and allowed a panoramic vision around the submarine.

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[38] The downed Stirling had the magnetron almost intact and the label "experimental 6". The story had a continuation on April 19th, 1943 when the Germans acquired in a similar manner the American radar *H2X* that was called *Meddo-Gerät*, from the name of a small village in the eastern part of Holland.

[39] While most of the microwave part was simply copied, the other parts were re-engineered because of the differences between the German and the British aircraft, the different measurement units systems and the different industry standards.

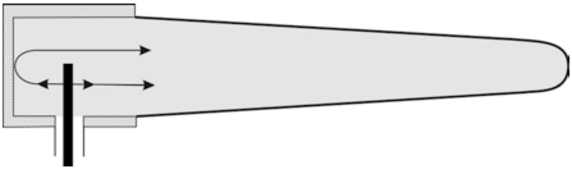

Fig. 6.20 The principle of the polyrod antenna used in the *Berlin A* airborne radar

Radars by the Gema were also converted to the 9 cm wavelength, such as the *Seetakt* renamed "*Renner*". Finally, at the end of the war the Germans had prototypes of 3 cm radars, among which the "*Bremen*".

With the W.W.II hostilities going on, even the United States of America needed airborne radar; starting from the British radar ASV Mark II, the Americans produced the "ASE" or SCR-521 radar, operating in the 170–196 MHz band. The SCR 521 was installed on the *Consolidated Catalina* and produced in more than twenty thousand sets, with the versions SCR-521-A or *ASVC*, and SCR-521-B or *ASE—Long Wave.*

In the USA the development of microwave radar, initially based on the S-band magnetron supplied by the Tizard Mission, included ensuing developments in the X-band (about 3.2 cm) permitting navigation and bombing with time cloud cover and at night. The British adopted the X-band with the version Mark III of the H2S that entered the service on November 18th, 1943 in "The Battle of Berlin".

On the Pacific war, the American B-29 had, in an underside "radome", an improved version of the H2X called AN/APQ-13,[17] developed by Bell, Western Electric and MIT (see Fig. 6.21); this radar was also used in the Korean conflict at the beginning of the 1950s, and, modified as a meteorological radar with the "storm warning" function, was the first *civil radar* derived from a military apparatus and used until its replacement with the AN/CPS-9 in 1949.

On the B-29 B (a lightened version of the B-29 with an increased bombs capacity, which, like the B-29, was used in the Pacific war but not in Europe) was installed another considerable apparatus, the AN/APQ-7 known as "Search and Bombing Radar *Eagle Mk1*".

The *Eagle* was a "high angular resolution" version of the H2S; it was produced by Western Electric, operated at X-band (around 9375 MHz) with an antenna 5.1 m long, granting a very narrow main lobe (less than 0.4°). The antenna, shaped as a wing beneath the fuselage and with the long side perpendicular to it, was only 20 cm thick. The idea of using a non-rotating microwave antenna, with electronic scanning of the beam, originated in 1941 at the *Radiation Laboratory*, and was due to Luis Alvarez,[40] who proposed the use of a slotted wave guide in which a

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[40] The physicist, and Nobel Prize (1968) Luis Alvarez (1911–1988) worked during W.W.II on many radar projects at the Radiation Laboratory. When working on the Microwave Early Warning system (MEW), Alvarez invented a linear array antenna to be electronically scanned without the need for physical motion, i.e., the first microwave phased-array antenna. The antenna (completed rather late in the war) enabled the *Eagle* radar to support precision bombing through clouds coverage. The development, however, was slow: the *Eagle* prototype flew the first time on May 16th, 1944, and the operational use for night bombing was limited to Japan, from mid-1945.

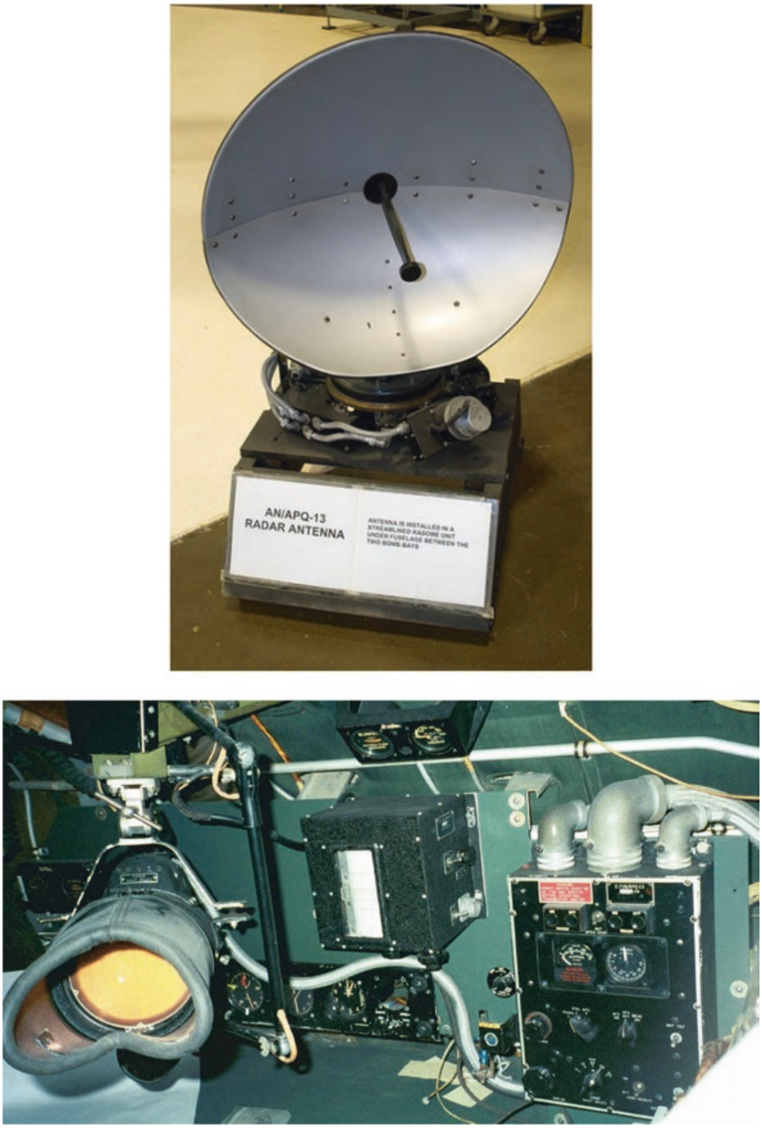

Fig. 6.21 The AN/APQ 13: antenna (from the New England Air Museum) and the installation on a B-29 (the restored Enola Gay): close up view of the Radar Operator's desk with the PPI (cathode ray tube) at the *left*, the range unit in the *centre* and the main control box at the *right*

moving wall changed the phase relationships of the numerous (over 150 on the 5 m length) openings and, then, scanned in azimuth the antenna beam at frequencies up to about 1 Hz, impossible to achieve with a movement of the entire antenna. With such a narrow lobe and thus a high gain, maximum radar ranges were obtained up to 260 km.

The Western Electric's S-band, AI radar *SCR 720* (see Fig. 6.22), a compact version of the *SCR 520*, was obtained from the Signal Corps Radar *SCR-268* to fit the Northrop's twin-engine, propellers night fighter *P-61 Black Widow*, which remained in service until March 1949, when the jet aircraft made it obsolete.

The British microwave radars were labeled from Mk. VII to Mk. X (see Fig. 6.23), and often derived from those in the United States. For example, the AI Mk. X,[41] a modified version of the SCR 720, was used on the Night Fighter version of the *Mosquito*.

The enormous technological and industrial effort connected to the development of airborne radar during the Second World War produced radar sets in previously unthinkable amounts. Some radars were of such a high quality as to be used for many years after the end of the war. The bombers *Avro Lincoln* of the RAF used the H2S after the war, and in the 1950s, the version H2S Mk 9 was part of the *Navigation and Bombing System* installed on the aircraft *Vickers Valiant*, *Avro Vulcan and Handley Page Victor* of the RAF. In 1982 the *Vulcan* and *Victor* bombers took part to the Falklands war, using effectively their H2S; some of them remained in service until 1993.

The development of AI radar after the war continued in some sites; one of them, the factory at *Crewe Toll*, Edinburgh, was founded during W.W.II as a part of the *Ferranti* Company for the production of gyro gun sights;[42] after the war, the British started the development of the *Lightning* fighter/interceptor, developed by English Electric, which first flew in 1954 and was in service at the RAF for a long period (1959–1988), see Fig. 6.24. This Mach-2 jet, able to rival the celebrated F 104, hosted in an unpressurized conical radome in the middle of the engine air inlet, the Ferranti AI-23 radar, Fig. 6.25. It was the first monopulse airborne radar, with a dual antenna feed assembly, generating sum and difference patterns in azimuth by the two halves of the antenna (amplitude monopulse) and sum and difference patterns, as well, in elevation, by phase monopulse. Thus, measurement of the azimuth and elevation angles of the target was possible in a single pulse, with enhanced accuracy and resistance to jamming and to deceiving.

During the Cold War, the need for protection against potential bombers attacks from the Soviet Union and the Warsaw Pact led the NATO nations to develop, in addition to missile systems such as Nike Hercules, fast fighter-interceptors, such as the *Lightning* described above. Probably, the most famous of them is the *Lockheed F-104*, a Mach 2 jet fighter used by the air forces of many NATO

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[41] This S-band (9.1 cm) AI transmitted 0.75 μs pulses with a peak power of 70 kW; the antenna was a parabolic reflector with a rotating dipole in his focus, and the lobe of the antenna scanned in a helix, or spiral, the angular sector in front of the aircraft. The display was a single cathode-ray tube in Mk. VIII, while in Mk X, the left display was of Type C (azimuth-elevation) and the right one of Type B (distance-azimuth).

[42] Then, the site became GEC-Ferranti, GEC Marconi Avionics, Marconi Electronic Systems, BAE Systems Avionics, Selex Sensors and Airborne systems, Selex Galileo, and finally Selex-ES (from autumn 2014, a part of Finmeccanica).

Fig. 6.22 The SCR 720 on the Northrop P61. This set operated on the 10 cm wave, had a 74 cm dish antenna with a main lobe of 10°. The feeder of the antenna was spinning at 360 or 100 rpm. 0.75 μs long pulses were transmitted with a pulse repetition frequency (PRF) of 1500 Hz and a peak power of 3 kW. Range on bombers at 3000 m: 16 km, on fighters: 8 km

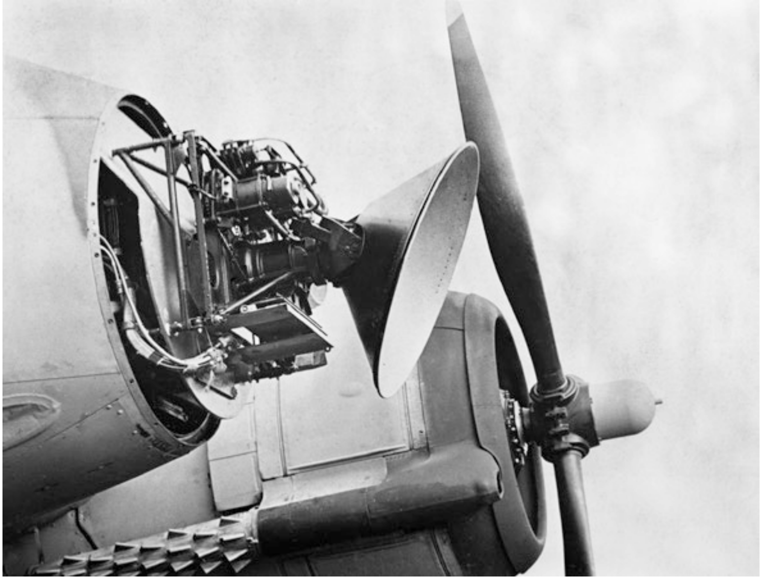

Fig. 6.23 Air Interception radar: AI Mark VIIIA scanner (antenna) unit mounted on the nose of a Bristol Beaufighter Mark VIF night fighter. The transmitter unit, not shown, was fitted to the mounting tray underneath the scanner mechanism

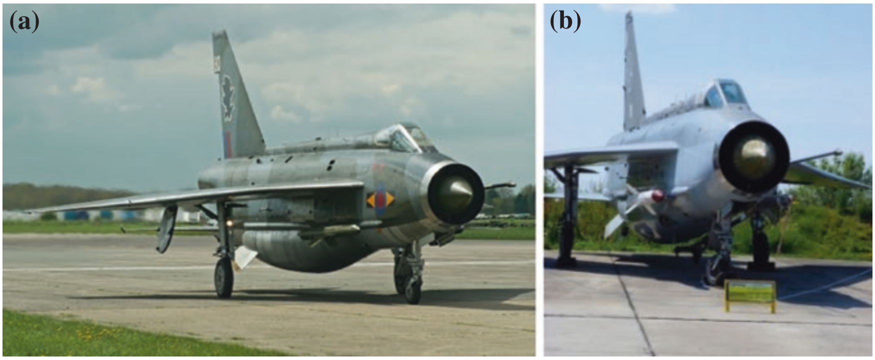

Fig. 6.24 **a** The English Electric Lightning aircraft after a high speed taxi run at 2012 Cold War Jets Day, Bruntingthorpe. **b** The EE Lightning on display at the Yorkshire Air Museum, Elvington

nations[43] from 1958 to 2004 (see Fig. 6.26). The F-104 "nose radar" is the NASARR (North America Search and Ranging Radar) R 21G by North American Aviation Autonetics; for the F-104 S, ASA version, operational in 1985 (ASA

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[43] The ultimate, all-weather interceptor version F-104 S equipped with radar-guided missiles (S stands for Sparrow, i.e. the AIM-7, an air- to-air missile with semi-active guidance) was designed by *Fiat Aviazione*, later, *Aeritalia*, for the Italian Air Force, where they remained in service for about forty years starting from 1963.

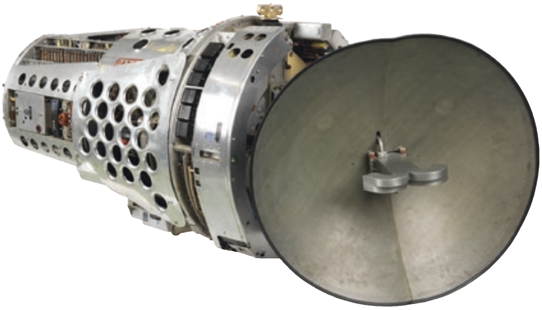

Fig. 6.25 The British AI-23 radar for the Lightning aircraft—photo taken in 2014 at the radar museum of Selex-ES UK, Crewe Toll, Edinburgh (courtesy of Selex ES, Ronald W. Lyon)

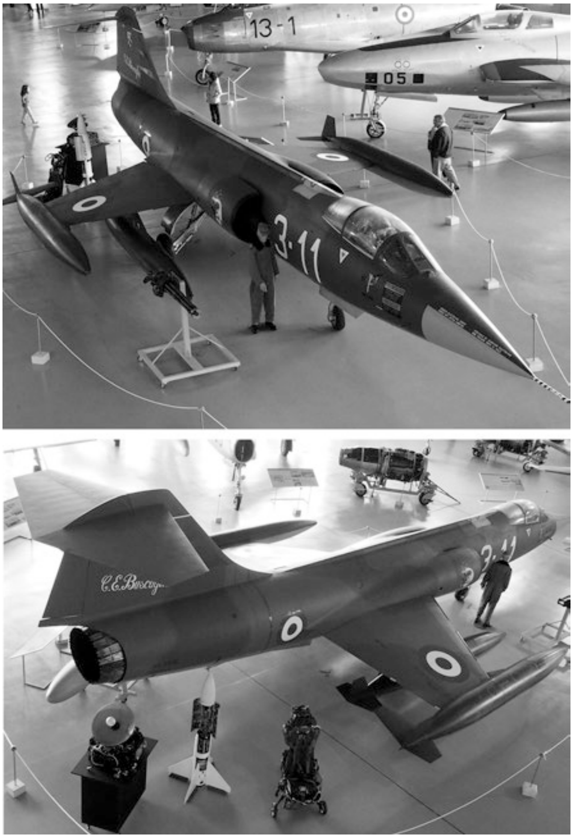

Fig. 6.26 The F-104 S of the Italian Air Force on display at the *Museo Storico dell'Aeronautica Militare*. Photo by the author. *Courtesy* Museo Storico dell'Aeronautica Militare, Vigna di Valle, Bracciano (Roma), www.aeronautica.difesa.it/museovdv

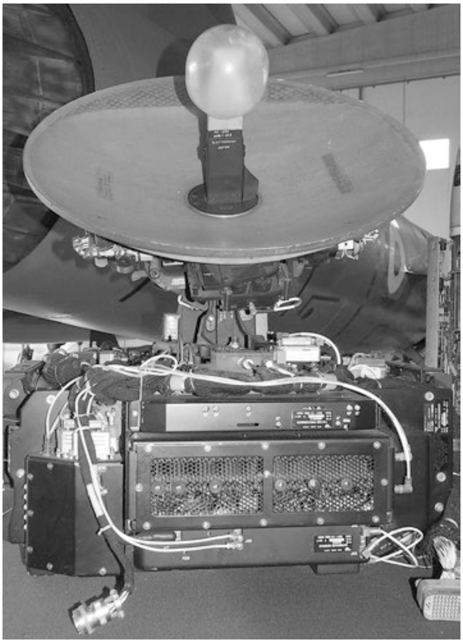

Fig. 6.27 The NASARR R 21G/M1 radar on display at the at the *Museo Storico dell'Aeronautica Militare*. Photo by the author. *Courtesy* Museo Storico dell'Aeronautica Militare, Vigna di Valle, Bracciano (Roma), www.aeronautica.difesa.it/museovdv

means *Aggiornamento Sistemi d'Arma*, i.e. Weapon Systems Update) the Italian company FIAR in Milan developed and built the modified version R 21G/M1,[44] shown in Fig. 6.27.

Another successful aircraft was the De Havilland *Vampire*, see Fig. 6.28.

In the decades after W.W.II the AI radar originated the multifunction airborne "nose" radar, while the Airborne Early Warning (AEW) radar systems were derived from the ASV radar. The concept of AEW implies a special (or modified) aircraft equipped with long-range radar to survey and search in the environment, both on land and on sea. The first aircraft designed for this type of missions was the Grumman E-1B *Tracer*, a modified version of the S-2 *Tracker* used for ASW (anti-submarine warfare) operations from 1958 through 1977. The E-1 *Tracer* entered the service in 1958 and was the first Airborne Early Warning aircraft used by the United States Navy, see Figs. 6.29 and 6.30.

The *Tracer* was soon replaced by the more modern E-2 *Hawkeye*, developed during the period from the mid-1960s to the early 1970s. In fact, in 1956 the U.S. Navy defined the requirement for an airborne early warning aircraft dedicated to long range surveillance, whose data had to be integrated in *Naval Tactical Data System*. The Navy then selected the project presented by Grumman in March

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[44] In addition to the CW (Continuous Wave) illuminator for the *Sparrow* and the Selenia's *Aspide* missiles, this version had monopulse, MTI (Moving Target Indicator) and ECCM (Electronic Counter Counter Measures) features including frequency agility.

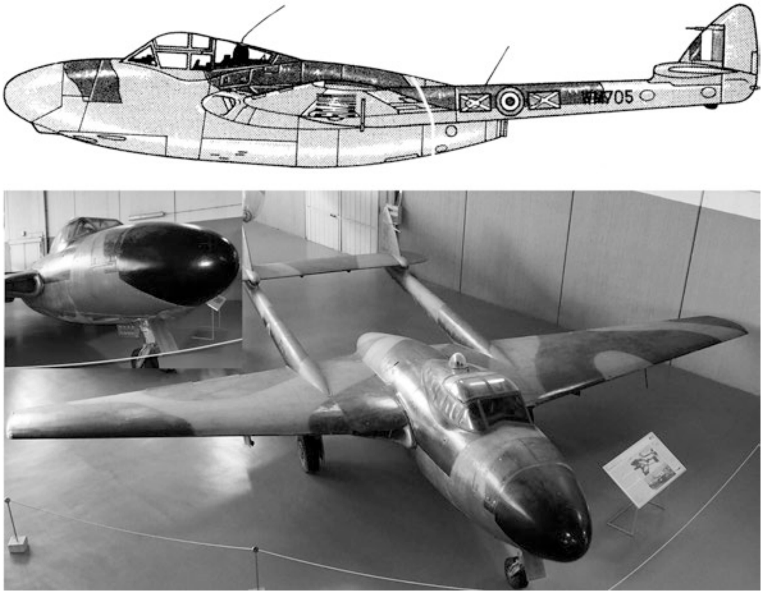

Fig. 6.28 The Night Fighter NF.10 Vampire, designed and built by De Havilland (U.K.) on the project called DH.113, started in 1947 (first flight in 1949, withdrawn from the service in 1954). An AI Mk X (SCR-720B) radar is hosted in the front radome. The NF.10 was replaced by the De Havilland NF2/2A *Venom* (first flight, 1950; in RAF squadron service until 1957). A few DH.113 were acquired by the Italian Air Force in 1951–53 for the "Scuola Caccia Ogni Tempo" (*All weather fighter school*) in Amendola, Foggia. Photo by the author. *Courtesy* Museo Storico dell'Aeronautica Militare, Vigna di Valle, Bracciano (Roma), www.aeronautica.difesa.it/museovdv

1957, initially called *W2F-1*, and then *E-2A Hawkeye*: the first aircraft purposely designed for AEW, command and control. The first experimental flights took place in 1960/1961, and the *E-2A Hawkeye* was operating for the U.S. Navy from January 1964, and followed by versions E-2 B and E-2C,[45] see Figs. 6.31 and 6.32.

The early warning system E-2 was developed and used over the course of more than half a century. It is, perhaps, the longest continually running radar surveillance system originating eight generations of radar equipment based on a same architecture, as shown in Table 6.1. The E-2 system, whose platform can operate

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[45] The so-called Group O has on-board the AN/APS-138 radar, *the Omnibus II Update Development Program* (UDP) Group I has the AN/APS-139 and has reached the *Initial Operating Capability* in December 1988. The most modern aircraft version of the *Omnibus II UDP Group II* Aircraft has on board the AN/APS-145, with *Initial Operating Capability* in April 1992. The ensuing version of the E-2C Aircraft, the "Hawkeye 2000", has been operational since 2002 as Group II (M).

Fig. 6.29 An E-1 tracer (*left*) of the carrier airborne early warning squadron (VAW) 11, EA-1 Skyraider, and an RF-8A Crusader of the photographic reconnaissance (VF) 63, all assigned to the carrier air wing (CVW) 5

Fig. 6.30 Folding the wings of an E-1 tracer of the airborne early warning squadron (VAW) 11 on the elevator of an unidentified aircraft carrier

Fig. 6.31 Grumman's twin turboprop W2F/E-2 Hawkeye (*right*) replaced the E-1B tracer as a carrier all-weather/AEW platform

Fig. 6.32 An E-1 Tracer (*right*) and an E-2 Hawkeye of the reserve airborne early warning squadron (RVAW) 120 pictured in flight near Naval Air Station (NAS) Norfolk, Virginia

from an aircraft carrier, is based on a radar in the UHF band[46] and on a IFF; the radar range declared on air targets is 550 km (version AN/APS 145), and the antenna is placed in the characteristic radome rotating at 5 or 6 rpm.

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[46] The choice of the UHF band was not common for long range surveillance radars after W.W.II. The—a little reticent—supplier of the radar justified this choice in terms of low sensitivity to sea and the rain *clutter*. Official sources did not provide the value of the central frequency used by the AHE of the Hawkeye, which seemed to be around the 430 MHz—a return to a wavelength of 70 cm often used in the Second World War!

Table 6.1 Half a century of Hawkeye

AEW system	Name of the radar	First year in service
E 2-A	AN/APS-96	1964
E 2-B	AN/APS-111	1965–70
E 2-C	AN/APS-120	1972–73
E 2-C	AN/APS-125	1977
E 2-C	AN/APS-138	1984
E 2-C	AN/APS-139	1988
E 2-C+	AN/APS-145	1991–92
E 2-D	AN/APY-9	2014

Fig. 6.33 *Radome* of the antenna of its AN/APY-1/2 radar, diameter 9.1 m, maximum thickness 1.8 m, rotation rate 6 rpm

The last version 2-D of the AEW has the AN/APY-9 radar also called *Advanced Hawkeye* (AHE) and uses a substantially redesigned aircraft (although, at a first glance, looking very similar to previous versions).

The E-2D aircraft first flew on August 3rd, 2007, was cleared for full-rate production in February 2013 and achieved Initial Operational Capability (IOC) on October 10th, 2014, with five aircraft on board the USS carrier *Theodore Roosevelt*.[47] In the AHE radar[48] electronic scanning in azimuth is used, which allows (scanning in the direction opposite to the rotation of the antenna) to increase the dwell time of a given target up to about half the revolution time, and to operate with the antenna non-rotating when only a limited angular sector is to be searched.

In addition to the Navy's system E-2, the Air Force's AEW system, named AWACS, is well-known. The E-3 *Airborne Warning and Control System* (AWACS) entered the USAF service in 1977 and was also acquired by NATO and by different nations. It is based on the B-707 platform—see Fig. 6.33—and has a crew

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[47] The life of this fortunate system will be extraordinarily long: the U.S. Navy plans to retire the last E-2C in 2027.

[48] This radar uses solid state transmitting modules and digital reception with direct sampling of the signal at the carrier frequency, at 3G Samples/s.

Fig. 6.34 The B-767 AWACS of the Japanese self-defence force

of eighteen members. The radar, called AN/APY-1 and then APY-2, operates in the S-band, with a range of 320 km. In 1991, a version has been developed based on the more modern and capable B-767, of which four units were delivered to the *Japan Aeronautical Self Defence Force* between 1998 and 1999, with entry to service in 2000, see Fig. 6.34. The AN/APY-2 radar has electronic scanning in elevation.

The version acquired by the Royal Air Force is called AEW *E-3D Sentry* and was used in 2012 during the international mission in Libya call *Unified Protector*, which led to the fall of the regime of Gaddafi, and the murder of the Libyan dictator. Even the former Soviet Union has developed at least one AEW, Fig. 6.35.

Fig. 6.35 The aircraft An-71 AWACS at the Aviation museum, Kiev. Features (from the display panel): two turbojet engines with 7500 kg of thrust each, maximum take-off weight 32 tons, cruising speed 530 km/h (maximum speed, 650 km/h), maximum height 10,800 m, up to 5 h endurance, 6 members crew, radar coverage: 360° in azimuth, from 0 to 30 km in altitude, up to 370 km in range. Photo by the author

The evolution of the AEW&C (*airborne early warning and control*) systems during the 1990s has seen to the use of active Phased Arrays. This happened, *inter alia*, in the AEW&C radar system developed, since 2000, for the Royal Australian Air Force (RAAF) as "Project Wedgetail", with the former two (out of six) *Wedgetail* aircraft accepted by the RAAF in May 2010. This *Multi-role Electronically Scanned Array* (MESA), operates in the L band and integrates the IFF. The range is 370 km for the radar and 500 km for the IFF. The platform is based on the well-known B 737 (long range version), with a crew of six to ten operators in addition to two pilots.

Even in Europe they developed an AEW&C system: this is the *Erieye* by Saab, based on the platforms *Embraer E-99/E-145*. The electronically scanning radar, in the S-band, covers 300° on both sides of the platform with ranges up to 450 km on air targets. Figure 6.36 shows the version installed on the Saab 340 aircraft. The need to monitor the movements on the ground and at low altitude (military land vehicles, helicopters etc.) has led to the development of the avionic system *E-8C Joint STARS* (Joint STARS stands for joint surveillance and target attack radar system), a joint development project of the US Air Force and the US Army based on an electronically-scanned radar in X-band with the antenna in the underside position of the platform, a modified B 707-300. The Phased Array radar sensor of the E-8 C can detect surface moving targets (G-MTI: Ground Moving Target Indicator) and has an

Fig. 6.36 The Saab 340 Erieye platform delivered to the Royal Thai Air Force (RTAF)

inverse synthetic aperture radar (ISAR) operating mode. The system is operational since the early 1990s, and allows surveillance at a range of over 250 km. The crew has twenty members and there are seventeen identical workstations on board.

The need to create radar maps of foreign territory has led the Americans to develop, in full secrecy, airborne synthetic aperture radars using the Phased Array technology since the 1980s. The X-band ASARS-1 and ASARS-2 (ASARS[49] stands for "Advanced Synthetic Aperture Radar System" for the "spy" aircraft *Lockheed SR-71* and *U-2 R*, respectively. Their successor, called ASARS-3, operating at the Ku-band, is much more lightweight[50] and has a much finer resolution, better than thirty centimetres, albeit with the limited range of 40–60 km. It is therefore suitable for missions on UAV such as the RQ-170 *Sentinel*.

Not all AEW systems have been successful: still burns the celebrated *fiasco* (see for example http://www.spyflight.co.uk/nim%20aew.htm) of the British system called ***Nimrod*** which was designed by the British Aerospace (BAe) in the 1970s, with which about one billion pounds was thrown to the wind. The radar was a Pulse Doppler in the S-band with a system called FASS (*Fore and Aft Scanner System*), of two antennas, at bow and at stern, each of which scanned half of the full azimuth.

The failure of the Nimrod has not led (as maybe one could expect) to a USA monopoly for the AEW systems. In Europe they have developed the already mentioned *Erieye*, and the People's Republic of China, since 2003, has its own AEW&C system of called KJ-2000 (NATO Code Name: *Mainring*) which uses the Beriev A-50 platform (derived from the Soviet soviet Iliushin-76[51]). A "reduced" KJ-200 version is based on the Chinese Shaanxi Y-8 turboprop. The remarkable L-band radar of the KJ-200/2000 is an active Phased Array with three fixed faces in the shape of an equilateral triangle inside the circular radome with a diameter of 14 m. This domestic radar has been developed by the Research Institute of Electronic Technology, or *Institute 14*, in Nanjing. The KJ-2000 was built in at least four sets, one based on the Beriev A-50-I and three based on the MD-76 modified from the Xian Aircraft Corporation, which entered the service in 2006/2007. In 2013 a new, more capable version called "KJ-3000", with a greater antenna and using the domestic, four-engines Y-9 jet aircraft platform was announced in the press. According to military experts this new AEW&C has greatly enhanced Chinese air force's and navy's capability of both attack and defence: compared with the Y-8 used by the KJ-2000, there is a significant increase in load, range and endurance.

As already stated, the evolution of radar techniques and technologies has made the modern *multifunction* airborne radar (nose radar) possible. This type of radar set, used in fighters, fighter-interceptors and military multi-role aircraft, has

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[49] The family of the ASARS comes from the efforts of a division of the Goodyear, based in Arizona; this division was acquired by Loral and then by Lockheed Martin.

[50] The ASARS-3 has a total mass of only 75 kg and 900 W power at the output of the antenna; the active-array antenna weighs just 12 kg.

[51] The delivery problems of the Russian Il-76 seems to have been solved in March 2011, when Russia/China negotiations reached an agreement to move production of IL-76s to Chinese owned companies.

Fig. 6.37 The airborne radar AN/APG-63 for the F-15 fighter

different operating modes (search, acquisition, air-fight, fire-control, missile guidance, navigation, meteorology…) against various threats (aircraft, missiles, surface targets…). The Pulse-Doppler technique is generally used with waveforms and values of the pulse repetition frequency (PRF)[52] dependent on the operating mode. The working frequencies are normally in the X-band, sometimes in the K band. From the 2000s, for the "high end" equipment the configuration with a mechanically scanning antenna (Fig. 6.37 shows the slotted waveguides, mechanical radar antenna of the F-15 *Eagle* fighter) is being gradually replaced by the electronic scanning of the beam[53] (the acronym normally used is AESA, Active Electronically Scanned Array; the number of transceiver elements is of the order of one thousand).

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[52] Usually, three configurations are available, i.e. "High PRF" (HPRF, where the measurement of the radial velocity of the target is not ambiguous), "medium PRF" (MPRF, where both measures of radial velocity and distance may be ambiguous) and finally "low PRF" (LPRF, where the measurement of the distance of the target is not ambiguous).

[53] There are, or will be soon, in the service the following AESA radars: AN/APG-63 (V)2 for the F-15 C and (V)3/D (2000), AN/APG-80 for the F-16 E/F (2004), AN/APG-77 for the F-22 A (2005), AN/APG-79 for the F/A-18 E/F (2007), AN/APG-63 (V)3 for the F-15 D (2010), RBE-2 (and its active array version RBE2-AA) for the Rafale (2013), AN/APG-82 for the F-15 E (2014), Captor-E for the Eurofighter *Typhoon* (2015), AN/APG-81 for the F-35 (2016), SH121 (a radar complex including three X-band AESA radars located on the front and sides of the aircraft and L-band radars on the wing leading edges) for the stealth fighter Sukhoi PAK FA (name of the prototype, which flew for the first time in January 2010: Sukhoi T-50), Raven ES-05 for the Gripen (2017).

The industrial development of airborne multifunction radar has been due, first of all, to the major groups in the USA (mainly *Raytheon* and *Northrop Grumman*, from the know-how of the former *Hughes* and *Westinghouse*) and, then, to a few major European groups.[54] Among them, the multinational *Selex Galileo*[55] is particularly interesting from the historical viewpoint. In the United Kingdom its origins can be traced back to the "lucky inventor" Guglielmo Marconi and his *Marconi Company* (1898), which in 1946 was acquired by the *English Electric Company* (EEC), and in turn acquired (1968) by the *General Electric Company*, hence the name "GEC Marconi". EEC/GEC Marconi was probably the main radar company of the United Kingdom from W.W.II till the end of the century, also thanks to the acquisition of two important, and historical, firms, i.e. *Plessey* (1989) and *Ferranti* (early 1990s), see [Sis 98].

In 1999 the industrial giant *British Aerospace* (BAe) acquired *Marconi Electronic Systems* (MES), the defence division of the GEC, thus forming *BAe Systems*, with the remainder of the GEC becoming *Marconi plc*. The activities of the MES were then divided into *BAE Systems Submarine Solutions*, *BAE Systems Surface Ships*, *BAE Systems Insyte* and *BAE Systems Airborne* group. In May 2005 from BAE Systems Airborne group was born the firm "SELEX Sensors and Airborne Systems Limited" (subsequently, SELEX Galileo Ltd.), of the *Finmeccanica* group.

The Italian company *Galileo Avionica* SpA in turn derives from the ancient (1864) *Officine Galileo* in Florence, which, after having incorporated in 1993 the historic firm radar SMA changed its name into "Galileo Avionica" since 2000, and merged with FIAR (SMA and FIAR are treated in the following) and other Italian realities. By July 2009 the English and Italian firms began to operate as a single company under the trade name "SELEX Galileo". In January 2010 the names of the companies were adapted to the trade name, and born "SELEX Galileo Ltd." and "SELEX Galileo s.p.a.", with the disappearance, then, of the name "Galileo Avionica". At the international level Selex Galileo was a unitary commercial entity with a single management, including, in addition to the Italian firm and to the English one, another company in the United States, SELEX Galileo Inc.

SELEX Galileo SpA, presently part of SELEX ES/Finmeccanica, is active in airborne and space systems and electro-optical instrumentation, in addition to tactical unmanned and target air vehicles and flight simulators.[18]

In particular, in the 1990s Selex Galileo, initially as FIAR (see the following), took part in the development of radar for the fighter aircraft *Eurofighter Typhoon*, called CAPTOR [Moo 10]. This is a multi-mode X-band coherent radar of the third generation, designed (1997) for a range of more than 160 km on fighter aircraft and an accuracy of one milli-radian and 10 m, respectively. The active

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[54] In alphabetical order: *Cassidian*/EADS (European Aeronautic Defence and Space Company, resulting from the fusion of DASA and *Aérospatiale*), INDRA (heir of Inisel and *Ceselsa*), *Selex Galileo* (from 2013, *Selex ES*), and finally the *Thales* group (heir of *Thomson-CSF*).

[55] Selex Galileo is now a part of Selex ES, see http://www.selex-es.com/about-us/heritage/technology-150.

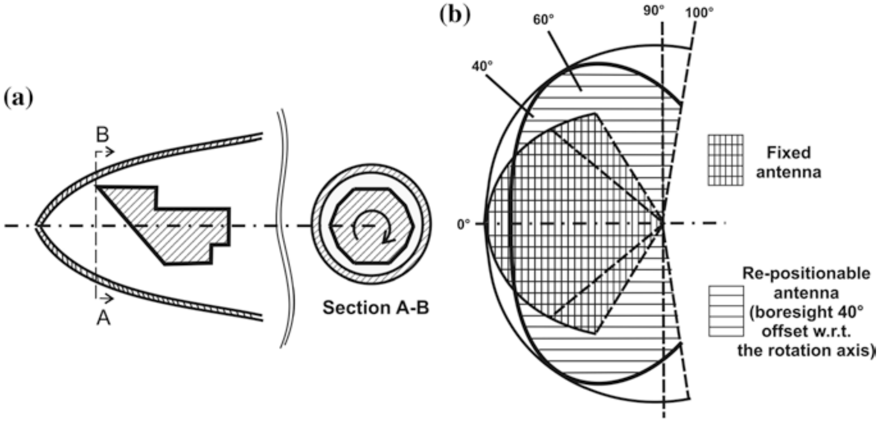

Fig. 6.38 **a** Schematic diagram of the system of *positioning* the antenna of the ES-05 Raven and of the Vixen 1000E. **b** Extension of the coverage of an AESA radar by the mechanical positioning (repositioning) of the antenna

electronically scanned array version (AESA) has been implemented as a prototype, the CAESAR (from *CAPTOR Active Electronically Scanned Array Radar*) which is presently called CAPTOR-E[56] and flew for the first time in May 2007 on the Eurofighter Development Aircraft 5 [Moo 10]. The Eurofighter and Euro Radar consortia have received renewed support from the partner countries of the program to continue the development of the AESA radar Captor-E, intended to be mounted on the Eurofighter Typhoon. In a similar manner to the APG-79 for the F/A 18 E/F and the ES-05 Raven (by Galileo Avionica, intended for the Gripen NG), the CAPTOR-E combines electronic scanning with mechanical *positioning* of the antenna, which allows extension of the angular coverage[19] from the typical 120° to about 200°, as shown in Figs. 6.38 and 6.39.

The AESA technology has been used by Galileo Avionica also in the family of multi-mode radars *Seaspray* for the surveillance of vessels by airplanes or helicopters (models 5000E, 7000E—see Fig. 6.40—and 7500E), a sort of heirs of ASV radar, as well as in the airborne multi-role radar *Vixen 500E*, see Fig. 6.41, a compact version of the Vixen 1000E. The Vixen 1000 operates in the X band, scans within ±100° and its mass is 215 kg. Has several operating modes: search and tracking air-to-air, air combat, search and tracking air-surface, weather radar, Ground Moving Target Indication and Tracking, Spotlight & Strip map Synthetic

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[56] The development of the CAPTOR has benefited from the previous research programs AMSAR (Airborne Multirole Solid-state Active array Radar) and CECAR (Captor E-scan Risk-reduction), as well as funds allocated privately from the United Kingdom for a technology demonstrator based on Raven ES-05 of Selex Galileo, chosen for the Gripen NG, to be tried on the Typhoon.

Fig. 6.39 The CAPTOR-E antenna on the Typhoon, with the repositioner shown

Fig. 6.40 The Seaspray 7000E

Fig. 6.41 The Vixen 500E (courtesy Selex-ES Edinburgh, R.W. Lyon)

Aperture Radar, Inverse Synthetic Aperture Radar Imaging, Air to Surface Ranging.

The AESA technology is now also available in the eastern world: China has developed, with likely sales to Pakistan, the updated version of their fighter J-10. This is the Chengdu J-10B, equipped with an Infrared Search and Track (IRST) and a multifunctional radar of the AESA type. The same equipment characterises the new *stealth* aircraft J-20 and J-31 (similar to the F-35 JSF).

Chapter 7
The Italian Radar Industry in the Post-war Period

In previous chapters it has been shown that the industrial developments related to radar had some noticeable extent in Italy before September 8th, 1943 but were blocked for months after the Armistice. During W.W. II small quantities of radar equipment (not more than some tens of sets) were produced [Cas 87] by some factories, mainly located in northern Italy, such as *SAFAR*, *FIVRE*, *Magneti Marelli*, *Allocchio Bacchini*, *San Giorgio* and, last but not least, the oldest one: *Galileo*. This wartime production of radars in Italy was numerically negligible when compared with the many thousands of sets manufactured by German and Anglo-American firms.

However, after these limited activities and in the post-war reconstruction, Italy developed technologically advanced industries with a significant radar scope, such as *Magneti Marelli*[1] which produced navigation (marine) radars and FIAR—*Fabbrica Italiana Apparecchi Radio* (Italian Factory of Radio Sets), see [Fio 01] and [Tel 12]. FIAR was established on July 31st, 1941 by C.G.E. (*Compagnia Generale di Elettricità*)[2] for licensed production of Telefunken's military radio transceiver sets. In 1943, FIAR remained related to C.G.E. and had two factories, in Milan and in Stockholm; in the post-war period the firm started an industrial conversion into the civil sector and in particular in television. In 1953 FIAR resumed military production with a licensed construction of the fire control radar

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[1] This firm was founded in 1891 by Ercole Marelli as "*Società Anonima Ercole Marelli*" for the production of electrical motors and other electrical equipment, and in 1919 changed its name into *Magneti Marelli*, see http://www.magnetimarelli.com/it/azienda/la-nostra-storia/1950-1970#0, http://www.magnetimarelli.com/sites/default/files/STORIA_MM_1919-2010_1.pdf.

[2] The C.G.E. was established in Milan in 1921, as the Italian branch of the American *General Electric Company*, aimed to construction of electric machines of various types (motors, alternators and transformers). In 1941 C.G.E bought the company FAR (*Fabbrica Apparecchi Radio*) and established FIAR. In 2003 FIAR S.p.A. was bought by Galileo Avionica (now Selex ES, Finmeccanica Group), and the brand FIAR was no longer used.

G. Galati, *100 Years of Radar*, DOI 10.1007/978-3-319-00584-3_7

AA3 Mk. 7.[3] FIAR was taken over by C.G.E. in 1967, and became its Electronics Department, with factories in Milan and in Baranzate.[4] In the same period two major programs started: the modernization of the *Hawk* missile system (on Raytheon license) and the design/production of the radar of the well-known fighter aircraft F-104 S (see the previous chapter) in cooperation with the American Rockwell (*Setter* radar).[1] The *Hawk* program, which lasted until 1978, was the largest production order for the company, and the four FIAR plants employed a workforce of 1700 people; in that program FIAR was engaged on continuous wave acquisition radar and on the target illuminator. In 1977, after a period of crisis, a recovery program started with production on three plants only (Via G.B. Grassi and Via Montefeltro in Milan, and Via Milano in Baranzate) and with three lines: airborne radar, Precision Approach Radar and electro/optical equipment, to which space activities were added later. During that period there was also a licensed production for the radar for the multi-role plane "Tornado" (also called *Multi Role Combat Aircraft*, MRCA) in the frame of a consortium made up by Ferranti, Marconi, Siemens, ASTER and FIAR. In the 1980s FIAR started also to produce the radar *Pointer* for the AMX airplane and started collaborations with *Bendix* for the *RDR 1400* and *RDR 1500* and its release *RDR 1500B*.[2] In 1980 the investment trust company *Setemer* (*Società elettrotelefonica meridionale*, Ericsson group) bought FIAR. In 1982–83 FIAR had a re-organization phase to allow an autonomous design ability in the radar field. In 1984–85 the consortium ELIRADAR with SMA was established for the design of the radar MM/APS-784[3] on board the antisubmarine version of the helicopter EH-101 for the Italian Navy. In the following years FIAR designed and built the coherent, pulse-Doppler radar CRESO[5] for the helicopter AB-412.[4] In those years the first studies started on the radar for the EFA (European Fighter Aircraft) and for the *Grifo* radar. In the 1990s FIAR participated in large-scale projects: the *CAPTOR* Radar in the EuroRADAR consortium (with Ferranti, Indra, AEG TELEFUNKEN) and the Grifo in the foreign versions Grifo-F, Grifo-L, Grifo-M (for Mirage) and the small Grifo-7 for the Chinese F7. In the early 1990s the transfer of FIAR to Finmeccanica took place, and at the beginning of 2000, Officine Galileo, FIAR, Meteor, and other companies, merged to create the *Galileo Avionica* company, which from 2008 operated with the name

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[3] http://www.duxfordradiosociety.org/restoration/equip/aa3mk7/aa3mk7.html. Committed "Off Shore" in the framework of the Marshall Plan, on February 11th, 1954 FIAR delivered the first two sets of the anti-aircraft radar AA3 Mk. 7 (with antennas developed by the firms *Galileo* in Florence and *Officine Meccaniche Olivetti* in Ivrea) for the US army, as reported in No. 8, May 1954, issue of the magazine ***Radio Industrie***, pp. 45 and 47.

[4] Since 1969 the name FIAR survived as "Division of Professional Electronics" of C.G.E. During the 1970s, FIAR suffered a company crisis and 400 workers were laid off temporarily.

[5] The technical data of the CRESO system are still classified, but the maximum range was claimed up to 150–200 km on small air targets.

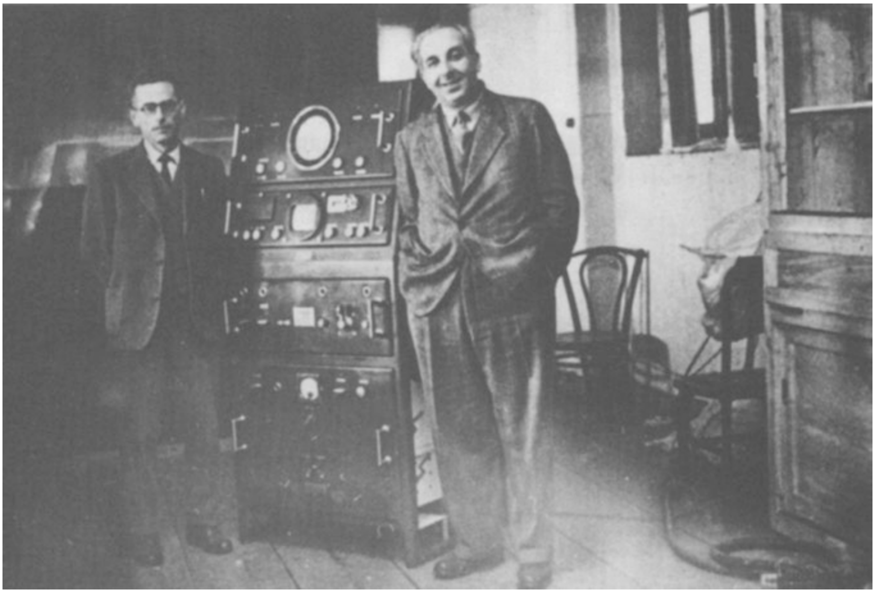

Fig. 7.1 Selex Galileo (SMA): CFL 3-C25, the first radar developed in Italy (Nello Carrara and Lorenzo Fernández, 1949–1950)

Selex Galileo, and in January 2010, joining with *Selex Sensors and Airborne Systems Ltd*., became SELEX Galileo (presently, SELEX-ES).[6]

In the post-war period, the former national company, carrying out an autonomous radar design and development, was the Florentine SMA—*Segnalamento Marittimo ed Aereo SpA* (Air and Sea Signalling Company), founded on August 2nd, 1943 in Florence by Enrico Bocci, Lorenzo Fernandez and Giuseppe Salvini in order to produce mechanical and optical signalling equipment based on French know-how. In 1949 SMA developed and produced the first Italian post-war radar, the CFL-3, a fire control radar operating in the X-band, designed by Nello Carrara, Lorenzo Fernandez and Pietro Lombardini (hence the acronym CFL; see Figs. 7.1, 7.2 and 7.3).

In 1950 SMA signed a contract with the Italian Navy to supply ten X-band navigation radars, called *3N-10* (Italian Navy name: *NMS 8*, Fig. 7.4) which were delivered in 1952. Developments followed for many military radars (see Fig. 7.5),

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[6] On November 2014 in Edinburgh, Eurofighter signed a €1 billion contract with the Nato Eurofighter and Tornado Management Agency (NETMA) to develop the Captor E-Scan airborne radar. Signed on behalf of the UK, Germany, Spain and Italy, the contract is aimed at integration of the Captor E-Scan radar as the primary sensor on the Eurofighter Typhoon multi-role fighter with a suite of Air-to-Air and Air-to-Surface modes. The large sized radar antenna had a 200° field of regard obtained with the electronic scan plus a mechanical *repositioner* (see the previous chapter).

Fig. 7.2 Selex Galileo (SMA): Antenna Group of the CFL-3 radar, 1950s

mainly navigation radar and air search radar for national naval units. In the 1960s SMA set-up the plant that will be used for more than a quarter of a century, at the beautiful Villa San Martino in Soffiano, above Florence, later enlarged even with the considerable difficulty due to the landscape-environmental constraints. In 1975 the development started of the APS-705 radar for helicopters. This set remained in service (with different upgrades) for over 20 years. The development of search naval radar of the 700 Series, including the SPS-701 on the *Nibbio* hydrofoil, and the SPS-702 (Fig. 7.6) on the ASW frigates *Maestrale* class began in 1976.

In the 1980s the SMA sought diversification in the civil area: the company acquired the Navigation Radar division of Selenia, thus setting up the Selesmar[7]

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[7] In 1960 *Selenia Marine* was established as a part of *Selenia* (see later) for the production in Fusaro (Naples) of maritime navigation radars under license of the USA group *Raytheon*. In 1970 Selenia Marine was separated from Raytheon and started to produce radars with its own brand. In 1980, the company SMA (Florence) acquired Selenia Marine with the name *Selesmar* (from Selenia-SMA-Radar; a few years later the name was changed into *Selesmar Italia*) and transfered the operational activities in Montagnana Val di Pesa, town of Montespertoli (near Florence). The new company was called *Selesmar Italy*. In 1995, the Sweden *Consilium* Group acquired Selesmar Italy from the Italian EFIM group. The new company was called *Consilium Selesmar*. On November 2013 *Navico Holding AS* (Norway), a parent company to the *Simrad* brand, and *Consilium AB* announced that Navico has agreed with Consilium to acquire Consilium's radar business, including research, design and development and, of course, the plant in Montagnana Val di Pesa, whose name is now *Navico RBU* (Radar Business Unit) s.r.l.. The other design and development site of Navico (mainly active in small CW marine radar) is in Oakland, New Zealand, i.e. at an opposite point of the Earth!

Rassegna delle
INDUSTRIE MARINARE
ed ausiliarie. Cantieri. Porti. Navi.

RADAR NAUTICO «SMA»
TIPO CFL 3 PN

LUNGHEZZA D'ONDA 3 cm.
POTENZA ANTENNA 30 KW
PORTATA MINIMA 40 m
PORTATA MASSIMA 25 mgl
INDICATORE PANORAMICO 25 cm.
4 SCALE: 1-3-10-30 mgl
QUADRANTE GRADUATO E LINEA DI FEDE
N°. 4 MARCHE FISSE E MARCA MOBILE
NUMERATORE DISTANZIOMETRICO TARATO IN MIGLIA NAUTICHE
INDICATORE RIPETITORE
ASSERVIMENTO ALLA GIROBUSSOLA
ALIMENTAZIONE 115V~ - 60 Hz.
TUTTI I COMANDI ACCENTRATI NELL'INDICATORE PRINCIPALE

«SMA» SEGNALAMENTO MARITTIMO ED AEREO
VIA RICASOLI 26 - FIRENZE

PUBBLICAZIONE TECNICA MENSILE

ANNO II - LUGLIO AGOSTO

7 8

Fig. 7.3 Selex Galileo (SMA): radar display CFL-3 PN

participation in the unfortunate [*Società Consortile*] T.I.M (Tecno-Idro-Meteo) for radar—meteorology, land management and the environment, and in 1987 began the equally unfortunate partnership with Fiat for automotive radar (Fig. 7.7). In parallel, SMA developed successful airborne equipment such as the SCP-01 (*Scipio*)

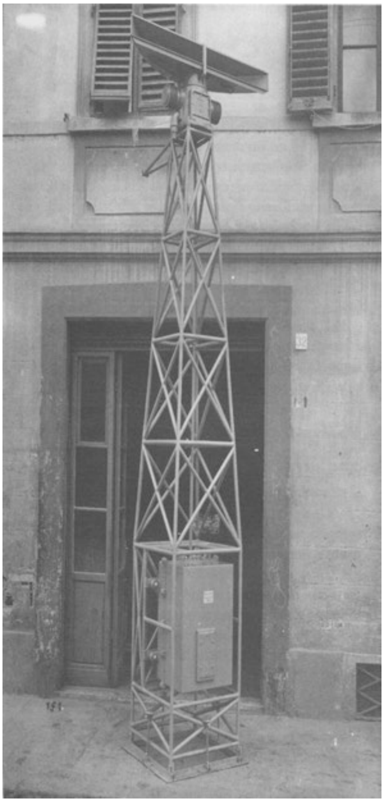

Fig. 7.4 Selex Galileo (SMA), 1950s: the naval radar 3N-10 (X-band) in an unusual urban environment. The acronym indicates: 3 cm wavelength, navigation, 10 inches display

radar for the AMX aircraft—Brazil (Fig. 7.8), and the APS 717. There were also special radar embodiments such as those for the armoured vehicle Otomatic (by OTO Melara, based on a 76 mm gun, Fig. 7.9), and for submarines (Fig. 7.10).

In 1988 EFIM[8] acquired up to 98 % of the SMA shares. At the beginning of the 1990s SMA developed the C-Band GPM 500, the first Italian polarimetric Doppler weather radar. In January 1993 (50 years from the establishment of SMA) the EFIM closeout officer rented the SMA activities to Finmeccanica. In 1994 the former-SMA activities were held by the Finmeccanica's Company *Galileo* (Campi Bisenzio, Florence), and in 1995, the acronym SMA changed its meaning into

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[8] *EFIM* stands for *Ente partecipazioni e finanziamento industrie manifatturiere*, i.e. Administration for participating and financing manufacturing industries. It was established in 1962 as a continuation of the FIM (*Finanziaria industrie meccaniche*), the Italian State holding company established in 1947 to finance the conversion of Italian industries (such as FIAT, Breda and Olivetti) from the war activities to the civil sector. Through his "Finanziaria Ernesto Breda", EFIM owned some significant defence industries, including: *Oto Melara* (La Spezia), *Officine Galileo* (Firenze), SMA-*Segnalamento marittimo ed aereo* (Firenze). Due to the very bad financial situation of EFIM in the 1980s, on 1992 the Italian government decided to put EFIM under closeout, and to transfer to Finmeccanica its defence activities. A few days before was passed away Dr. Ing. Gustavo Stefanini, the "father" of the company OTO Melara [Mar 10].

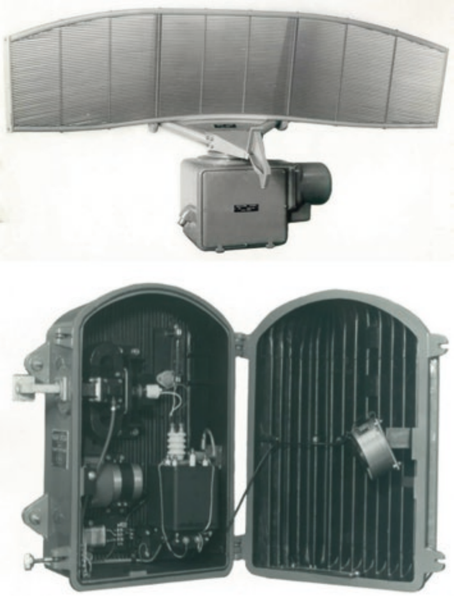

Fig. 7.5 Selex Galileo (SMA), 1960s: antenna assembly and transceiver of the SPQ-2A radar

Fig. 7.6 Selex Galileo (SMA), 1970s: surface search radar SPS-702

[*Sistemi per la Meteorologia e l'Ambiente* (Systems for meteorology and the environment). In 2001 they closed the history of SMA, the oldest Italian radar company, an industry that had operated continuously since the Second World War and for over half a century. However the know-how from SMA, very relevant in the area of "small" radars on a mobile platform, in particular for sea and air applications, was not completely lost, being transferred to the company *Galileo Avionica*, subsequently *Selex Galileo*, *Selex Sistemi Integrati* and *Selex-ES*. Farther in the past, the SMA was culturally the daughter of the "Tuscan" *microwave and radar*

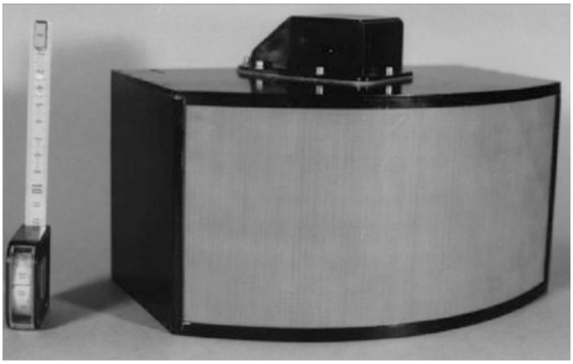

Fig. 7.7 Selex Galileo (SMA), 1980s: prototype of automotive radar developed in cooperation with *Centro Ricerche FIAT*

Fig. 7.8 Selex Galileo (SMA), 1980s: multimode airborne radar SCP-01 developed in cooperation with the Brazilian Air Force

Fig. 7.9 Selex Galileo (SMA), 1980s: radars in S-band (search) and in K_a band (fire control) for the Otomatic tank

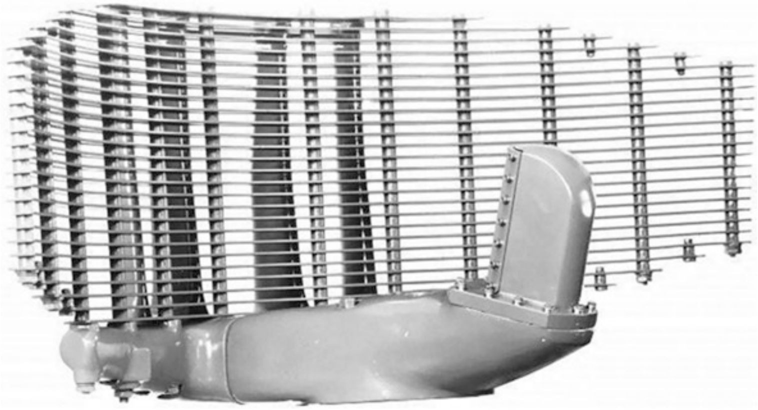

Fig. 7.10 Selex Galileo (SMA), 1980s: Antenna Group of the BPS-704 radar for submarines

school represented by Nello Carrara (who was president of the company) and Ugo Tiberio, side by side with the school of Barzilai and Latmiral which were mainly active in the Central Italy (Rome and Naples areas).

After W.W. II, the list of significant members of this latter "*Roman—Neapolitan school*" included, above all, Dr. Ing. Francesco Musto[9] as well as prof. Giovanni Picardi.[10] In fact, a few years after the war, and independently of the war-time

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[9] Francesco Musto, born in Cerignola (FG, Italy) on 25 April 1928, received the dr. engineering degree at the University of Rome followed by ta post-graduate special diploma in radar technologies, after a two years course by the National Research Council and the Ministry of Defence. At the time of the merger originating Selenia, he was head of the Radar systems in Microlambda where he had designed different radar sets, including the MLV-4 for the infantry, with a transmitted signal in continuous wave, phase-modulated with a pseudorandom binary phase code, and a "matched filter" in reception, permitting the unambiguous measurement of the distance with a 50 m resolution. In spring, 1960 he went to the Selenia plant in Via Tiburtina, Rome, seat of the design activities; he headed the Surveillance Radar department, then the whole Radar design directorate, and later, the Radar Division. In 1975–1990 he headed the Education and Training Division, which produced top-level and international activities.

[10] Giovanni Picardi, born in Sarnano (MC, Italy) on December 16th, 1936, graduated in electrical engineering at the University of Rome in 1960. In 1961 he joined Selenia SpA (now Selex ES) working on radar signal processing and telecommunication subsystems. Picardi led the Signal Processing laboratory of Selenia managing, *inter alia*, the transition from analog to digital techniques. In 1970 he began teaching Cybernetics and information theory at the University of Perugia. In 1975 he joined the University of Bari as a Full Professor of Communications. Since 1978 he has been full professor of "Radar and Remote Sensing Systems" in the "Sapienza" University of Rome where he was in charge of space-based radars, namely Synthetic Aperture Radar (SAR) and Radar Altimeter, for the "*sounding*" of celestial bodies. He is, since 2011, Professor Emeritus at the Sapienza University of Rome. With the European Space Agency (ESA) and the Italian Space Agency (ASI), he has been a member of the Science Teams for Rosetta Comet Nucleus Sample Return, Cassini Radar, SHARAD and other Deep Space missions. He is Principal Investigator of the ESA MARSIS—Mars Express experiment, being responsible for the radar inversion processing with the aim to estimate the subsurface bedrock dielectric constant and, possibly, the presence of liquid water in the martian crust.

situation, the largest Italian radar industries (initially, producing under license) were established in the centre-south of the peninsula, based on the international context of those years. Throughout Europe, in fact, a tremendous boost to the establishment of new radar and electronic industries and to the acquisition of the related know-how derived, as already stated, by licensed production of American radars. One of them was the AN/TPS 1-A by Raytheon, a wartime mobile surveillance radar for the U.S. Army.[11] At the end of the war, a significant number of radars of the AN/TPS 1 series was handed over to allied countries for surveillance of airspace and for air traffic control. They were L band (about 23 cm wavelength) "primary" radar sets composed of units to be installed in the field, in a stack with a 4 m antenna at the top. Using this system, entire generations of air traffic controllers in many countries of the world migrated progressively from the "procedural" air traffic control mode to the "radar control" mode. A later version, the AN/TPS-1D,[5] produced in thousands of sets in Europe for the NATO forces, was the test bench for the European emerging radar companies.

In Italy [Mus 90], [Ray 62] about 400 sets of the TPS-1D and 1-E radar were produced by the company *Microlambda*[12]—Society for Studies and Applications of Electronics—originated from the work of Carlo Calosi[13] [Mar 09], a scholar and an industry man of top international level, a pioneer of the radar industry in the USA and in Italy. Calosi acted as a bridge between the *Tuscany radar school* and the *Centre-southern* one allowing a great radar development in Italy from the 1950s to the 1970s. At his side there was a younger, equally noticeable person: Franco Bardelli,[14] [Mar 09], [Fov 12], who has been a very respected general

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[11] The Americans, who initially used for air surveillance the British transportable radar "LW" operating in the 200 MHz frequency band, and then rebuilt it with the name SCR-602, finally decided for an autonomous radar development in the L band (about 1.25 GHz). The resulting AN/TPS-1 radar was relatively light and transportable (could be divided into ten parts for transport). At its former, wartime model TPS-1B, in the mid 1940s Raytheon added an MTI (Moving Target Indicator) kit, thus creating the TPS-1C and, with further improvements, the TPS-1D and 1E. Over 1500 TPS-1 sets were produced by Raytheon.

[12] At that time Raytheon had a strong interest in Microlambda, which remained as high as 40 % of shares when Microlambda and Sindel merged in the new firm Selenia.

[13] Carlo Calosi (Intra, now Verbania, Verbano-Cusio-Ossola, Italy, September 25th, 1905–Rome, June 12th, 1997) graduated with honours at the University of Genoa in 1927; worked at the *Regio Silurificio* in Fusaro (Naples) and was the inventor of the "magnetic detonator system" for torpedoes, patented as SIC—*Siluro Italiano Calosi*. In the winter of 1944 he ran away from the central Italy occupied by the Germans; drawn into military service (naval weapons) by the Badoglio's government based in Brindisi, Calosi was sent on a special mission to the USA (1944–46). On 1951 Calosi was appointed "vice-president" of Raytheon, and president of its "*Microwave and Power Tube Division*", which at that time hosted the most advanced radar technologies of the firm. Finally, he was consultant of Finmeccanica.

[14] Franco Bardelli (Alessandria, October 19th, 1925–Pisa, January 21st, 2010), after receiving the degree in Industrial Engineering from the University of Pisa in 1948, approached the radar technology in the Nello Carrara's *Centro Microonde* (1948–49) and in the Naval Academy in Livorno (1950), where he cooperated with Ugo Tiberio. In 1951 he accepted the offer by Raytheon to join *Microlambda* in Naples, a company just founded by Carlo Calosi, where in the same year they signed the contract for the construction of 250 sets of the TPS 1 D. In 1956 Franco Bardelli contributed to the birth of the *Studio Tecnico di Consulenza*—STC in Roma (then, Sindel company),

manager of the hi-tech Italian radar and microwave industry. The birth of Microlambda is remembered by Ing. Bardelli in his text related to Calosi: "…*we had together the great opportunity to create from scratch the first company in 1951, in a cellar in Roma,* Via *Ferdinando di Savoia, near Piazza del Popolo… I knew him when I was just graduated and he called me because he wanted to create in our Country a working group with the help of Finmeccanica, the basic national reality for this sector. Calosi brought to Italy a significant contract for the production of 300 large radars. Finmeccanica and Raytheon created Microlambda and put him at the head. From the cellar, later, we moved to Naples* ***in an old factory of torpedoes****…*". This is the well-known *Fusaro* plant, still operating today.[6] Calosi built up the agreement between Raytheon and the *Finmeccanica* holding (established in 1948 from the IRI—*Istituto per la Ricostruzione Industriale*—group) that led to the foundation of Microlambda, established on April 16th, 1951. Microlambda built (under a Raytheon license) a batch of 250 TPS 1D radars in three years (to which more 50 were added). The first set, fully realized in the Microlambda plant in Fusaro, (see Fig. 7.11), was delivered in 1953, before the contractual terms. The TPS-1D resulted in a successful radar, used for Air Traffic Control in many parts of the world; from it, Selenia designed and produced, for the U.S. Marine Corps, the version ***TPS-1E***, a transportable, medium range, L band (1220–1350 MHz) radar for air search and target acquisition with both a normal channel and a range-gated MTI channel for detecting moving targets in areas with strong ground echoes, or *clutter*. It was a NATO standard radar used in many countries, either with the ML E antenna or, as *Selenia Modification Kit*, with the ML G7 antenna, see Figs. 7.12, 7.13 and 7.14.

So, Microlambda was born thanks to a leading major contract of licensed production of Raytheon radars, intended for the "marines". Microlambda produced several hundred sets of this radar in a few years and also improved some of its characteristics and performance.[15] In particular the antenna had different improvements till the replacement of the original antenna with a much larger antenna of Microlambda design called ML *G7* and built in the Fusaro plant. Microlambda

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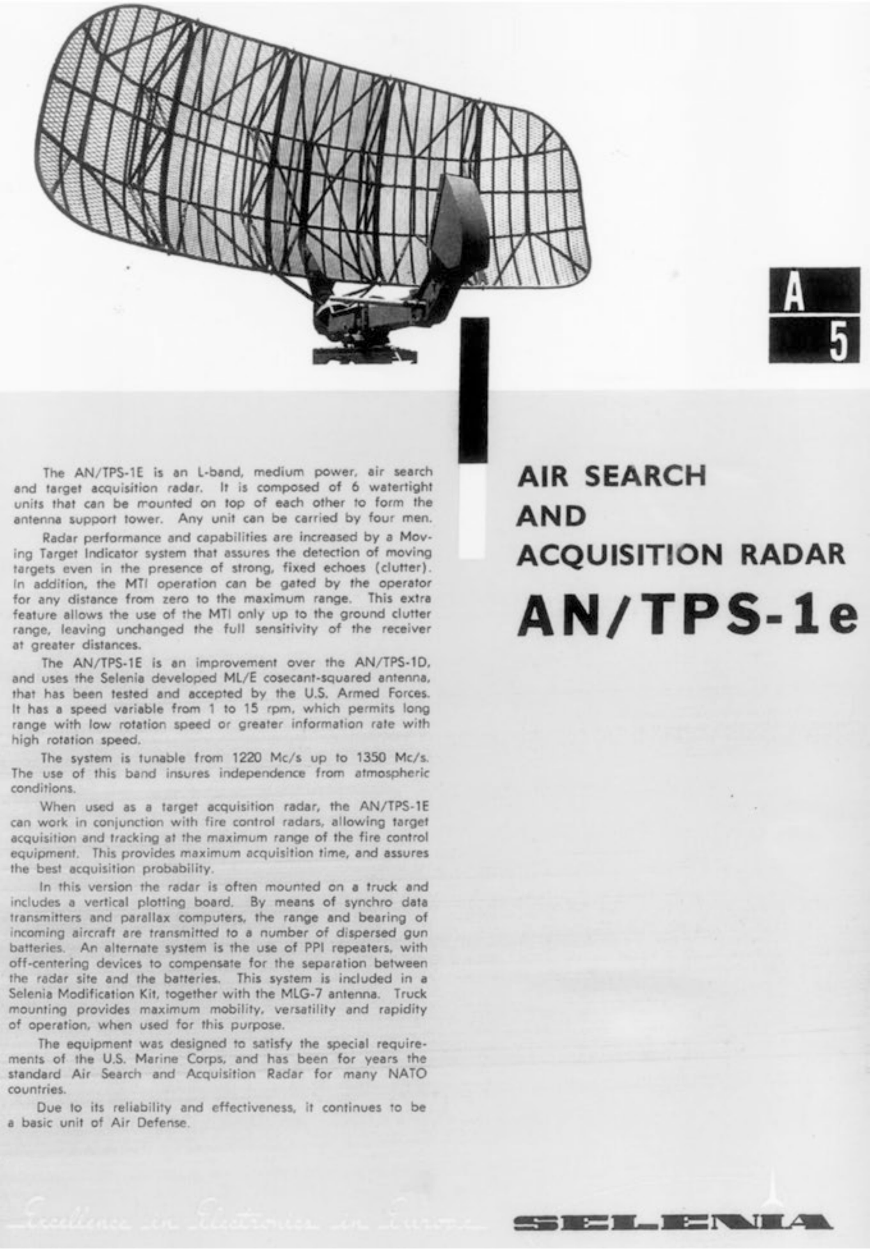
Footnote 14 (continued)
where the first fire control radar of the Orion series (X band, 250 kW) was designed. In 1960 he contributed to the birth of Selenia (merge of Sindel with Microlambda, with Carlo Calosi CEO and Franco Bardelli technical director). Finally in 1980 Bardelli founded the IDS—*Ingegneria dei Sistemi* s.p.a., now an international group with over 450 employees.

[15] Microlambda's engineers [Ray 62] designed new antennas, a high gain "cosecant square" antenna used in the TPS-1E, and two much larger (14 m) antennas, one of them being of the "modified cosecant square" type, i.e. with an extra-gain at high elevation (above 15°) in order to improve the visibility of high and nearby aircraft in the presence of "ground clutter". Moreover, in addition to the antenna, the Microlambda—then, Selenia—engineers improved the original Raytheon TPS-1D radar by adding a pre-selector filter, a parametric amplifier and a kit for range-gating between "Normal" and MTI video. On the other hand, other radars were derived in the USA form the TPS-1D: among them, the FPS-19 (of which seventy sets were produced for the Distant Early Warning line), with components and circuitry largely derived from the TPS.

Fig. 7.11 Delivery of the last TPS 1D in the *Fusaro* plant; from *left* to *right*, standing: an engineer from Raytheon, Corbò, Cassia, Isidori, Calosi, Bardelli

also produced from scratch radars for civil applications, in particular for the navigation of medium-large ships, initially on Raytheon license (in one case, as director of Microlambda, Calosi had to stop the production of navigation radars for the Italian Navy to accommodate the production of the TPS 1D).

But, very soon, the far-sightedness of professor Calosi aimed to a much more ambitious scope, which a very few people in Italy and in Europe could pursue in similar conditions: to create in Italy a completely autonomous capability of radar design and production, in a worldwide competition with Raytheon; and, as a result, to develop similar capacity in other fields and application domains exploiting the so many enabling technologies coming from the radar itself. In 1954, after the "happy end" of the US Navy contract and of the related tremendous effort, different opinions came out. Calosi and Bardelli intended to design and develop new equipment (there were contacts with *Contraves*, of the Swiss group *Oerlikon Bürle*) but the Finmeccanica strategies were different. This mismatching very soon pushed Calosi to come back to the USA, at Raytheon. In this frame, Franco Bardelli—encouraged from the other side of the Atlantic by Calosi—founded with its colleague Roberto Corbò, in April, 1956, the *Studio Tecnico di Consulenza* (STC) in via Tomassetti near via Nomentana in Rome, to which other "drop-outs" of Microlambda soon joined, disgruntled by the behaviour of the management and the poor attention of Microlambda to the innovation; among them (in STC by



A
5

AIR SEARCH
AND
ACQUISITION RADAR
AN/TPS-1e

The AN/TPS-1E is an L-band, medium power, air search and target acquisition radar. It is composed of 6 watertight units that can be mounted on top of each other to form the antenna support tower. Any unit can be carried by four men.

Radar performance and capabilities are increased by a Moving Target Indicator system that assures the detection of moving targets even in the presence of strong, fixed echoes (clutter). In addition, the MTI operation can be gated by the operator for any distance from zero to the maximum range. This extra feature allows the use of the MTI only up to the ground clutter range, leaving unchanged the full sensitivity of the receiver at greater distances.

The AN/TPS-1E is an improvement over the AN/TPS-1D, and uses the Selenia developed ML/E cosecant-squared antenna, that has been tested and accepted by the U.S. Armed Forces. It has a speed variable from 1 to 15 rpm, which permits long range with low rotation speed or greater information rate with high rotation speed.

The system is tunable from 1220 Mc/s up to 1350 Mc/s. The use of this band insures independence from atmospheric conditions.

When used as a target acquisition radar, the AN/TPS-1E can work in conjunction with fire control radars, allowing target acquisition and tracking at the maximum range of the fire control equipment. This provides maximum acquisition time, and assures the best acquisition probability.

In this version the radar is often mounted on a truck and includes a vertical plotting board. By means of synchro data transmitters and parallax computers, the range and bearing of incoming aircraft are transmitted to a number of dispersed gun batteries. An alternate system is the use of PPI repeaters, with off-centering devices to compensate for the separation between the radar site and the batteries. This system is included in a Selenia Modification Kit, together with the MLG-7 antenna. Truck mounting provides maximum mobility, versatility and rapidity of operation, when used for this purpose.

The equipment was designed to satisfy the special requirements of the U.S. Marine Corps, and has been for years the standard Air Search and Acquisition Radar for many NATO countries.

Due to its reliability and effectiveness, it continues to be a basic unit of Air Defense.

Excellence in Electronics in Europe

SELENIA

Fig. 7.12 General description of the TPS 1 E

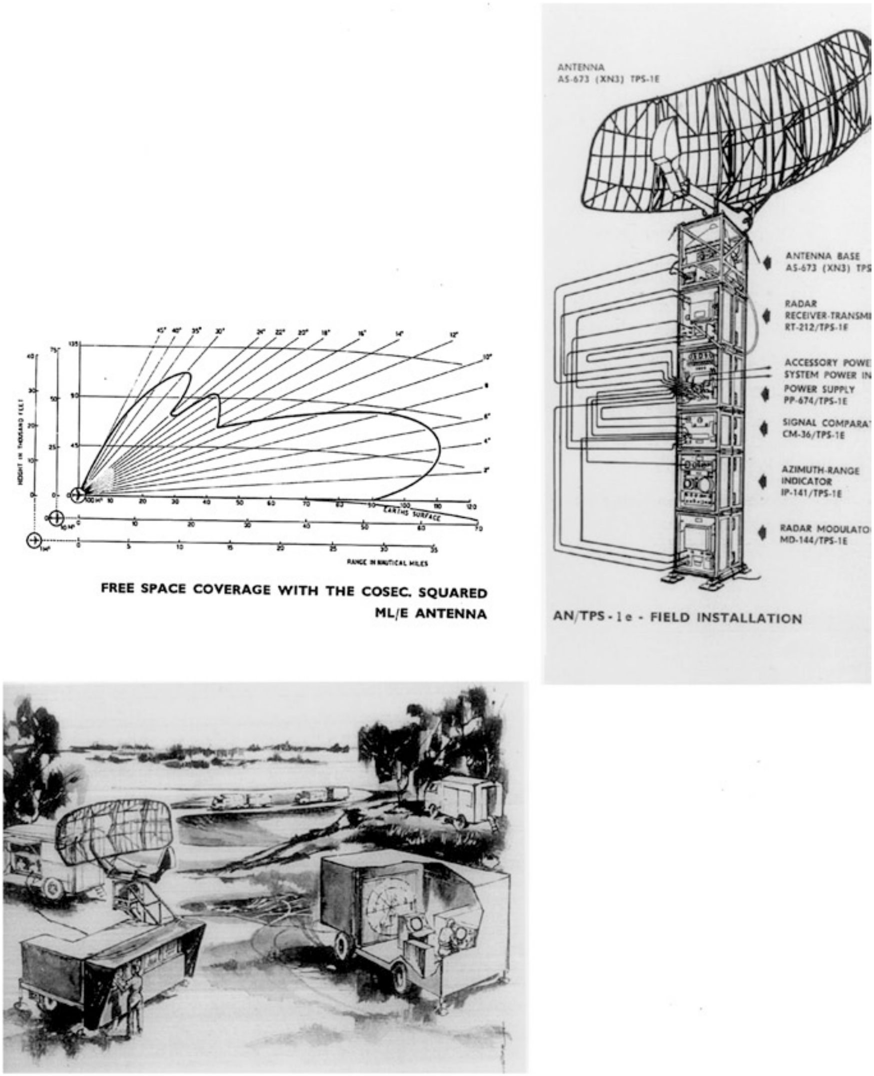


Fig. 7.13 Installation and coverage diagram of the TPS 1 E

August 1956) was Dr. Antonio Teofilatto.[16] Very soon, in May 1956, the STC contacted the *Edison* company which had much capital to invest because of the nationalization of the electric power system by the Italian government. Edison

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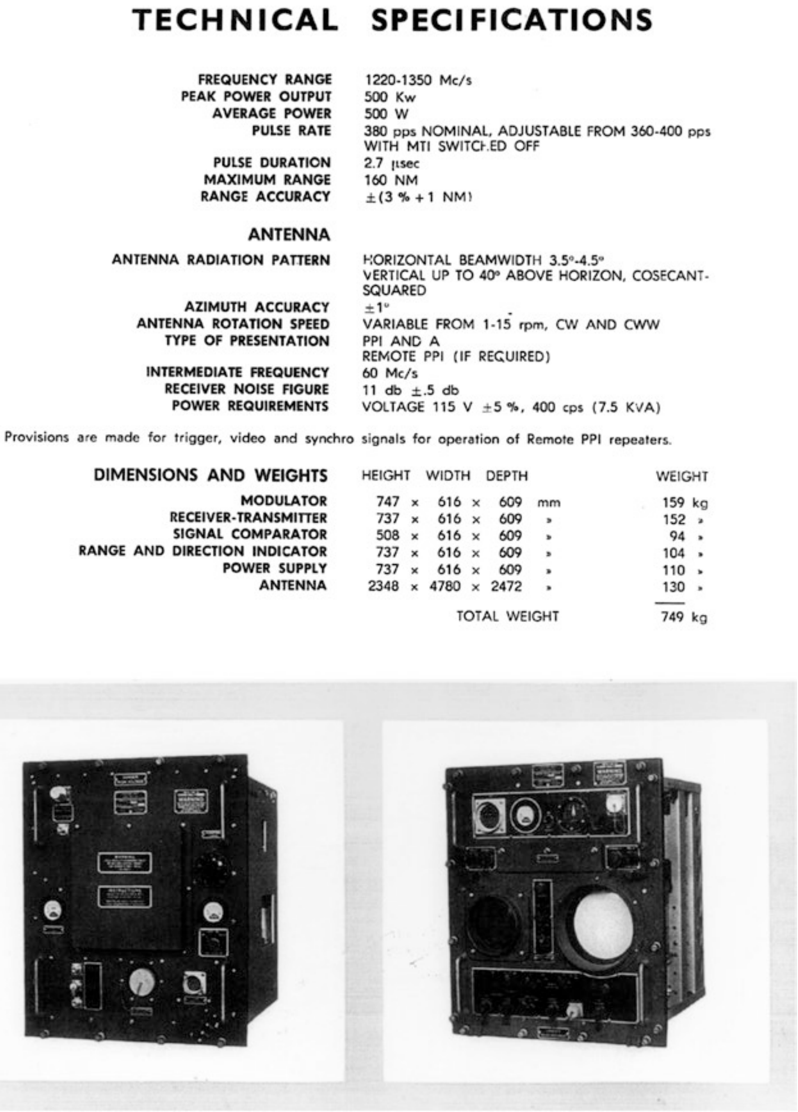
[16] Born in Rome on February 23rd, 1927, Antonio Teofilatto was electronic and aerospace designer in Sindel and then in Selenia where, by mid-1960s, worked on space systems technologies in the frame of the Satellite Test Vehicle (STV) for the European Launcher Development Organisation, ELDO. Then he was responsible for the SIRIO (*Satellite Italiano di Ricerca Industriale ed Operativa*) project.



TECHNICAL SPECIFICATIONS

FREQUENCY RANGE	1220-1350 Mc/s
PEAK POWER OUTPUT	500 Kw
AVERAGE POWER	500 W
PULSE RATE	380 pps NOMINAL, ADJUSTABLE FROM 360-400 pps WITH MTI SWITCHED OFF
PULSE DURATION	2.7 μsec
MAXIMUM RANGE	160 NM
RANGE ACCURACY	±(3 % + 1 NM)

ANTENNA

ANTENNA RADIATION PATTERN	HORIZONTAL BEAMWIDTH 3.5°-4.5° VERTICAL UP TO 40° ABOVE HORIZON, COSECANT-SQUARED
AZIMUTH ACCURACY	±1°
ANTENNA ROTATION SPEED	VARIABLE FROM 1-15 rpm, CW AND CWW
TYPE OF PRESENTATION	PPI AND A REMOTE PPI (IF REQUIRED)
INTERMEDIATE FREQUENCY	60 Mc/s
RECEIVER NOISE FIGURE	11 db ±.5 db
POWER REQUIREMENTS	VOLTAGE 115 V ±5 %, 400 cps (7.5 KVA)

Provisions are made for trigger, video and synchro signals for operation of Remote PPI repeaters.

DIMENSIONS AND WEIGHTS	HEIGHT		WIDTH		DEPTH		WEIGHT
MODULATOR	747	×	616	×	609	mm	159 kg
RECEIVER-TRANSMITTER	737	×	616	×	609	»	152 »
SIGNAL COMPARATOR	508	×	616	×	609	»	94 »
RANGE AND DIRECTION INDICATOR	737	×	616	×	609	»	104 »
POWER SUPPLY	737	×	616	×	609	»	110 »
ANTENNA	2348	×	4780	×	2472	»	130 »
					TOTAL WEIGHT		749 kg

Fig. 7.14 Technical data of the TPS 1 E

took over STC in September 1956, enrolling Bardelli, Corbò and more colleagues and creating the new company *Sindel*,[17] with 25 employees including 10 engineers. Bardelli designed a new, efficient fire control radar (with the internal name: *Ugo*, then called *Orion 1A*) for naval use, which he showed and proposed to

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[17] Acting as a licensee by Raytheon, *Sindel* produced weather radars (in which Raytheon had a very good reputation) and other radar sets.

Fig. 7.15 The Selenia plant in Via Tiburtina, Roma

Contraves, a manufacturer of fire control systems. In just six months the radar was produced and used by Italian Navy and Contraves. Edison built a new plant in Rome at the 12.4 km of via Tiburtina (Fig. 7.15), which became the Sindel site and, later, the roman site of Selenia. Microlambda complained about unfair competition in December 1956 and the controversy, through Finmeccanica, reached Calosi, who made a visit to Italy and came back there permanently in 1959.

A memoir of those years is due to Francesco Musto: "I had been recruited in Microlambda in November, 1956, a few months after the great "exodus" of some professional people, which also included professor Calosi; they had just founded in Rome the *Sindel*, financed by Edison. We in Microlambda—for four years, up to the fusion and the birth of Selenia—were engaged in a tough competition with the Sindel". In his long, interesting remembrance, at the pages 189–199 of [Gal 12], Ing. Musto recalls most of the radar developments and achievements of Selenia.[18] Perhaps the most significant of them is in the field of Air Traffic Control radars,[7] see Figs. 7.16, 7.17 and 7.18.

As a matter of fact, the dispute between Microlambda and Sindel did not last after the 1950s. The president and CEO of Microlambda, Leone Mustacchi, understood, with a noticeable farsightedness, the chance of an alliance with Sindel. In these years the *Hawk* NATO program just started, for which the European firms

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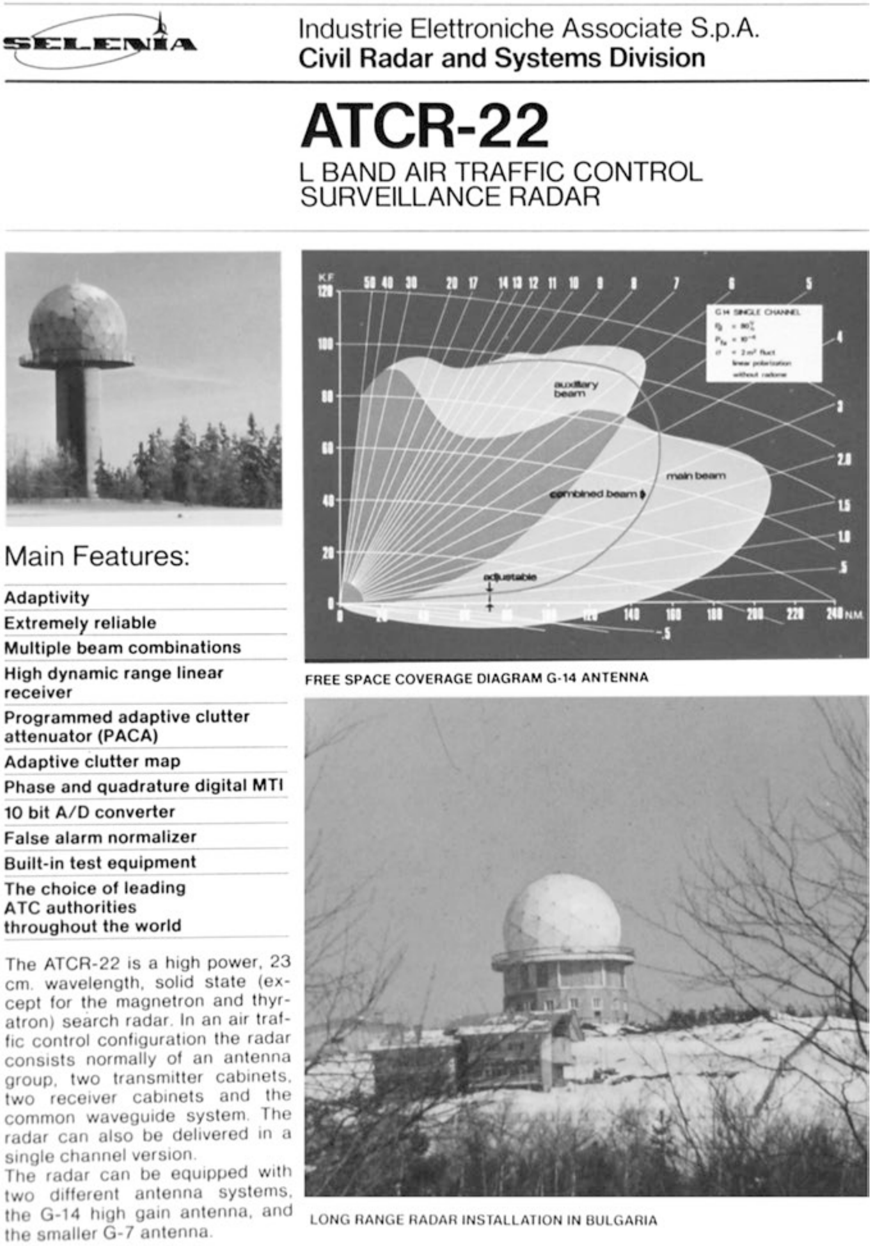
[18] For reasons of room, the whole text by Francesco Musto is not reported here, but the key elements only.



SELENIA

Industrie Elettroniche Associate S.p.A.
Civil Radar and Systems Division

ATCR-22

L BAND AIR TRAFFIC CONTROL
SURVEILLANCE RADAR

Main Features:

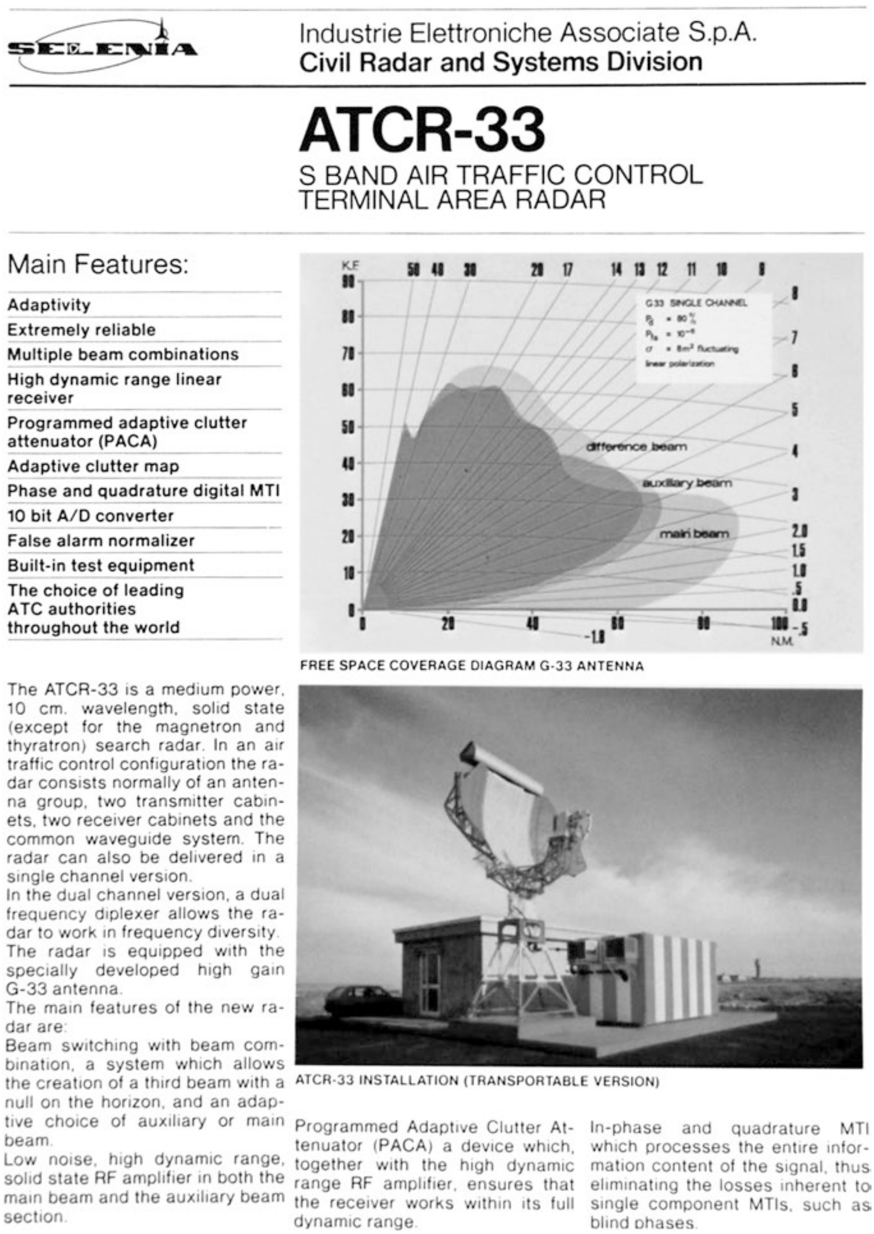
- **Adaptivity**
- **Extremely reliable**
- **Multiple beam combinations**
- **High dynamic range linear receiver**
- **Programmed adaptive clutter attenuator (PACA)**
- **Adaptive clutter map**
- **Phase and quadrature digital MTI**
- **10 bit A/D converter**
- **False alarm normalizer**
- **Built-in test equipment**
- **The choice of leading ATC authorities throughout the world**

The ATCR-22 is a high power, 23 cm. wavelength, solid state (except for the magnetron and thyratron) search radar. In an air traffic control configuration the radar consists normally of an antenna group, two transmitter cabinets, two receiver cabinets and the common waveguide system. The radar can also be delivered in a single channel version.
The radar can be equipped with two different antenna systems, the G-14 high gain antenna, and the smaller G-7 antenna.

FREE SPACE COVERAGE DIAGRAM G-14 ANTENNA

LONG RANGE RADAR INSTALLATION IN BULGARIA

Fig. 7.16 The brochure of the Selenia air traffic control radar ATCR-22



SELENIA

Industrie Elettroniche Associate S.p.A.
Civil Radar and Systems Division

ATCR-33

S BAND AIR TRAFFIC CONTROL
TERMINAL AREA RADAR

Main Features:

- **Adaptivity**
- **Extremely reliable**
- **Multiple beam combinations**
- **High dynamic range linear receiver**
- **Programmed adaptive clutter attenuator (PACA)**
- **Adaptive clutter map**
- **Phase and quadrature digital MTI**
- **10 bit A/D converter**
- **False alarm normalizer**
- **Built-in test equipment**
- **The choice of leading ATC authorities throughout the world**

FREE SPACE COVERAGE DIAGRAM G-33 ANTENNA

The ATCR-33 is a medium power, 10 cm. wavelength, solid state (except for the magnetron and thyratron) search radar. In an air traffic control configuration the radar consists normally of an antenna group, two transmitter cabinets, two receiver cabinets and the common waveguide system. The radar can also be delivered in a single channel version.

In the dual channel version, a dual frequency diplexer allows the radar to work in frequency diversity.

The radar is equipped with the specially developed high gain G-33 antenna.

The main features of the new radar are:

Beam switching with beam combination, a system which allows the creation of a third beam with a null on the horizon, and an adaptive choice of auxiliary or main beam.

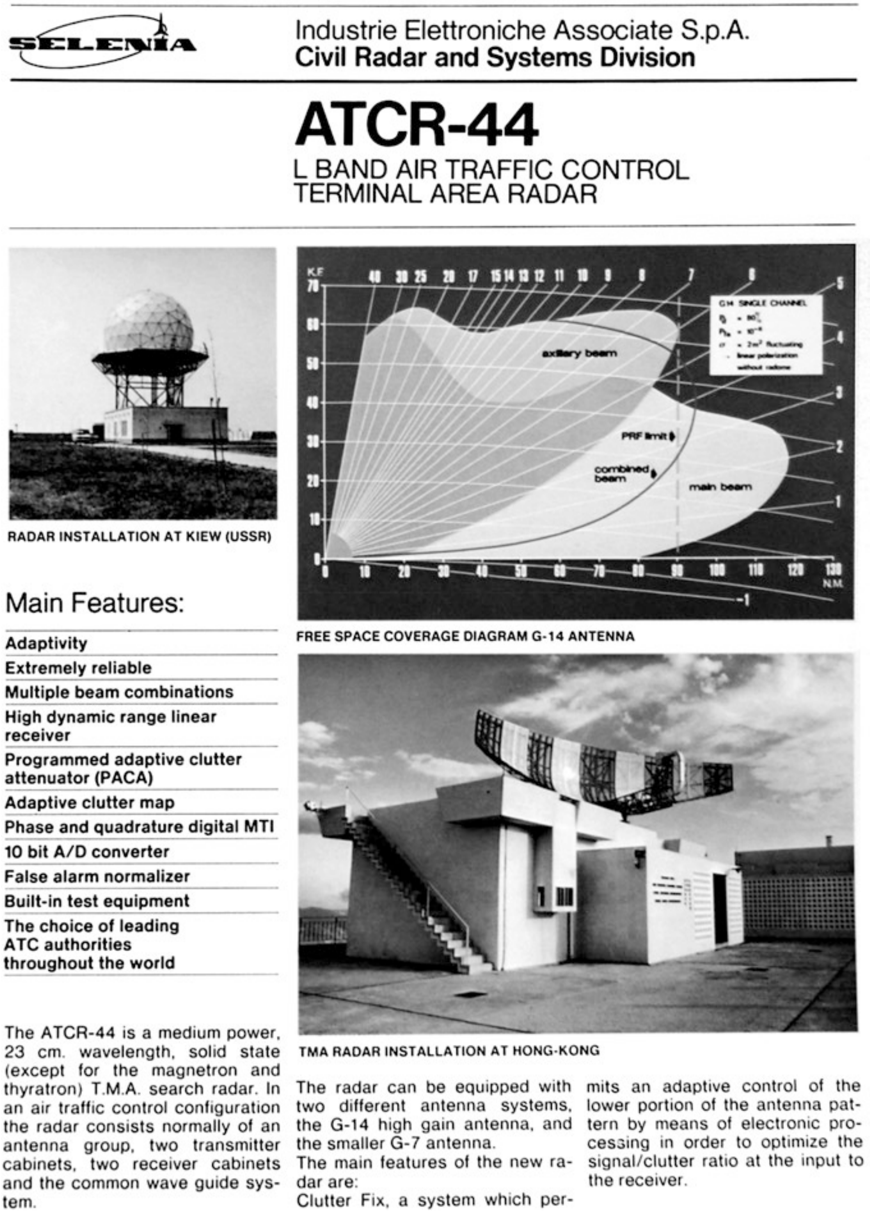
Low noise, high dynamic range, solid state RF amplifier in both the main beam and the auxiliary beam section.

ATCR-33 INSTALLATION (TRANSPORTABLE VERSION)

Programmed Adaptive Clutter Attenuator (PACA) a device which, together with the high dynamic range RF amplifier, ensures that the receiver works within its full dynamic range.

In-phase and quadrature MTI which processes the entire information content of the signal, thus eliminating the losses inherent to single component MTIs, such as blind phases.

Fig. 7.17 The brochure of the Selenia air traffic control radar ATCR-33



SELENIA

Industrie Elettroniche Associate S.p.A.
Civil Radar and Systems Division

ATCR-44

L BAND AIR TRAFFIC CONTROL
TERMINAL AREA RADAR

RADAR INSTALLATION AT KIEW (USSR)

FREE SPACE COVERAGE DIAGRAM G-14 ANTENNA

Main Features:

- Adaptivity
- Extremely reliable
- Multiple beam combinations
- High dynamic range linear receiver
- Programmed adaptive clutter attenuator (PACA)
- Adaptive clutter map
- Phase and quadrature digital MTI
- 10 bit A/D converter
- False alarm normalizer
- Built-in test equipment
- The choice of leading ATC authorities throughout the world

TMA RADAR INSTALLATION AT HONG-KONG

The ATCR-44 is a medium power, 23 cm. wavelength, solid state (except for the magnetron and thyratron) T.M.A. search radar. In an air traffic control configuration the radar consists normally of an antenna group, two transmitter cabinets, two receiver cabinets and the common wave guide system.

The radar can be equipped with two different antenna systems, the G-14 high gain antenna, and the smaller G-7 antenna.

The main features of the new radar are:

Clutter Fix, a system which permits an adaptive control of the lower portion of the antenna pattern by means of electronic processing in order to optimize the signal/clutter ratio at the input to the receiver.

Fig. 7.18 The brochure of the Selenia air traffic control radar ATCR-44

indicated by Raytheon had to produce under license missile batteries and radars. Calosi had obtained funding for Microlambda and for the power tubes factory in Palermo, Italy, founded by him, the *Elsi* (Elettronica Sicula, then *Alelco*, Selex, Galileo Avionica, today part of Selex ES). So, in the early 1960s the creation of Selenia started. The firm was established on March 22th, 1960, with headquarters in Naples, from the fusion of Sindel and Microlambda, with the name of *Sipel—Società industriale prodotti elettronici s.p.a.* A subsequent deed dated June 6th, 1960 recorded the birth of *Selenia—Industrie Elettroniche Associate* s.p.a., with the following share: 40 % Finmeccanica, 40 % Raytheon and 20 % Edison. Mustacchi was general director and Bardelli technical director. The number of employees in Selenia increased from about four thousand in 1970 to about six thousand five hundred at the twenty-fifth anniversary in 1985, see Fig. 7.19. Calosi, just returned to Italy, became president and CEO of the new firm, keeping this position during the whole 1960s.[19]

In 1961, Selenia, able to design (in Rome, in the plant of Via Tiburtina) and produce (at the *Fusaro* plant near Naples) electronic devices and systems, in particular radars, initiated the autonomous development of a new line of air traffic control radars.[8] Even though starting from the experience of radar sets built *ex-novo* in the United States (for example the ARSR-1), the Selenia Air Traffic Control radar for the Swedish first customer, i.e. the first ATCR-2 in the L band (wavelength of 23 cm) and with antenna G7, see Fig. 7.20, was a radar set 70 % different from the American one, and with performance complying to the international standards of that time. The first ATCR-2 was installed in Sweden at the Stockholm *Bromma* Airport. In Italy, the Italian Air Force (through his ITAV—*Ispettorato Telecomunicazioni ed Assistenza al Volo*, i.e. Telecommunications and Flight Assistance Directorate—in charge for the *Air Navigation Services* on all the national airspace[20]) decided to install two fully fledged ATCR-2 systems, at *Roma Fiumicino* and *Milano Linate* airports, operational from 1967 until the beginning of the 1990s. In the 1970s Selenia arrived to be the number two in the world for the number of civilian airports equipped with its Air Traffic Control systems, mainly based on its radar. The first radar i.e. the ATCR 2, L-band long-range for traffic control on the network of airways, "son" of the TPS 1, had an MTI canceller with analog technology (quartz delay lines). In 1972, for the

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[19] Carlo Calosi has been publicly remembered by Franco Bardelli, Raffaele Esposito, Francesco Musto and Carlo Alberto Penazzi on April 2nd, 2009 during the inauguration of the Radar Museum at the Selex plant in Fusaro and the presentation of the book [Mar 09] describing his life. A second noticeable museum inside an industrial plant of the Finmeccanica group is that of Selex-Galileo (now, Selex ES) near Florence, in Campi Bisenzio, called "Museum of Technology Adolfo Tiezzi".

[20] Unlike most Western nations, the Air Traffic Services provider in Italy has been the Air Force (*Aeronautica Militare Italiana*) till 1980. In fact, after an announced "Class resignation" by the (military) air traffic controllers in 1979, a three-years process initiated by the President of the Italian republic *Sandro Pertini* led, in 1982, to the establishment of a civil air service provider, the AAAVTAG, then (1996) ENAV (*Ente Nazionale Assistenza al Volo*, a public body), and from 2001, ENAV S.p.A.

Fig. 7.19 The bronze medal celebrating the 25th anniversary of Selena. This firm was established in 1960 in order to create a single industry from a mostly manufacturing one (Microlambda) and another one mainly oriented to the design (Sindel)

Fig. 7.20 The Selenia G7 antenna

Swedish customer, the PS-810/F radar followed for the military air traffic control, equipped with a digital MTI.[9]

Just before the 1960s the government of the Soviet Union called for proposals for four important Air Traffic Control Systems to be installed in the Moscow region with a view to the future (1980) Olympic Games. This international competition was a wonderful occasion and a new opening toward the West. And of course all the large companies in Europe and in the USA were anxious to participate and to win the race; it was not only an important contract, but the opportunity to enter positively in a huge new market, which was, until then, completely closed. While taking a low profile (or perhaps just because of it: the Soviets did not want to put too much in evidence their dependence on foreign technology for applications so important and critical), Selenia won the race, thus entering the small group (three or four companies in the world) of suppliers of ATC systems. In the same year (1961) Selenia started the development of weather radar with

Fig. 7.21 The Orion, ancestor of Selenia's fire control radars

the Meteor 200 TRM1 C. Also at the beginning of the 1960s the naval fire control radars of the successful series Orion were launched. Their parent, the ORION 1A (see Fig. 7.21) had been developed in Sindel from the group headed by Ing. Bardelli some years before. In addition, there was the development of many products: naval collision-avoidance system—initially licensed by Raytheon—of the 1600 series, as well as the long-range naval surveillance radar named *Argos 5000* (from which in the early 1970s was originated the ground-based long-range radar *Argos 10* produced in 1972–75 and used in the national air defense). Even more important, Selenia developed for the Swedish Air Force the low altitude search radar *Argos 2000*, code-named "Paolo", with technical solutions absolutely original, produced in different units in 1964–71.

Among these developments, the one of *Argos 5000* [Mus 14] is particularly interesting both for its very high power (5 MW) and for its new technical solutions. The naval surveillance radar *Argos 5000* was the first one conceived and designed by Dr. Francesco Musto (just arrived in Selenia from Microlambda) in the early 1960s in order to reply to a request for a naval, long-range radar by the Italian Navy, which wanted—new (and possibly "made in Italy") equipment for their first big military vessel of the Cold War period after W.W. II, i.e. the missile launcher cruiser *Giuseppe Garibaldi*, obtained by various transformations (1947, 1960) of the "light cruiser" *Giuseppe Garibaldi* of the 1936 time frame. This cruiser was equipped with the American *Polaris* missiles with nuclear warheads, then, with the *Terrier* ones, making *Garibaldi* the first European missile launcher cruiser, delivered to the Italian Navy—after the transformation works—on November 1961 and operational from the early 1962. The *Argos 5000* radar had the task of early warning and acquisition of far-away targets, to be transferred to the NATO standard, three-dimensional radar *FreScan AN/SPS-39*, to establish their direction, distance and altitude for the *Terrier* missile guidance system. Other on-board radars were the Westinghouse *AN/SPS-6*, the surface surveillance radar *SET-6B* and the SMA navigation radar *CFL3-C25*. The Navy requirements for the *Argos 5000* included a maximum range of 200 nautical miles on a 2 m^2 airplane, a resolution in azimuth of 1.5°, a period of rotation of the antenna of 10 s, and a coverage in elevation up to 20,000 m. Italy still lacked a network of ground-based radars for the air defence (which would have been implemented some years later with the *Selenia Argos 10* as main sensor). In this frame, the *Argos 5000* was expected to satisfy the air defence needs on the "warm" Eastern side of Italy (between Istria and Yugoslavia) with the advantage of being mobile. But this meant that it had to operate mainly "in a narrow sea" (the Adriatic) with significant levels of ground clutter, whose suppression called for advanced, original solutions to be found by Selenia.

In particular, the ship's motion (with a maximum speed up to 35 knots) caused a Doppler shift of the strong clutter echoes received both from the main-lobe and from the side-lobes of the antenna, putting them out of the rejection band of the MTI filter. While the main-lobe clutter could be treated with the injection of a signal to compensate for the motion of the ship, to solve the problem of the clutter via the side lobes of antenna, the waveform transmitted during each "sweep" was formed by a train of 7 pulses, each lasting 0.9 μs, spaced among them according to a "magic code".[10] The receiver had a "normal" channel with "anti-jamming" features ("Back-bias" and "Dicke-fix"), and an MTI channel with correction of the motion of the ship. Downstream both channels was a video integrator. The antenna was a parabolic cylinder reflector illuminated by a feed made up by a vertical array of horizontally-polarized dipoles. Another vertical array of vertically-polarized dipoles realized, through the same reflector, the IFF antenna, see Fig. 7.22. Probably, the only drawback of this antenna was an exceeding weight due to concern of the designer about the possible vibrations of the reflector, harmful for the MTI operation. Finally, the antenna was not mechanically stabilized, as the entire ship was stabilized.[11]

The Italian Navy was very satisfied by this new Selenia radar (see Fig. 7.23) and by its ability of operation in a difficult environment such as the Adriatic sea, where the radars of other Navy's, designed to operate in the open sea, were in trouble due to the clutter.

After a life of about 10 years, the *Argos 5000* radar ended its service with the cruiser Garibaldi, dismantled in the mid-1970s due to the shrinking of budget for the Italian Navy and the radically changed strategic and geo-political scenario. The air defence was based on a network of ground-based surveillance centres and an integrated command and control system, to control fighter-interceptors (such as the F 104) and anti-aircraft missile batteries (NIKE, HAWK). In Italy the changed operational role of naval surveillance radar required smaller sets such as the more sophisticated Selenia RAN 10S.

In 1966 an important international defence program started: the NADGE (*NATO Air Defence Ground Environment*), an air defence system integrating the radar

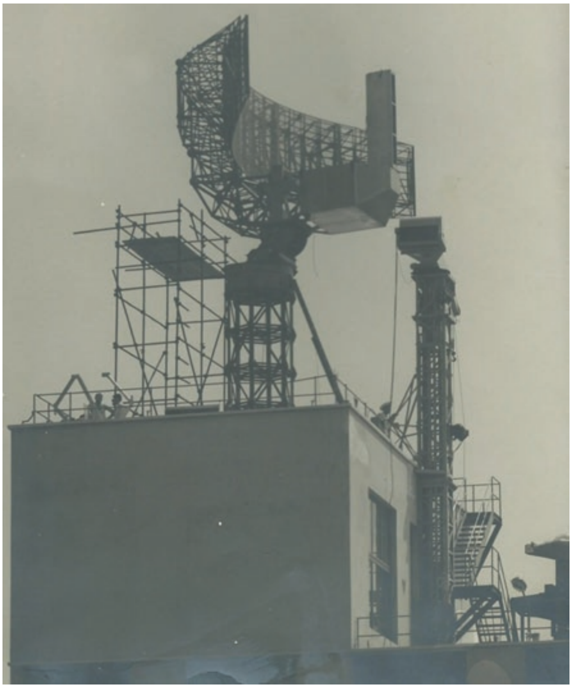

Fig. 7.22 The Antenna of the Argos 5000 under test in the Selenia plant, 1962 (*courtesy* Dr. Ing. Francesco Musto)

coverage of the NATO participating European nations for the airspace from the Scandinavia to the Turkey. This program allowed Selenia to enter into the world of digital techniques and of automatic computation: the first Selenia computer, the ***GP-16***, was developed in those years. According to [Mar 09], this was the last big result obtained by the Selenia of Calosi, one of the first companies in Europe adopting digital technology. In fact, those years, with rapid progress, the processing of radar signals was carried out more and more in a digital way,[21] with a wired logic that initially was a simple "translation" of the previous analogue schemes.[12] In 1973 Selenia created its *Division of Informatics and Civil Telecommunications* (ITC), transferred to Pomezia (near Roma) in 1974 and subsequently to Giugliano near Neaples. The birth in Selenia of activities on Informatics and Civil Telecommunications at the beginning of the 1970s is connected to the Italian events in late 1960s when Raytheon, not satisfied too much by the growing autonomy of the increasingly fierce Selenia, no longer had confidence in Calosi and reduced its shareholding, up to its cancellation in 1969. The changeover took place in 1970.[13] In that year the Italian government decided to transfer Selenia into the STET group[22]—and Marcello Biagioni was appointed CEO in place of Calosi, with

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[21] For example, the MTI cancellers with analogue delay lines (made by mercury, water or quartz) were replaced by digital MTI.

[22] STET means *Società Torinese per l'Esercizio Telefonico*, a society of the IRI group established in 1933, from 1997 included in *Telecom Italia SpA*.

Fig. 7.23 The *Giuseppe Garibaldi* cruiser exiting the harbour of Taranto with the Argos 5000 on board. (*courtesy* Dr. Ing.Francesco Musto)

Franco Bardelli and Leone Mustacchi remaining in service as Technical and General Director, respectively.[23] The memoir of that period of Selenia, kindly written and provided by Ing. Biagioni, is at pp. 205–214 of [Gal 12]. In short, Biagioni quickly understood that investments in Research and Developments were essential, and succeeded in convincing STET to accept a three-years investment plan, also considering the fact that positive economic results would have taken the needed time to arrive. Moreover, he reorganized Selenia creating an autonomous unit for each type of market.[14] Perhaps the greatest Biagioni's achievement were two. First, he was able to establish new relations between Selenia and the Genoa-based *Elsag*: Biagioni understood, and convinced Italian Navy, that the most attractive military naval market was to provide to the builder of the ship (at that time, *Cantieri del Tirreno* above all) the whole of electronic equipment for the purpose of weapons control, which was achieved by developing complementary products between both companies. Moreover, Selenia took the initiative to extend the cooperation between Selenia and Elsag to other Italian companies providing equipment for military vessels, such as *Oto Melara* and SMA, paving the way to Consortia and associations

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[23] To them, after the arrival of Biagioni, were added Dr. Leonardo De Renzi, Director of Human resources, and Dr. Vittorio Facciotti, Administrative Director who had the know-how needed to organize an industrial accounting system for controlling monthly the costs of a complex company, with many products and over two thousand employees.

Fig. 7.24 The coherent radar MM/SPS-68 is presented to the Italian Navy, ca. 1974 (from *left*, in the *front row*: Ing. Iorio, Dr. Mustacchi, Adm. Barontini, Cdr. Navequarto, Adm. Di Giovanni and Ing. Gasperini; second row, third from left: Ing. C.A. Penazzi)

such as *Melara Club* and *Selenia Elsag Sistemi Navali*—SESN. The second success of Biagioni's era was the *Aspide* missile, first launched in the *Salto di Quirra* test base in Sardinia in 1975. This missile, in its long life, was the backbone of the Fusaro plant employment for decades (in 1976 Selenia employees reached the noticeable figure of seven thousand).

In the 1970s the telephone-service STET company imposed to Selenia some choices, such as the production of communication devices and of support subsystems for telephone services, most developed in the Selenia plant in Giugliano. However the developments in the areas most suited to the nature of Selenia continued in various programs and contexts: NADGE, Air Traffic Control, naval radars—such as the MM/SPS-68, see Fig. 7.24—and systems.[24] In particular, fire control radars evolved from the *conical scan* of the Orion RTN 10X to the *monopulse technique*. This important advancement in tracking radars was applied (1970s and 1980s) to the RTN 20X and the RTN 30X. The latter (Fig. 7.25) had been in service on ships of different navies for over thirty years. To the new

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[24] Naval surveillance radars had the acronym RAN (*Radar di Avvistamento Navale*), while tracking radars had the acronym RTN (*Radar di Tiro Navale*), both followed by a figure (e.g. 10, 20, 30… and the letter indicating the frequency band (e.g. L, S, X).

Fig. 7.25 The monopulse, coherent Fire Control naval radar RTN 30 X

Fig. 7.26 The ground-based, 3D long-range, S-band radar RAT 31 SL

ground-based surveillance radars[25] the measurement of the target's height—of great importance in Air Defence—was soon added. The resulting sets are called *three-dimensional or* 3D; the former of them was the RAT 31 S (also called: "medium range" 3D radar in the S-band), ancestor of a long-lived and successful generation of sets that includes the long range version RAT 31 SL and that—NATO standard—"D"-band (i.e. operating in the L band) RAT 31 DL, see Figs. 7.26 and 7.27.

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[25] Selenia's ground-based surveillance radars had the acronym RAT (*Radar di Avvistamento Terrestre*), maybe not very suited to an English-speaking international environment.

Fig. 7.27 The NATO standard, 3D long-range, L-band radar RAT 31 DL

Even with Biagioni CEO, in the 1970s the basic Selenia management setting due to Calosi and Bardelli continued, with the executive group including (the list is partial) people such as Domenico Formato, Paolo Piqué, Cesare Iorio, Marcello Franchetti Pardo, Osvaldo Abbondanza, the already mentioned Francesco Musto, and finally with Aldo Gilardini[15] head of Research. The central structures such as the Technical Directorate with its Development Laboratory, directed by Benito Palumbo,[16] flanked the divisional structures oriented to the market.

On another front, after the arrival of STET there was a growing weight (negligible at the origins of Selenia) of the political parties and of the politicians within the Company, as it was the case throughout most of Italy. So, in February 1980 Franco Bardelli left Selenia, after having inspired its technological choices and strategies for over twenty years. But this was not the end of a career for this extraordinary person, as he recalled in the following memoir written on request by the author in January 2010, published in [Gal 12] and presented, in a slightly shortened version, in the following Annex No. 2.

7.1 Annex No. 2—Memoir Written by Ing. Franco Bardelli in Early 2010

Sixty years of radar, and more

I am pleased to revisit the early years of my life as an engineer with a *60-years-long telescope*.

Radar soon entered in my heart: during 1948–1949 I attended the Microwave Centre of prof. Nello Carrara. Inside his laboratory there was an

X-band airborne radar ready to be installed; it was clear that this set was from a production line for large quantities. In the months I attended the Centre I understood the large difference between what professors Tiberio and Carrara had developed in Italy and the results of the great technical and industrial American effort. After a few months, in April 1949, I accepted a first assignment by Raytheon as radar engineer for the installation of navigation radars on board civilian vessels. Navigation was probably the first civil, large-scale application of radar, driven by a growing market just after W.W. II. After this experience, I wanted to become more experienced in radar theories and techniques, and in 1950 I became research assistant of prof. Tiberio in the Naval Academy in Livorno, where they broadened the horizon of radar applications and of the problems due to the operating environment. Very soon, in 1951, I joined Microlambda, the Company just established by Raytheon and Finmeccanica under the sponsorship of the Italian Navy and under the guidance of prof. Calosi, with its plant in the former "Silurificio" in Fusaro near Naples. Thus started the Italian radar production industry with the arrival of the first packages of drawings, specifications, standards, etc. The books of the MIT Radiation Laboratory Series became our primary source. We had to stay between the complexity of the structure that the customer (in our case, the US Navy) had set up in order to obtain an industrial production complying with regulations, reproducibility, quality etc., and the atmosphere of scientific and technical advancement that Prof. Calosi had established. Of course this was an unique opportunity for understanding and professional growth.

The contract for production of the surveillance radar TPS arrived at the end of 1951 in Microlambda. This L-band, transportable, MTI radar, had to be produced in an industrial series of 250 sets in 3 years: again, a mix of industrial needs and of new technical matters to be understood. For everybody, from engineer to simple workers, those years of implied a deep commitment and a great satisfaction.

In Figs. 7.28, 7.29, and 7.30 some of the personalities of that time are shown.

After the TPS era, new problems arose: how to follow-on the industrial activity? Which markets were ready to receive our products? Microlambda initiated projects for navigation radar, for surveillance and tracking radar for the anti-aircraft artillery, and others. But in those years the market was moving slowly and the company Microlambda went into crisis. Prof. Calosi decided to come back to the USA and, from my side, I understood that I had to best exploit what I had learnt by restarting on a smaller size and by concentrating on a single, new product whose solutions implemented a technical break-through.

Thus the *Studio Tecnico di Consulenza* (STC) was born in 1956 and with it, the first fire control radar (X-band, 250 kW, tri-port feeds, modular, the first of the long-lived Orion family) was born. Prof. Calosi became the paladin of STC and persuaded Raytheon to help it. So, the *Sindel* was

Fig. 7.28 SINDEL plant in via Tiburtina, 1958/59. At centre, in dark dress, Ing. Valerio, Ceo of *Edison*; on the right, in clear dress, the Commander Vangeli from the American Navy

Fig. 7.29 Visit of the Swedish committee (1964, before the ARGOS 2000 contract)—some people: Ciaramiccoli, Bardelli,Calosi, Sacchetti

navigation radars. Finally, in 1958–1959 the Sindel plant was built in Via Tiburtina Km 12 + 400 (see Fig. 7.31).

At the end of the 1950s Italy became a partner of the new European armament programs: the anti-aircraft *Hawk* was born, a missile system

Fig. 7.30 Visit at Selenia plant in via Tiburtina (1962/63)—from *left* to *right*: Giuseppe Petrilli, Chairman of IRI (*Istituto per la Ricostruzione Industriale*), prof. Calosi and the Minister of Defense Giulio Andreotti

Fig. 7.31 The *SINDEL* plant (1959) in Via Tiburtina, Roma

designed and produced in the USA by Raytheon. There was the opportunity to reorganize the Italian industrial structure: in 1960 the Company *Selenia* was born, with participation by Raytheon, Edison and Finmeccanica, and with Calosi chairman.

Connections with the Raytheon were open and intensive. With the *Hawk* program, Selenia entered in the missile world characterized by new standards, facilities, equipment and know-how. The production was focused to Naples with the plant in Rome mostly dedicated to the design of new equipment. Concerning the future of Selenia, the Hawk program guaranteed work only for a few years; so, we had to be ready by playing a highly technical role for the national and international markets. These years were dedicated to give Selenia an evolutionary structure: I studied for long time the Raytheon industrial organization. So, we created structures oriented to the market: Naval, Air traffic control, Search, Tracking and Fire Control systems, Navigation, Meteorology, etc. In parallel, a great Laboratory was born, divided into technical areas to focus the capabilities of design and test the relevant components for radars and missiles, i.e. Antennas, Transmitters, Microwave, Receivers, Signal processing, Displays, Servo systems, Microelectronics, Power supplies, Ferrite and other technologies. Moreover, we created a Research direction and a System analysis group.

We evolved from the design with electronic tubes to the one with transistors, to the use of digital technologies and digital signal processing, to the miniaturization techniques, to the digital computers as the core of Command and control centres (the *Nadge* program saw us among the first in Europe to develop the new *digital displays*).

Selenia participated to the first *space programs*: a great technical impulse arrived to the Antennas laboratory from the successful participation to space international competitions.

The Laboratory was the forge of the business which were consolidating: Air traffic control radars, in the endless competition with Thomson-CSF [today, *Thales*], Surveillance radars and weapons systems for Military Navies, radars for the network of air surveillance with the related Command and control centres, Navigation radars, and more. In this products frame, Selenia was structured to stay on the market and to play a high-level technical role. At the end of 1970s prof. Calosi left, the Raytheon exited, Selenia control was transferred to STET: communications had to enter in Selenia. The 1970s were a result of the industrial setting as consolidated with the *Aspide* missile, the *Sirio* satellite, and the completing of many more product lines. On the other hand, the 1960s were the *education and training* years for Selenia: the strong cooperation by Raytheon with the mutual respect that was established, the wish to play a competitive technical role, and, finally, the many opportunities for contacts and developments, created the character, the participation, the quality and the commitment of the staff as well as the structure of the Company.

I left the Selenia in 1980, and I established the new company "*IDS—Ingegneria dei Sistemi* (Systems Engineering)" with the objective of generating new creative skills, by leveraging on highly specialized knowledge (electromagnetism, signal processing and others…).

After a period of commitment at the Officine Galileo (where I learned the great potential of the optical and infrared technologies) I have focused this new company to four lines of business and of market. The former three concern both the control and the ability of simulation and forecasting of the electromagnetic field in the following environments: (a) naval, (b) aerospace and (c) airport. In these three activities we have progressively emphasized and developed the system aspects and have integrated them into software products (Framework Design). As an example, a Radar Cross-section Laboratory born with capabilities of simulation, prediction, interpretation and measurement. The fourth line of business, (d) uses the radar as a sensor non-destructive, close-range analysis (Ground Probing Radar, Trough the Wall Radar, etc.). With respect to classical radar, this is a completely different side of techniques and systems with potential for a large growth. Figure 7.32 shows a GPR produced by IDS.

Fig. 7.32 Multi-antenna ground probing radar GPR (2009) model *Stream Street* by IDS

Today, the IDS Group has about 400 employees; to reach the export goals, four Companies were established from it, i.e.: *IDS UK*, *IDS North America* in Canada, *IDS Australasia* in Australia and finally *IDS Brazil*. The IDS products have customers in approximately 35 countries.

The radar is still a technique of great potential and wide applications.

The memoir by Ing. Franco Bardelli contains extensive references to the Selenia Development Laboratories [*Laboratori Sviluppo*], directed by another remarkable person, Ing. Benito Palumbo, author of the memoir reported below, which to some extent complements the previous one.

7.2 Annex No. 3—Memoir by Ing. Benito Palumbo, End of 2009

The Design and development laboratories of the Company *Selenia*. The case of the radar antennas for ground-based defense systems

Development activities and organizational structures

The activities of basic design, preliminary study, development, and performance evaluation of the prototype units of the radar equipment were carried out in Selenia—since its establishment in 1960—by a central structure (a group of specialized laboratories) organized according to a scheme which was substantially one-to-one related to the different areas of technology characterizing the single functional blocks typically present in each radar set.

So, in front of the individual units which constituted the radar set in its simplest scheme (i.e. transmitter, antenna, receiver, radar signal processor and data processor, display system, servo-system, power supply system), there were corresponding organizational units (called *Reparti*, Departments: Antennas, Microwave, Transmitters, Receivers, Signal processing, etc.), responsible for each area of the relevant activities of study, analysis, development and test of the prototypes. These *Departments* were operationally coordinated in the context of a single structure, called, for short, *Laboratories*.

Within the Laboratories the Company had concentrated the capacity of design and functional tests of the prototypal units in the various areas of technology in order to support the developments for radar and missile equipment and, subsequently, for the new lines of products of the Company.

The possibility of re-using—for different applications—some basis functional blocks (for example, the transmitter, the antenna, the display unit) as well as previously developed components and instruments, design techniques and tests equipment was advantageous to effectively manage a broad spectrum of applications, and to support initiatives in the very different market areas. At the beginning of the international space programs, the recognized technical and industrial capacity of Selenia in the area of radar antennas has allowed the company to simultaneously participate to the preparation of proposals for international projects in competing consortia.

Each of the Laboratories was made up by a core of design engineers with varying degrees of technical and management experience flanked by technical and supporting operators, essentially dedicated to test and verify the performance of the components and devices under development.

Supporting Units, located in some cases within the area of the Laboratories and sometimes outside them, but always satisfying the addresses of a common technical direction and functionally operating in a common way, ensured the needed contributions for the complete process of development. Among them, there were the mechanical design and the development of documentation, as well as the implementation of prototypical parts and assemblies, and, last but not least, the technological laboratories, ensuring the knowledge and the expertise in the areas of microelectronics technologies, plastic materials and composites. Some of these tasks were entrusted to external suppliers of certified quality, but the outsourcing of critical tasks, such as those linked to new developments, had not any significant size through the early 1980s.

An essential contribution to the definition of technical solutions and to the verification of expected performance has been provided by software tools for modeling and simulation, analysis and synthesis of active and passive circuits, of electronic components and of microwave and electromagnetic devices.

In the early years of operation of the radar industry in Italy, commercial software tools able to support the activities of design and development were not generally available. Therefore in Selenia it proved necessary to create this type of resources, as it happened, in fact, in almost all the world industries in this domain. Software tools to help the design in the technological areas of interest appeared later on the market; however, sometimes they not suited to the specific needs, being too general. Moreover, software tools for the mechanical design and the creation and management of automated documentation were soon available on the market.

Furthermore, it is worth mentioning the valuable contribution resulting from the studies and the capabilities of two significant central structures present in Selenia, i.e. the "Research Laboratory" and the "Analysis and Scientific computing", acronym: ABCS [*Analisi di Base e Calcolo Scientifico*], then called "System Analysis" group.

The Laboratories constituted, since the 1960s, a strategic core for the Company in order to ensure valuable products in an international market with a strong competition from large industries. Over the course of the years, the structures and the composition of the Laboratories have undergone some changes resulting from the need to be adapted to the new scenarios and to market requirements as well as to the evolution of technology. However, they remained substantially unchanged in their fundamental mission. The constant relationship with the Company's groups dedicated to the industrialization of the new products and to their production was further strengthened during the 1980s with the creation, in the main production plant (Fusaro), of a multi-technological design group, closely related with the "historical" Laboratories.

To a privileged relationship with system engineers, responsible for the design and the acceptance of the whole product, the Laboratories have normally added the needed help to the commercial structures, providing technical support and the insurance of the technological feasibility of the proposed solutions in during the first contacts with the potential customer. This type of cooperation has been essential in various situations, as in the example provided in the following paragraph related to a very advanced product, with the customer having doubts about its feasibility.

Role of the Laboratories in relationship with the structures of the Company

With the quantitative growth of the Company's activity and for a best control of some strategic market areas, sometimes whole Selenia's parts were detached in order to form autonomous Companies constituting their design group core. Such a situation happened, for example, at the beginning of the 1980s, on the occasion of the birth of the new company *Selenia Spazio*, then, *Alenia Spazio*.

In addition to the main core of development of new products, in the Laboratories always special attention was paid to the study activities aimed at the acquisition of new skills and to the ability to innovate Selenia's products. These activities were supported both by internal funding (private venture funds) and by institutional Bodies. Through these instruments it was possible to pick up even those initially weak signals, showing the benefits of new approaches and design solutions, and sometimes prospects and opportunities for entering into new areas. In addition, through the active participation to scientific events, the contributions to technical publications and the participation to initiatives of professional associations, such as the IEEE and the AEI (*Associazione Elettrotecnica Italiana*, now *AICT Society* of the AEIT), it was possible to build-up and to maintain relationships, often even personal, with institutions and people of high international level, which helped to keep a technically advanced position in the various design and development areas. To ensure an advanced knowledge level, it was also very important to maintain a close relationship with the national and international academic world.

It is also important to point out the far-sighted vision of the Company which always ensured the availability of the best human resources, the necessary investments in the most advanced instrumentation and the access to the most suited computing tools.

An example: Array antennae with electronic scanning of multiple independent beams

The history of the Laboratories, in addition to moments in which the problems seemed too hard, are also rich of successful events, sometimes with unforeseen risks and difficult relationships with the customer as well as with the other internal structures involved in the development process.

In all the technical areas, the evolution of the skills necessary to ensure winning opportunities for new products has seen a trend of steady growth, favored by a stimulating environment. However, there were situations in which, under the urgent need to ensure a better positioning in the market, the need became apparent to design and develop solutions that represented a real leap concerning quality and performance, and at the same time were economically competitive. In all the areas, there were many of these moments, which stimulated the evolution, levering the innovative capacities of resources devoted to new developments.

As an example, it is believed that a significant step for the defence radar systems was the design and adoption of an original configuration for the beam forming network capable of independent scanning of multiple beams with electronic control. Such a configuration was intended to be used for high performance array antennas, also capable of good mobility for some specific applications. This element has allowed Selenia to provide surveillance radar for defence systems with much better performance than those previously obtainable in terms of accuracy and quality of the target data.

The goal was to obtain, in a planar array antenna with mechanical revolution in azimuth, different beams in the vertical plane, each of them being independently pointed in its relevant elevation sector with electronic phase control. The core of the selected solution consisted in a waveguide network feeding a number of superimposed planes, each one containing the radiating elements and the beam forming network in azimuth. Such an architecture permits the independent optimization of each elevation beam, in particular, of the sum and the difference beams for the Monopulse operation, allowing a high degree of accuracy in the measurement of the height of the target, in addition to the usual data of distance and azimuth (3D radar). In addition to the multiple, simultaneous beams forming on different elevation angles, other features of this 3D antenna permit, via multiplexing of different frequency bands, to form multiple simultaneous beams in the same elevation sector when needed (operation in jamming conditions). The 3D antenna solution is flexible in the number of beams and in the width of each beam, permits a very low side lobe level and is compatible with a wide band frequency agility. Environments with heavy ground *clutter* levels are dealt with the creation of a lowest elevation beam with very low levels around the horizon.

The antenna scheme of this novel 3D solution appeared very complex, but it was nevertheless appreciated by the potential customer from the defense administration of a technically very advanced European country. On the other hand, the commercial manager of the Company responsible for the geographical area where the action of bid started, was very doubtful about the feasibility of this advanced solution. However, this business manager wanted to congratulate and apologize for its diffidence, when the prototypic model, mounted on the terrace where the antennas were installed in the test phase, demonstrated that the performance expectations were realized. Figure 7.33 shows this antenna.

The evolution of the requirements influenced the change of the organization of the Laboratories and the relationships of their design and development groups with the marketing groups as well as with the system designers. The original structure that organized the Laboratories as a whole implemented a

Fig. 7.33 The Selenia 3D radar (the S-band multi-beam antenna of the 3D radar has a co-rotating L-band, open-array IFF antenna on its *top*)

configuration of the functional type, because it reflected the different nature of the various units of a radar set. Later on, the technological evolution towards unities integrating several, not easily separable, functions, and the greater interaction of the various components have pushed toward more integrated forms of organization, calling for a high degree of flexibility and of capacity of reorganization in order to better cope with the individual projects. Moreover, the technical culture of the design engineers had to be modified to include a higher level of knowledge of the "neighbors" technologies.

The concept and the solutions adopted for the multi-beam 3D *surveillance* radar has been extended, later on, to the antennas of a line of *multifunction* radars for shipborne and ground-based applications. In this case, the functions of surveillance, tracking, and weapons control for a number of different targets require an extremely high number of radar data per unit time. This has been obtained by adding the ability to scan multiple independent beams (in elevation and in azimuth) with a fast rotation of the antenna.

The heritage of the multi-beam antenna array also includes the family of radar with a distributed generation of power, using solid status sources installed directly in the antenna, and integrated with the radiating elements, and having, *inter alia*, a graceful degradation, i.e. the capacity to provide only slowly downgraded performance in the case of failures of a limited number of power sources.

The beginning of the 1990s, with the fall of the Berlin Wall, the collapse of the Soviet Union and the subsequent geopolitical changes, sees a state of crisis for the entire industrial sector of the defence. Anyway, in that period Selenia (then, Alenia and Alenia Marconi Systems), although at a slower pace than in the past, developed new radars, including the RAN 20 S, the mentioned 3D radars, and its first multifunction phased array radar, i.e. the naval set EMPAR (a "passive" phased array, i.e. with a bulk transmitter rather than one distributed it in the radiating elements, and electronic scan in azimuth and in elevation), see Fig. 7.34.

The matter of military ships and their radars, especially in Europe and in Italy, had a complex evolution after the mid-1980s. In fact, new operational concepts for the various Navies have been conceived and formalized after the collapse of the URSS and with the new threats (e.g. sea-skimming missiles, tactical/theatre ballistic missiles, and those typical threats of the "asymmetric war").

In the 1980s the Italian Navy asked for compact and fast vessels of the Frigate type (about 2500 tons), with an important weapon system. First orders for this "Maestrale" class frigates were placed in 1985. Then, the initiative for a NATO standard frigate failed due to disagreements concerning the operating profile and the composition of the combat system.

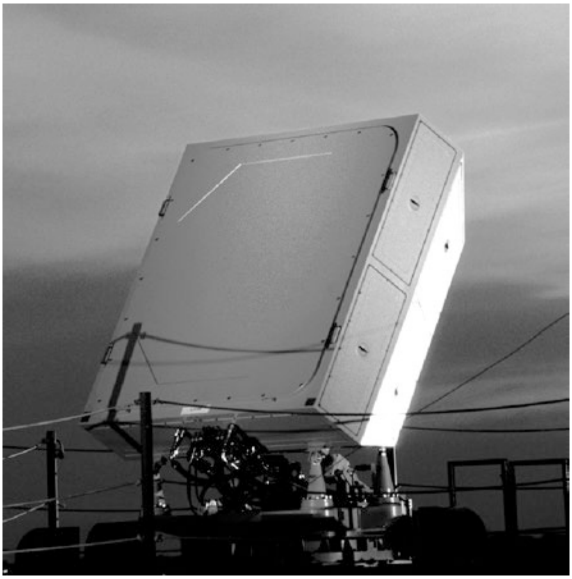

Fig. 7.34 The EMPAR multi-function naval radar

In those years, the idea of substituting the plethora of on-board radars with a few, multifunction ones (hereafter called MFR) was receiving increasing consensus.[26] In 1993 Italy participated to the "Horizon Program" established by France and UK, and aimed to large/medium size frigates (about 6500 tons). Two systems were proposed, the C-band *EMPAR* MFR (the reference system for Italy and France, described in the following) and the S-band *Sampson* MFR (the reference system for the UK).[27] Later, the UK abandoned the Horizon program and developed its own 8500 tons Type 45 Destroyer, class "Daring", using the Sampson and the S 1850 M long-range radar.[28]

In 1995, the former studies started with an aim to solve the difficult problem of co-existence of many radio-frequency sets on board (radars, electronic warfare, communications) by a (light or strict) integration in a common functional and

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[26] Of course, a single MFR is in theory the best solution, but this is not always true in practice, as putting together the various requirements for short/medium/long range and high/medium/low elevation surveillance of air and sea, as well as for weapons control (missiles guidance, fire control) could produce a "monster" radar, technically feasible but not necessarily cost-effective (only consider the simple way a conventional, simple Monopulse tracking radar with a mechanically steerable dish antenna satisfies the very stringent requirements for fire control in terms of data renewal interval and accuracy in range and angle, especially when "smart ammunitions" are not used).

[27] Sampson is a solid-state MFR based on the active phased array technology; two planar arrays rotate, back-to-back, at 30 rpm, hence permitting a 1s data renewal interval.

[28] The *S 1850 M* by BAe Systems—Thales, derived from the SMART-L (by Thales Netherland), is an L-Band 3D radar with digital beam forming in elevation and a maximum range up to 250 nautical miles on aircraft targets.

physical entity called "Integrated Mast" , present in the four Holland-class offshore patrol vessels of the Royal Netherlands Navy. The resulting mass balance and radar observability problems[29] have made, however, the integrated mast solution out of date in a relatively short time. In fact, these problems can be better solved, according to some modern point of view from the USA, by an "*integrated topside*" (deckhouse)[30] with a multiband (C and X or S and X) radar.[31]

The story of the first Italian phased-array multifunction radar is told by its main responsible in the Annex No. 4 that follows.

7.3 Annex No. 4—Memoir by Ing. Sergio Sabatini, Mid 2011 (Shortened and Updated)

A professional career developed on active and passive Phased Array Radars

Historical Background: the "passive" phased array radar EMPAR

In the early 1980s the radar state-of-the-art in Italy, in particular in Selenia, consisted of three-dimensional radar (3D); but there were preliminary discussions on a multifunction radar (capable of operating in both search mode and tracking mode) based on a "*full phased array*" antenna (capable of scanning on two directions: azimuth and elevation).

When I started working on the project of a shipborne multifunction radar, in addition to some studies, there was also a prototype implementation for a *phased array* antenna. I remember that at the end of 1970s Ing. Francesco Lomaglio (future head of the antenna department) came with me on the roof of the main, central building of the Selenia plant to show me an antenna, part of the prototype of an "X-band Phased Array" antenna, built to demonstrate the development capabilities of the Company in this field.[17] As recalled by Ing. Benito Palumbo, it was the result of a research and development project funded by the CTSD (Scientific and Technical Committee of Defense) and running in the period 1963–1968, whose project leader was Ing. Edoardo Mosca,[18] see Fig. 7.35.

This study was aimed to introduce "phased array" techniques in the X-band fire control radars; its remarkable innovations included, (in addition, of course, to the "phased array" itself), the "monopulse" technique for the instantaneous

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[29] It is well known that joining two "stealthy" parts together,e.g. a ship by one manufacturer and a mast by another manufacturer, a stealth result is NOT obtained.

[30] Implemented in the destroyer "USS Zumwalt", 2014, first of a group of three DDG 1000.

[31] For cost reduction reasons, the initial configuration has the X-band MFR AN/SPY-3 possibly supplemented by the S-band AN/SPY-1E.

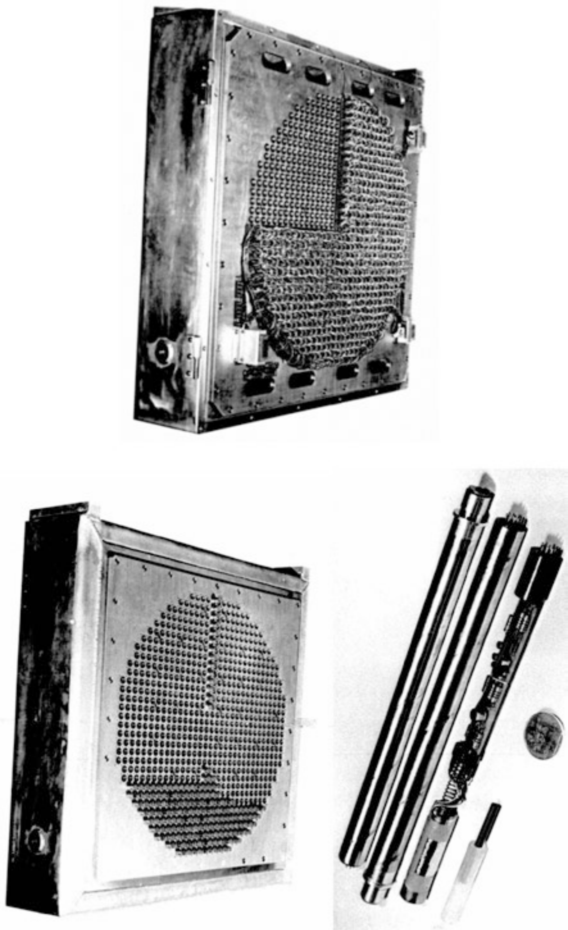

Fig. 7.35 The early X-Band Phased Array prototype (Selenia 1966)—*Courtesy*, Ing. Edoardo Mosca (*original document* Selenia RT-66/318 In. by Edoardo Mosca, 13.04.1966)

and precise measurement of the offset (azimuth and elevation) of the target with respect to the antenna boresight. The, more conventional, transceiver was substantially taken by a radar of the *Orion* series, a Selenia workhorse. Ing. Palumbo reminded me that the performance evaluation agreed with the expected results. However, the study did not led directly to a new product. In fact, too important were the criticalities of such a complex antenna, whose structure, without any axial symmetry, was based on analog phase shifters, not fully suited to comply with the requirements for that type of radar in terms of polarization purity, depth of the null, high angular gradients and so on.

However, the development of the demonstrator established an extraordinary school for many designer engineers, without which, perhaps, the success that occurred in significant subsequent projects would not be granted.

Even if the period of the “cold war” was ending, but with the United States and the Soviet Union competing, the requirements for new point defense systems were aimed to counter a possible multiple missile attack, which, at that time, resulted well beyond the capabilities of search radars and, especially, of fire control and missile guidance radars.

In this context, since the early 1980s the Italian Navy (MMI) began to consider a new generation radar sensor, capable of search and—at the same time—tracking on multiple lines of sight, to manage its own resources in an adaptive way with respect to the threats; summing up, a type of radar capable of countering multiple attacks. This sensor had to control the missile defence system of the ship in order to effectively counter attacks from different directions, able to saturate the “conventional” defence systems.

Another important requirement was that the system could be installed on board of small/medium tonnage vessels (e.g. corvettes and frigates): the radar antenna had to be light enough and its size, limited, in order to be installed as high as possible to provide maximum visibility at low altitude, against threats such as the “sea-skimmer”-type missiles. The above constraints for the installation were betted defined by MMI taking, as a reference, a frigate naval platform of the *Maestrale* type (3200 tons). The resulting best suited antenna architecture was the one of a single array in the C-band, on a rotating pedestal, in order to achieve the best trade-off between radar performance in search and tracking, and compliance with the size and weight constraints.[19]

The noticeable radiated power, necessary to obtain the required performance in search and tracking, was provided by a TWT-based transmitting unit installed below-deck, hence the name “passive” phased array. The radar was built by what is now the company SELEX ES of the Finmeccanica Group, see Fig. 7.36.[20]

The fundamental requirement for this radar was to combine the functions of search and precision tracking on many targets and to guide the intercepting missiles. The great flexibility of radar allowed to counteract multiple threats, either from different angles and/or angularly concentrated, protecting not only the own ship but also other ships in the own fleet (*Self Defense*, *Local Area Defense*).

Once completed the development and the acceptance tests by the Company, the radar today called *EMPAR* (European Multifunction Phased Array Radar), and, at that time, *MFR-1C* (MultiFunction Radar of the Italian

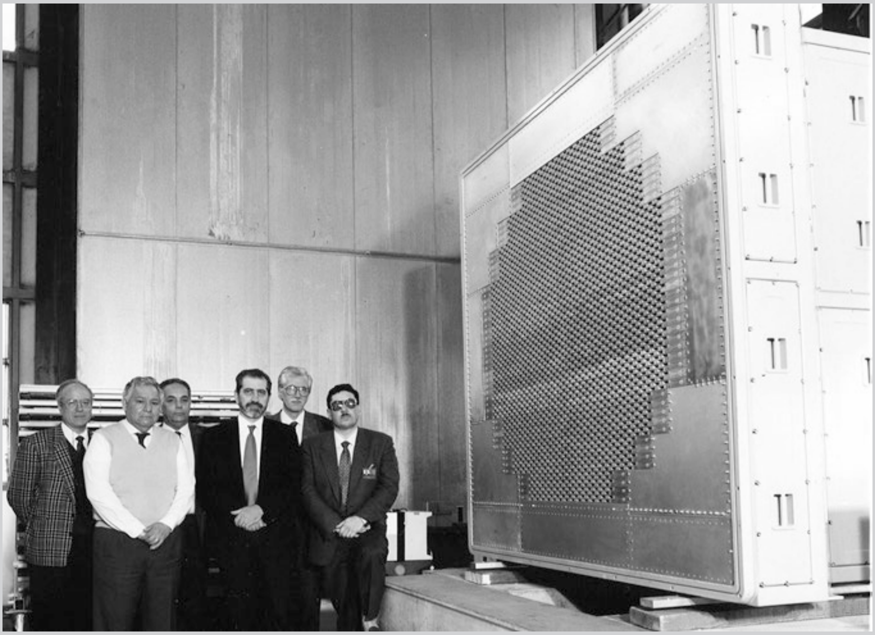

Fig. 7.36 The Prototype of the MFR-1 C/EMPAR in the Alenia (now: Selex ES) laboratory, spring 1993. From *left*: Giuseppe Di Gesaro, Francesco Valdivia, Benito Palumbo, Carlo Alberto Penazzi, Sergio Sacchi and Giuseppe Ilacqua (image kindly supplied by Adm. Comm. Giuseppe Ilacqua)

Navy, first type, C-Band), was installed on the ship *Carabiniere*[21] (see Fig. 7.37) and field evaluated by complete and detailed assessment tests with various targets in the second half of the 1990s. The overall result was a complete success.[22]

In the same period, the French and Italian Ministries of Defense agreed on a joint development of point defense systems, in the so-called FSAF[23] programme.

The EMPAR radar, derived from the existing MFR-1C with a very few modifications, was considered the candidate in the role of multifunction radar in the naval FSAF. In particular, the integration of EMPAR with the missile system *ASTER* was carried out during the "Phase 1" of the FSAF program. After a test campaign to demonstrate the "non-regression" with respect to the done changes, the whole defence system (radar, missiles, command and control) was tested on the ship *Carabiniere* with good results (in three launches of the missile ASTER-15 the success rate was 100 %).

The "Phase 2" of the FSAF programme—started in 1997—has brought significant changes to the radar, also providing the defense capabilities for extended areas with sophisticated ECCM capabilities and reduction of weight and size of the antenna.

Fig. 7.37 The *Carabiniere* with the MFR-1C/EMPAR radar installed for tests

Within the framework of this program, launches were made of the missile ASTER-30 from the *Carabiniere*, again, with full success.

Summing up, the planned production of EMPAR has covered the following operational needs for:

- The major naval unit of the Italian Navy (the new Air Carrier *Cavour*)
- 4 *Horizon* Frigates (2 for Italy plus 2 for France)
- 2 *Reference systems* (Taranto and Toulon).

In May 2011 two successful launches were performed from the ship *Cavour* (Fig. 7.38). The EMPAR radar guided two launches of an ASTER 15 missiles towards a drone and in both cases the intercept occurred with full success.

In the early 2000s the requirements of defense systems changed, and become, in some way, more general with respect to those that gave rise to the project EMPAR. To the "old" operational concepts were added those of *coalition* and *cooperation*, also *joint*, in scenarios often far from the national ports and with coverage requirements for the landing troops. In addition, greater importance was attributed to the functionalities related to anti-terrorism and anti-piracy.

The new operational needs required ever more flexible radar sets with a higher operational availability to guarantee the operation with a given level of failures ("*graceful degradation*"), associated to redundancy and reconfiguration capabilities, and to reduced Life Cycle Costs. In this new context, the "passive" EMPAR had some limitations due to the seniority of the project:

Fig. 7.38 The EMPAR installed on board the aircraft carrier *Cavour*

- The generation of power is entrusted to a transmitter of the TWT type with the bulky and expensive power supply unit representing a "bottleneck" from the point of view of the operational availability of the system;
- The aging technology, especially in some COTS parts, being a problem of obsolescence and reproducibility for a radar set conceived for ships entering into service from 2010 on.

The "*active array*" technology is the answer to the operational needs before mentioned; it also enables the design of a fully modular family of radars that can respond to a differentiated market (ranging from high end to "low cost" products).

The new configuration of "active EMPAR", later renamed "Kronos", has been the candidate for the new ships (European Multi-Mission, Frigates FREMM, see Fig. 7.39), whose joint French-Italian development follows the type of cooperation experienced in the Horizon program. This program produces, starting from 2011, ten new naval units for the Italian Navy (MMI).

Fig. 7.39 Computerized image of a FREMM frigate

In this context, the design of the new active array was presented to the Italian Navy in October, 2007; in 2008 followed the pertaining revision to the FREMM contract and the subsequent development of the entire radar, inclusive of the embodiment in the national field of the receiving channel previously developed by *BAE Systems* (originally, *Marconi Radar*). In 2009 the installation on the test site at Pratica di Mare was completed and in 2010–2011 radar qualifications were carried out, including the demonstration with targets of opportunity and the completion of the flight tests by the first half of 2011.

So technological evolution of EMPAR between 2008 and 2011 led to an *active* version called Kronos- MFRA (*Multi-Function Radar Active*). The active version has in antenna a number of TRM's (Transmit and Receive Modules) that replace the phase shifters in the EMPAR and are developed and produced entirely in Selex Sistemi Integrati (presently, Selex ES). Other radars of the *Active EMPAR* type, then called *Kronos* family, are the Kronos Naval and the Kronos Land, see Figs. 7.40, 7.41 and 7.42.

The Kronos 3D Naval has the following characteristics:

- Coverage: up to 180 km in range and 70° in elevation;
- Antenna revolution at 60 rpm;
- Antenna patterns: in transmission, Pencil beam, in reception, Sum, Azimuth Difference, Elevation Difference, Side Lobe Blanking;
- TRM's: based on high power amplifiers of the p-HEMT type.

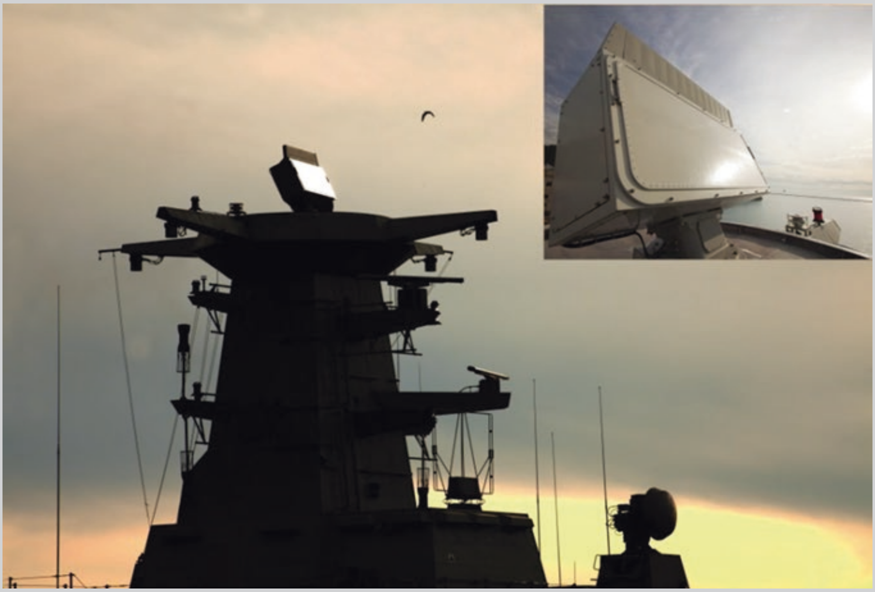

Fig. 7.40 The Kronos naval

Fig. 7.41 The Kronos naval radar under radome and the RTN-30 X (directing the OTO-Melara 76 mm gun—on the *right side*) on board of the anti-submarine warfare ASW vessel ABU DHABI class—Overall length 88.40 m, full load displacement 1650 tons—*Courtesy* Etihad Ship Building (ABU DHABI, March 2015)

Fig. 7.42 The Kronos land

On the world market of radar and radar-based systems, Selenia competed directly with the two main European groups which have also been mentioned previously, i.e. *Thompson-CSF* (then, Thales), heir to the French school, and *Marconi Electronic System*, heir to the English school. In 1990 Selenia merged with *Aeritalia*, leader of the Italian aerospace industry, thus originating a new company called *Alenia*,[24] active in aeronautics, radar, naval systems, missiles, space. Alenia was growing quickly and at the end of the 1990s was divided into two companies: *Alenia Aerospazio*, for the design and implementation of aeronautical and space systems, and *Alenia Difesa*. In 1999, *Alenia Marconi Systems* (this company name was soon shortened in *AMS*) was born. The shares of company were equally owned by Finmeccanica and by GEC-Marconi. A few months later the control of Marconi was taken over by *British Aerospace*, a giant of the aerospace and defense industrial sector, which, as a result of the merge with GEC-Marconi, assumed the name *BAe Systems*. The merger created a non-trivial evolution of the old Selenia/Alenia organizational models and rules of behavior of the staff,[25] managers included. In 2005, Finmeccanica acquired 100 % of the AMS shares and in the same year the heir of the historical Selenia was born with a greater company, called[26] *Selex Sistemi Integrati*. After the affair of black funds and false invoicing in 2010–11, and a radical change of top management, the assets and the activities of Selex Sistemi Integrati were transferred from January 1st, 2013 to the new Company *Selex ES*.[32]

Another post-war "product" of the "Tuscan radar school" was the design radar team operating in the firm *Contraves* and led by Ing. Giuseppe Gommellini (born in Livorno and Director of *Studies*, i.e. of R&D, in Contraves) who was helped by his deputy Dr. Leonetto Bianucci, a pupil of Ugo Tiberio. Gommellini and Bianucci were educated at the Academy of Livorno: Gommellini in analogue computers and Bianucci in radar. Gommellini led the research and development activities in Contraves from 1953 to 1989. The Contraves radar design team has worked in Rome since the early 1950. The Swiss firm *Oerlikon Contraves*[33] was born in the early years of the Twentieth Century and has produced the machine guns and anti-aircraft artillery used in both World Wars. *Contraves AG*[34] was established in 1936 as a company of the *Oerlikon Contraves group* with the mission of short-range defence systems. In 1952 *Contraves Italiana* (a company of the Contraves Group) started his operations in Italy at his headquarters in Roma (see Fig. 7.43). Its main mission was the production of short-range air defence systems, mainly for NATO countries. The company quickly developed engineering capabilities, particularly in electronic and radar technologies.

In 1954 Contraves opened his new factory in via Tiburtina (Ponte Mammolo area), Roma[35] (Fig. 7.44). In the 1960s the Company began developing products for the industrial and commercial market as well, and in 1978, opened the brand new, large warehouse in Via Affile (in the "Tiburtina Valley"), see Fig. 7.45, fully operational in 1979/1980; in the 1980s his staff reached the top number of 1200 people.

Between the end of the 1980s and the beginning of the 1990s the Company faced with a period of deep crisis linked to the changing geo-political conditions (and to the conflict in the Middle East); in 1993 the Company merged with

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[32] More precisely, from January 1st, 2013, Selex ES (ES stands for *Electronic Systems*) incorporated the companies Selex Galileo and Selex Elsag, and bought the assets of Selex Sistemi Integrati—so avoiding the acquisition of the contentious jurisdiction originated from that firm. This new company of the Finmeccanica group, organized in three divisions (Air and Space Systems, Land and Naval Systems, and Security and Smart Systems) started with a workforce of about 17,900, with a decreasing trend.

[33] *Oerlikon Italiana* (an *Oerlikon Group* company) was founded in Milan in 1948 and initially specialized in precision machine tools. In the 1960s entered the defence sector, producing 20, 25 and 35 mm automatic guns, as well as mechanical parts for *Contraves Italiana* systems. In 1993, in response to profound, fast-moving changes in the global defence market, Contraves Italiana S.p.A and Oerlikon Italiana S.p.A. merged to form *Oerlikon Contraves S.p.A.*, mirroring the merger of the Oerlikon and Contraves groups.

[34] Despite some current feeling, the Swiss are sometimes fanciful, as reflected in the choice of the name, of Latin origin: *Contra-Aves* = Against-Birds = Anti-Air (attacks).

[35] Unfortunately this industrial complex of significant historical interest was demolished many years later to build the headquarters of *Telespazio*, established in October 1961, and, from December, 2002, controlled by Finmeccanica.

Fig. 7.43 The first *Contraves* site in Lungotevere delle Armi 12, Roma

Fig. 7.44 The old Contraves site in Roma, Via Tiburtina, 1950s

Fig. 7.45 The Contraves plant in Roma, Via Affile, 102

Oerlikon Italia and became *Oerlikon Contraves* S.p.A.; in 1999 it was taken over by the German group *Rheinmetall AG*, a leading German defence and automotive technology group. In August 2007, Oerlikon Contraves S.p.A. changed its name into *Rheinmetall Italia S.p.A.*, and from the beginning of 2009 this firm has been part of the group *Rheinmetall Air Defence*.

The situation of "radar house" of the group (the first radar was delivered around 1958) has generated and grow up in Contraves all the basic and applied know-how necessary for the development of short-range (order of tens of km) surveillance, acquisition and tracking radars capable of operating in environments with strong "clutter" echoes and with electronic interference or "jammers". This know-how includes the knowledge related to Doppler techniques (and the usage of the FFT), to Pulse Doppler systems, to the Monopulse technique, to microwave, especially—but not only—at X-band.[36] With regard to the highest frequency bands, we should mention the tracking radar of the 1990s operating at a wavelength around 3 mm (W band) for low and very low altitude targets, to assist the X-band tracking radar, and later, with hardware partially derived from the previous one, the "millimeter wave" civil radar for control of the airport surface. This experimental radar set was developed and tested at the *Marco Polo* airport of Venice in the early 2000s by a temporary consortium made up by Tor Vergata University, Thales ATM (Gorgonzola, Milan) and Oerlikon Contraves Italy, on the basis of a study by the University of Rome Tor Vergata, see Figs. 7.46 and 7.47.

The main products of the Company since the 1950s are radar sensors for the fire and missile control stations against air threats at short-range and at low altitude, both for land and sea applications. The early control stations, produced over a thousand units from the 1950s to the 1960s and beyond, were the *Superfledermaus* and the *CT 40* (see Fig. 7.48) for the Army, with the technologies of that time: magnetron transmitter and conical scan. In the 1960s and 1970s Contraves developed autonomously the *Vitex*, (see Fig. 7.49), a navy radar system derived from the Superfledermaus, and the short-range (20 km) search radar *LPD*

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[36] The X band is, by far, the most used in Contraves/Rheinmetall but there have been developments in the C, Ku and W bands in addition to the L-band for the IFF.

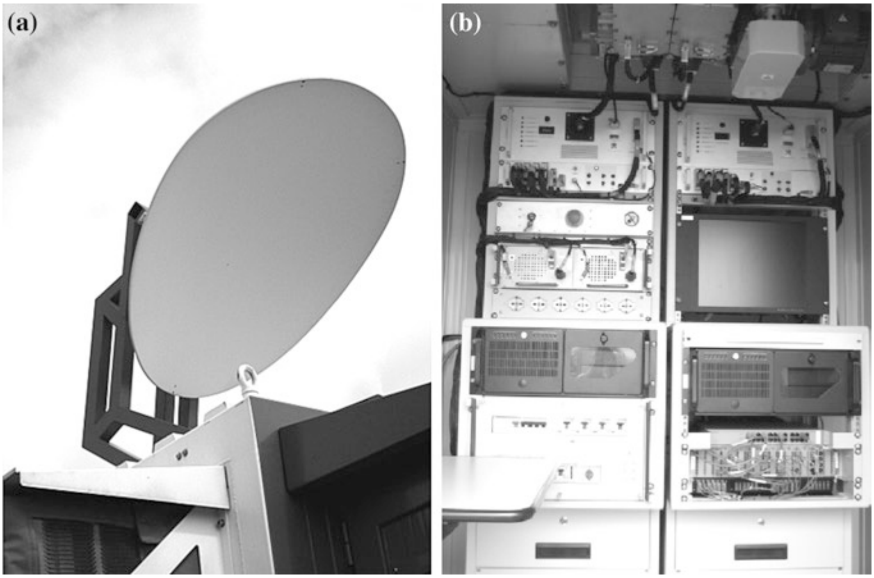

Fig. 7.46 The twin-channel millimetre wave radar for airport applications installed in the "Forlanini" airport, Milano Linate, 2000s: **a** the "nail-shaped" reflector, the only rotating part of the antenna, **b** interior of the shelter hosting the whole radar,

20 with a Klystron transmitter; these were the former applications of digital techniques in Contraves radars.

In the 1970s and 1980s Contraves developed (on Ericsson's license), and improved, the very popular *Skyguard*, a land mobile system for search, tracking and control of anti-aircraft weapons and missiles (between the latter, the well-known *Aspide*).

In 1979, development began of coherent radars, using TWT, frequency and PRF agility, coded pulses (pulse compression) and other innovations. Among them, the *ADATS* system (Fig. 7.50), whose prototype operated in 1982 and saw the massive used digital techniques, and the naval *X-BTR* (i.e. X Band Tracking Radar).

Among the most recent products, in addition to the wheeled *Shorar* (Fig. 7.51) and to the *Skyshield*, there are two compact sets with all the electronics in the movable part behind the antenna and the distributed transmitter using mini—TWT's or solid-state power amplifiers. They are the tracking radar *X-BTR Mk 2*, and the surveillance radar *X-TAR 3D* (Fig. 7.52), an X-band three-dimensional Target Acquisition Radar with twelve elevation beams obtained by digital beam forming, which is particularly suitable against the new threats of rockets and mortar shells.

The framework of the Italian radar industrial activity has to be completed with two private, medium-size companies, i.e. GEM Elettronica and IDS—Ingegneria dei Sistemi.

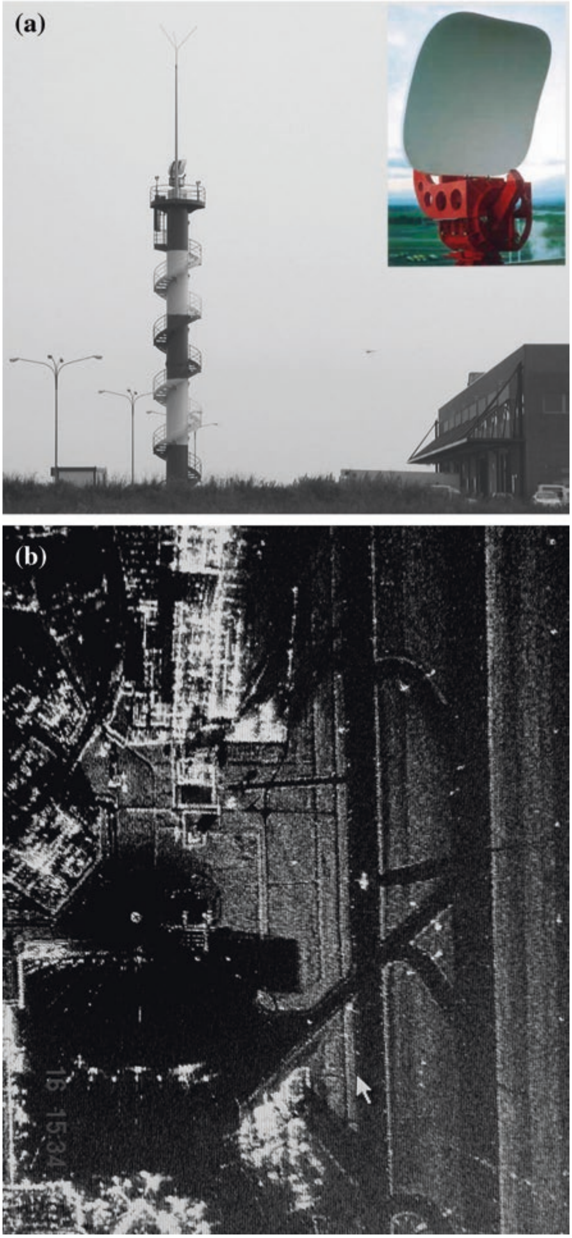

Fig. 7.47 The millimetre wave radar for airport applications **a** the set operating in Venice during the early 2000's ; **b** an image of the Venice airport where it is possible to notice the taxiways, an aircraft with its electromagnetic shadow, and—on the *right*—a series of signs (and poles) at the beginning of the lagoon

The former, which has its headquarters in *S. Benedetto del Tronto* (AP) and its production plant in *Monteprandone* (AP), is owned by the founder Giuseppe (*Peppino*) Merlini (S. Benedetto del Tronto, August 9th, 1945). In 1968, Giuseppe Merlini established a small company in San Benedetto del Tronto to provide the

Fig. 7.48 The anti-aircraft fire control system *CT 40*

Fig. 7.49 The naval fire control system *Vitex*

Fig. 7.50 The ADATS system

technical service for navigation radars, echo-sounders and radio transceivers on board of local fishing and commercial boats.[37] Mr. Merlini called this company

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[37] S. Benedetto del Tronto is one of the main European sites for fishing and seafood industrial processing.

Fig. 7.51 The Shorar system

Fig. 7.52 The three-dimensional surveillance radar X-TAR 3D

"*Giuseppe Elettronica Merlini*", hence the acronym GEM. At these times, not so many fishing boats used radar and sensor technology, and the company started operating with only two technicians, but the service business grew up progressively and was extended to new areas including Sicily and Sardinia. Soon, with noticeable entrepreneurial spirit, Giuseppe Merlini considered the option to produce and sell those not too complicated and very popular radar sets. So, in 1977, the company—which was renamed "GEM elettronica Srl"—started to produce its own design of navigation radars (see Fig. 7.53) and plotters, committing itself to the installation and service of its own naval products. At its establishment, GEM

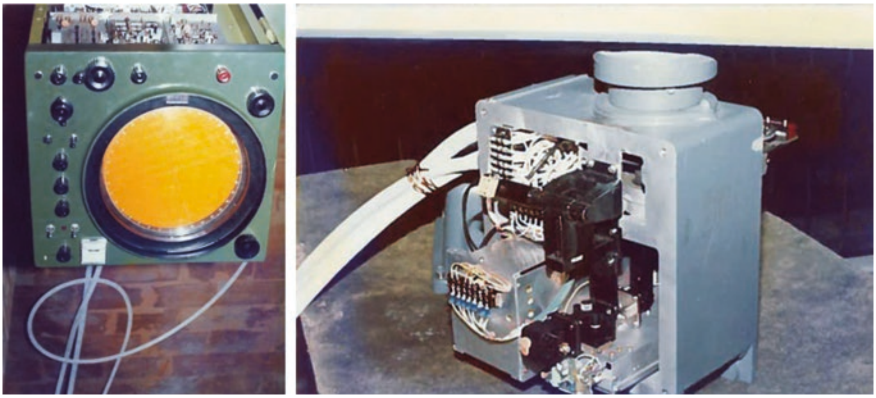

Fig. 7.53 The first radar produced by GEM (1978)

elettronica had three shareholders (Giuseppe Merlini, Augusto Merlini and Piergiorgio Di Filippo) and 5 employees.

Since then, the breadth of maritime sensors, technology and hardware/software capabilities by GEM elettronica has grown steadily thanks to the acquisition of domestic and international customers for both commercial and military applications.

Since 1977, GEM elettronica's naval products have undertaken a number of technical evolutions accompanying the growth of the company, as outlined below. The first technological impact in mid 1980s came with introduction of the "television CRT display", a type of "bright display" which, unlike the previous, fully analog CRT (Cathode Ray Tube) display shown in Fig. 7.53, made the radar screen visible to several people in normal light conditions, rather than to one observer only. The products developed in those years included the radar series BX (see Fig. 7.54), SC (See Fig. 7.55), LD, the GEOMAP plotter, the military GEMANT, the command and control tactical consoles and the Electronic Chart Display & Information System (ECDIS).

The second half of 1990s saw the widespread utilization of LCD (liquid crystal display) replacing the CRT displays.

In 1998, GEM elettronica acquired a branch of *Microtecnica SpA*, specializing in mechanical gyros and in autopilots. Through this acquisition, GEM elettronica acquired know-how and technical skills needed to enter the highly-technological market of Fiber Optic Gyroscope systems and started offering a wide range of products which were totally designed, developed and manufactured in house.[38]

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[38] In the frame of high-end sensors for attitude computation and position fix, currently GEM produces and sells fiber-optic based gyrocompasses with up to 0.05° RMS heading accuracy, inertial navigation units with up to 1 nm/12 h Circular Error Probable, and dual-axis fiber optics gyroscopes.

Fig. 7.54 The BX-132/732/1048 scan converter radar system with circular CRT (1985)

Fig. 7.55 SC radar series with television CRT (1990)

In 2004, GEM elettronica opened a new R&D group focused on Fiber Optic and Laser Technology, presently, "*Photonics Research and Applied Navigation Sciences* (PRANS)" Division, for advanced sensors technologies and innovative solutions in the areas of Guidance, Navigation and Positioning.

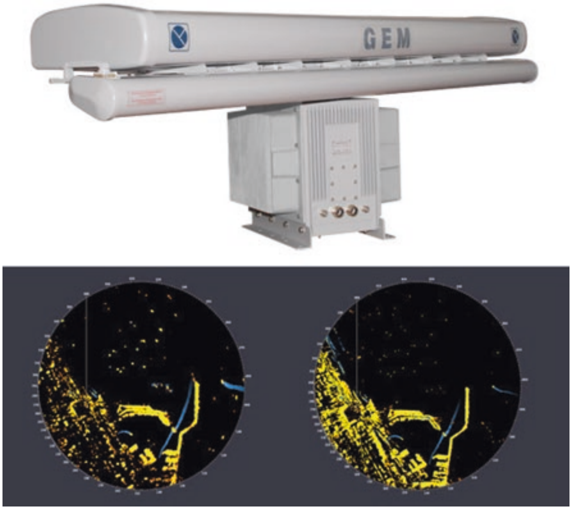

Fig. 7.56 Compact X-Ka band radar (2000s) and its compound display

In 2008, the company introduced its new generation of 2D X-band radar based on solid state transmitter technology featuring frequency agility, frequency diversity and pulse compression/coherent processing for improved performance in high sea-clutter and for detection of small targets. The solid state radar SENTINEL-200 is able to track up to 1000 targets.

Another noticeable system is the X-K_a band radar, see Fig. 7.56.

So, GEM elettronica and has grown to occupy over one hundred sixty people in the business areas of maritime navigation equipment, navigation radars and coastal radars for the Vessel Traffic System (VTS)—of which over 15 are operating in Italy for the national VTS—see Fig. 7.57—and for the coastal security.

Throughout about forty years, GEM elettronica has remained a sole-ownership company led by Mr. Merlini and focused on the design, development, and manufacturing of radar, optical and opto-electronic sensors, as well as integrated on-board systems, for civil and military applications.[39]

The second noticeable medium-size firm, *IDS-Ingegneria dei Sistemi* (Systems Engineering), was founded—and chaired until the beginning of 2010—by Ing. Franco Bardelli who, having left Selenia in February 1980 (as described above), created a new company aimed to exploit some very specialized expertise (in electromagnetism, signals processing and so on) in four lines of business.

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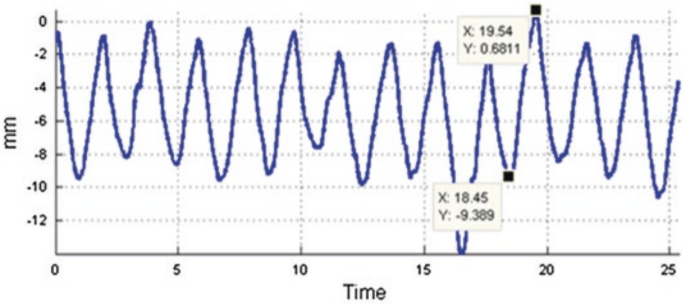
[39] More details on *GEM elettronica*, its products and its achievements are available on www.gemrad.com.

Fig. 7.57 VTS displays and systems

Three of them are related to software products for Air Navigation procedures and for control and forecasting of the electromagnetic environment. The fourth line of activity utilizes radar as a sensor for non-destructive investigations. In this sector, the IDS since the 1980s developed the RIS (*Radar per l'Ispezione del Sottosuolo*, radar for underground monitoring), a GPR (*Ground Probing Radar*) initially marketed for the location of services (cables and tubes) under the road surface. The development followed of "Trough the Wall Radar" sets and of Synthetic Aperture Ground-based radars. An example of the latter is the IBIS radar, in the Ku band, in which the displacement of the sensor by translation on a rail (see Fig. 7.58)

Fig. 7.58 The IBIS, Synthetic Aperture Interferometric radar in the K_u band, by IDS

Fig. 7.59 The RIS, ground probing radar by IDS



Breath Signature

Heartbeat Signature

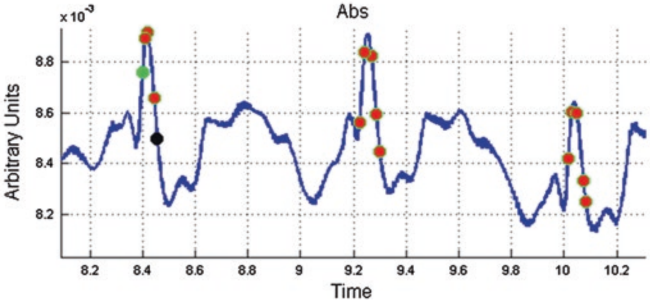


Fig. 7.60 A Through-the-wall radar by IDS applied to monitoring of vital signatures

permits the generation of a Synthetic Aperture. IBIS is used to accurately monitor, thanks to the measurement of the phase variation for each pixel of the image, sub-millimeter movements of the observed surface [Mec 10]. In the case of open pit quarries, these very small movements define impending landslides and potential rock-fall. Examples of IDS systems, i.e. GPR and Through-the-wall radar, are shown in Figs. 7.59 and 7.60, respectively.

Chapter 8
From Ground to Space-Based Radar—The Adventure of the Italian Synthetic Aperture Radar

The development of Italian space-based radars (i.e., Synthetic Aperture Radar—SAR, Radar Altimeter for remote sensing satellites—RA, and finally radar for deep space probing) is strictly related to the history of Italian space activities, of course framed in the national and international context [DeM 11].

The main related milestones are:

- 1959 (September 8th): within the CNR (*Consiglio Nazionale delle Ricerche*, the National Research Council of Italy), a Committee for space research (CRS—*Commissione per le Ricerche Spaziali*) was established and chaired by Luigi Broglio[1]; a year later, in April, CRS and NASA signed the first agreement for scientific collaboration, and in the following year (1961) Telespazio[2] was established.
- 1964 (December, 15): launch of *San Marco A*[3], an experimental satellite for high atmosphere studies, first of a family of five satellites launched from 1964 to 1988.
- 1968: start of the *SIRIO* programme (*Satellite Italiano per la Ricerca Industriale Operativa*—Italian Satellite for Operational Industrial Research), an experimental communications satellite operating in the ranges of 12 and 18 GHz. From the end of 1971 the Sirio programme was managed by the new SAS (*Servizio Attività Spaziali*, Space Activities Service) of the CNR.

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[1] Luigi Broglio (1911–2001) was lieutenant colonel of the Italian Air Force, dean of the school of aeronautical engineering at the *Sapienza* University of Rome and director of the Italian Space Agency (ASI). He conceived and operated the *San Marco* programme with which Italy became the third country worldwide to build and operate its own satellite.

[2] Telespazio is a multinational space services company—presently, a joint venture between Finmeccanica (67 %) and Thales Group (33 %)—, with headquarters in Rome, Italy. It is the oldest company worldwide working exclusively in the market area of space services (communications, Earth observation and management of orbital satellites, system engineering and other) and operates worldwide through many subsidiaries.

[3] The launch vehicle was provided by NASA and was launched with an Italian launch crew.

G. Galati, *100 Years of Radar*, DOI 10.1007/978-3-319-00584-3_8

- 1977 (August, 25th): **Sirio** is launched from Cape Canaveral after a 10 years "gestation" and the significant expenditure of 90 billion lire.
- 1979 (October, 25th): approval of the Italian National Space Plan (*Piano Spaziale Nazionale*) with allocation of 200 billion lire for space activities in the time frame 1979–83.
- Late 1970s—early 1980s: Italy participates in ESA remote sensing programs, including *ERS-1*, a satellite for radar remote sensing.
- 1988 (May 30th): establishment of the ASI, *Agenzia Spaziale Italiana*—Italian Space Agency[1].

The concept of the SAR—the most complex radar sensor that has ever flown—was firstly developed by Carl Wiley from the *Goodyear Aircraft Company* in 1951 and was demonstrated at the *University of Illinois* in the following years[2]. Wiley patented the system, that today we call *Synthetic Aperture Radar* (SAR), on July 20th, 1965 (US Patent 3196436), with the name "Pulsed Doppler Radar Methods and Means". In reality, the first airborne SAR on an aerial platform (called *DOppler Unbeamed SEarch Radar*—DOUSER) was built and tested by the company *Goodyear* between 1952 and 1953; the very late date in which the patent (initially dated August 13th, 1954) was published is due to the confidentiality which was imposed by the US government and remained in force for many years. One year after Wiley, some researchers from the University of Illinois developed, in a wholly independent manner, the same idea and the same "beam-sharpening" and "autofocus" concepts. In the summer of 1953, the *University of Michigan* with his Radar Laboratory and the "Project Wolverine" initiated the work that would have resulted in an operational SAR. The needed processing burden was, by far, beyond the capacity of computers of that time but, thanks to Prof. Emmett Leith (1927–2005), a pioneer of the optical holography, an adequate optical processor was designed and constructed. In 1957 at the University of Michigan they obtained images of unexpected quality with a first airborne SAR and the optical processing of the radar signal, recorded on a photographic film.

The main steps of SAR development can be synthesized as follows.

- 1957: the first SAR images are generated with an optical correlator (University of Michigan).
- 1964: the University of Michigan tests the first analog correlator applied to the SAR, which operates in deferred time.
- 1969–1972: several companies (Goodyear, Westinghouse, and Hughes) build digital correlators, firstly in deferred time, then in real time.
- 1978: the *SEASAT satellite* is launched, and becomes operational, with the first space-based SAR (L-band) developed by NASA/J*et Propulsion Laboratory* (JPL); the generation of images takes place on ground in deferred time.
- 1981: first SAR mission on the *Space Shuttle*, the SIR-A, followed in 1984 by the SIR-B (L-Band), in which the raw data are transmitted to ground in digital form and processed with digital techniques in order to obtain the image (in deferred time).

- 1986: a first *real-time processing* of the signals from satellite SAR is carried out by the JPL.
- 1987: the Soviets launch their first SAR satellite, on the *Cosmos 1870*.
- 1990: the *Magellan* mission provides the first SAR images of the surface of Venus, which is covered by dense layers of vapours and is not visible with optical techniques.
- 1990/1: Soviet mission ALMAZ-1 (S-band SAR).
- 1991: European mission ERS-1, followed by ERS-2 in 1995 (C-band).
- 1992: Japanese mission JERS-1 (L-band).
- 1994/5: Canadian mission *Radarsat 1* (C-band).
- 1994: SAR missions on the Space Shuttle: SIR-C, with three bands (L and C developed by the USA, and X, developed by Germany and Italy) and polarimetry on L and C bands.
- 2001: *interferometric SAR* mission called *SRTM* (Shuttle Radar Topography Mission) on the Space Shuttle.
- 2002: European mission *Envisat* (SAR in the C-band).
- 2006–2008: orbiting of five identical German satellites SAR-Lupe-1 … -5 for military purposes (X-band, sub-metric resolution).
- 2007: second Canadian mission, *Radarsat-2*.
- 2007–2010: launch of the four *COSMO-SkyMed* satellites (SAR in the X-band for dual use).
- 2007: German Mission *TerraSAR-X* with an X-band high resolution SAR.
- 2010: German Mission *Tandem-X* with two identical TerraSAR-X satellites in close formation (distance: hundreds of m) for interferometry and creation of digital of terrain elevation models (DEM).
- 2011: start of the development phase (by ESA) of the pair of satellites *Sentinel-1*[4] with a C-band SAR, which will operate jointly in a sun-synchronous orbit, as a part of the European program (EU-ESA) GMES— *Global Monitoring for Environment and Security* now named *Copernicus*.
- 2014 (April 3rd) launch of the first Sentinel-1 satellite from Europe's Spaceport in French Guiana.

The first satellite SAR system for civil applications was developed by the Jet Propulsion Laboratory (JPL) and launched on June 26th, 1978; on board the ***Seasat*** satellite, together with other sensors (Radar-altimeter, Scatterometer and Microwave Radiometer) was the L-band (23.5 cm) SAR operating at single (HH) polarization and beam pointing at 20° from the vertical (antenna beam width: $1^\circ \times 6^\circ$)[3].

Although designed for oceanic monitoring, the *Seasat* SAR has produced interesting radar images of the Earth's surface in the hundred days of its operation,

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[4] Sentinel-1 is a two satellites constellation with the prime goal to provide medium and high resolution SAR imaging data for the continuity of Land and Ocean monitoring, following the retirement of ERS-2 and the end of the Envisat mission.

and is the leader of a series of increasingly complex SAR systems characteristics, i.e. multi-frequency, multi-polarization, operating modes *wide swath Scansar* and *high resolution Spotlight*, interferometry etc., with ability to extract more and more environmental information. In the 2000s [Per 99] the detection of the moving targets on the surface of the Earth was added, making SAR imaging a common means of land surveillance from airborne radars for many tactical applications[4].

Within **Selenia**, the space activities started with its *Divisione Spazio* (Space Division), which in 1983 became a new company, subsidiary of Selenia: the *Selenia Spazio S.p.A.*, then renamed *Alenia Aerospazio Divisione Spazio* and, soon after, *Alenia Spazio* (1990), a company of the *Finmeccanica* group, specialized in components, subsystems and systems for space missions. In 2005 Alenia Spazio merged with the French company *Alcatel Space* originating a new company called *Alcatel Alenia Space* having in France and in Italy most of its design and production activity. On April 5th, 2006 Alcatel decided to sell his stake in Alcatel Alenia Space to the *Thales* group. This operation was completed on April 10th, 2007 with the establishment of *Thales Alenia Space*[5] for the space manufacturing part, two-thirds owned by Thales group and one third owned by Finmeccanica, while the space services part was attributed to the company *Telespazio*, two-thirds by Finmeccanica and one third by Thales group.[6]

The development activities for space-based radar in Selenia Spazio started in the 1980s with the project of an *X-band synthetic aperture radar for the Space Shuttle*, under the aegis of the *Servizio Attività Spaziali*/CNR and with funds from the *Piano Spaziale Nazionale* (National Space Plan). So, the SAR-X (or X-SAR) was developed in collaboration with the German *Dornier,*[7] and, as an integrated *Shuttle Imaging Radar SIR-C/X-SAR* system, flew in April, 1994 with the mission STS-59 (and subsequently with the mission STS-68, from September 30th to October 11th, 1994) of the Shuttle *Endeavour*.

The German program for space-based radar imaging (SAR) dates back to the 1980s with the *Microwave Remote Sensing Experiment* (MRSE) of the first Spacelab mission in 1983, of which the SAR-X is a follow-on. Operating at a wavelength of 3.1 cm (9.6 GHz) and in the VV polarization, the SAR-X, although devoid of the polarimetry capabilities of the SIR-C, was an important complement to the SIR-C to obtain a three bands (L, C, and X) system.

An example of SAR-X product is the image of the 20 km × 17 km region around Florence, taken on April 14th, 1994, with the North in the left direction

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[5] Thales Alenia Space is organized in two companies called TAS-I and TAS-F, of Italian and French law respectively.

[6] This—symmetrical looking but not necessarily fine for Italy—arrangement has been strongly criticized by the new CEO of Finmeccanica (Mauro Moretti) in different speeches between end 2014 and 2015, especially for the lack of Italian control of strategically relevant space activities. Therefore some changes can be expected.

[7] The *Dornier-Werke* GmbH (originally *Zeppelin Werk Lindau* GmbH) was taken in 1985 by the *Daimler Benz* group, and its aeronautical activities were transferred in 1995 to the *Fairchild*, establishing the society *Fairchild Dornier* which ended its activities in 2002.

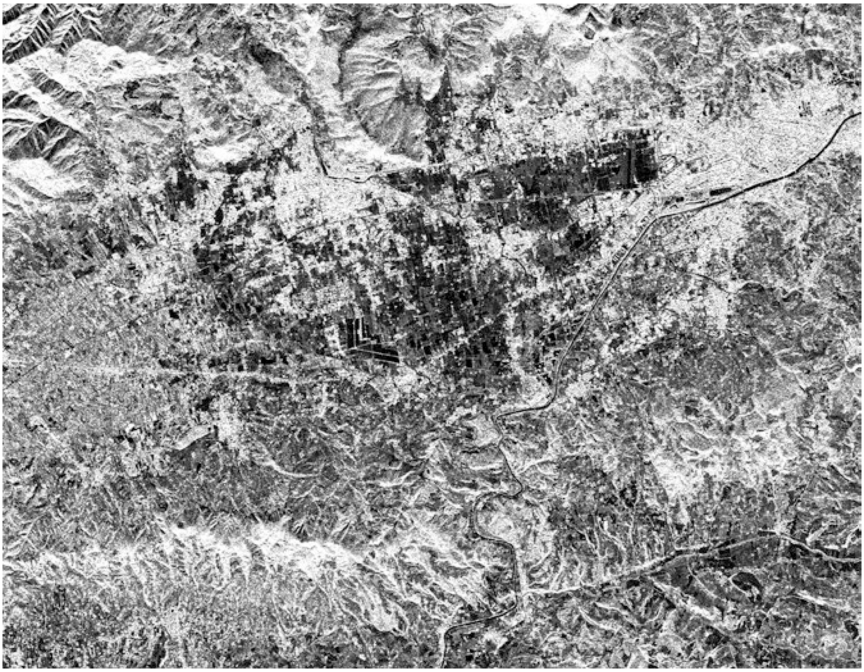

Fig. 8.1 SAR image of the Florence area taken on April, 1994, by SIR-C/X-SAR

of the image, where it is possible to notice the Arno River, the *Ponte Vecchio* and finally the *Santa Maria Novella* train station as an asymmetrical V-shaped dark block in the centre, see Fig. 8.1.

To the activities related to the X-SAR program and to the related missions *SRL-1* (April 1994) and *SRL-2* (October 1994), Alenia Spazio added the design and development of the *radar-altimeters* (RA's) for the *Earth Observation Satellites ERS-1* (1991) and *ERS-2* (1995), the *Cassini* probe with the *Titan radar mapper* instrument developed in cooperation with the JPL[8] (1997), the *Shuttle Radar Topography Mission* (SRTM) in 2001, with interferometry in a single orbit, the *RA-2 altimeter* for the *Envisat* satellite in 2002, the *Mars Express* (2003) and *Mars Reconnaissance Orbiter*—MRO (2005) with a radar sounder (*ShaRad*: Shallow Radar) for the sub surface analysis, and finally the *COSMO SkyMed* (2005) described below.

After the SAR-X program, Alenia Spazio (then: TAS-I) undertook, under the guidance of the Italian Space Agency (ASI), the development of

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[8] The Jet Propulsion Laboratory (JPL) is a federally funded research and development centre (FFRDC) managed and operated by the California University of Technology, Caltech under a contract from NASA and located in the Pasadena area, California, USA. Its Director from May, 2001 is the SAR and space radar scientist Charles Elachi (born in Lebanon in 1947) who and also holds professorships in electrical engineering and planetary science at Caltech.

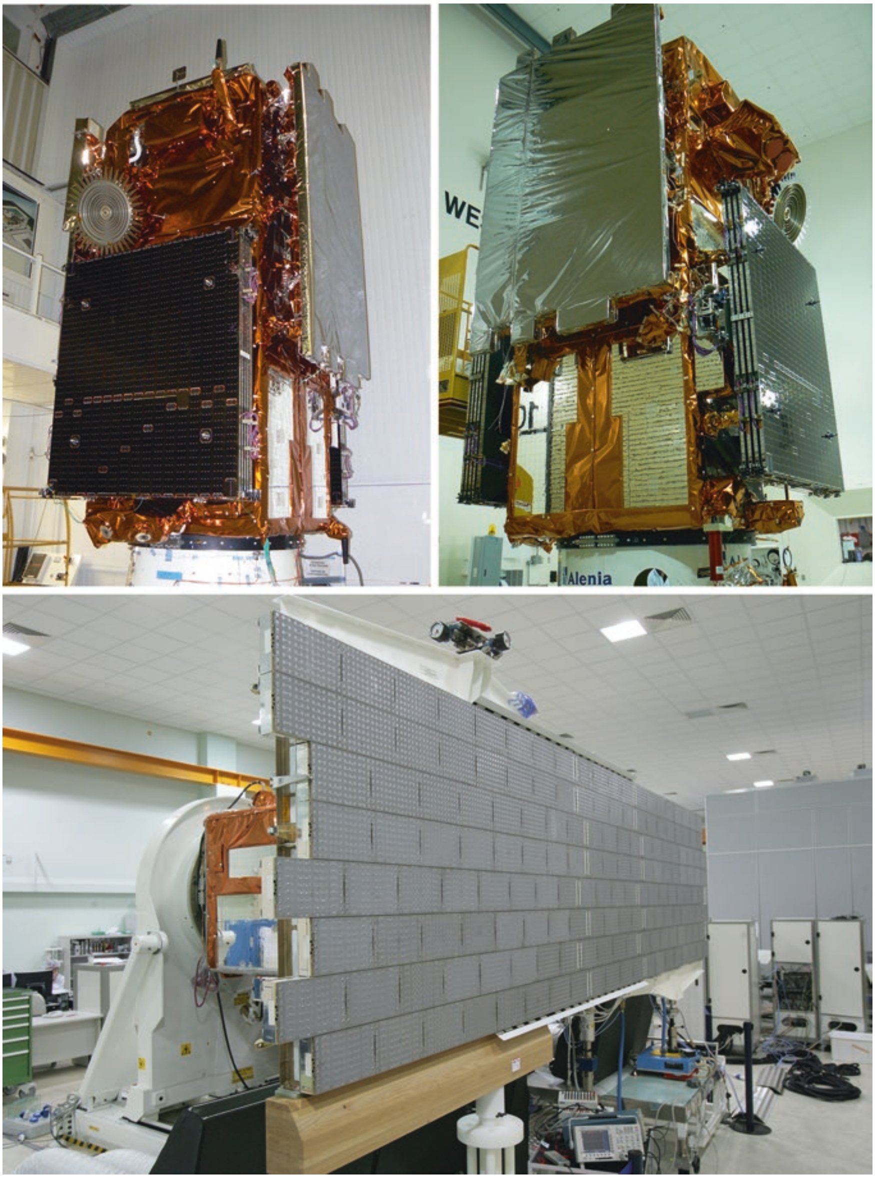

Fig. 8.2 The satellite and the antenna of the COSMO-SkyMed system in the Thales Alenia Space (TAS-I) laboratory, Rome (courtesy of TAS-I)

COSMO-SkyMed, an "All Italian" SAR in the X-band, with an *active phased array antenna* (SAR-X had a slotted- waveguide antenna, with mechanical scanning of the beam) for dual-use. This program is jointly funded by the ASI and by the Ministry of Defence. The COSMO-SkyMed system is based on a constellation of four identical satellites (see Fig. 8.2) able to carry out up to 450 acquisitions

Table 8.1 Operating modes of COSMO SkyMed (courtesy of TAS-I)

	HIMAGE	PING PONG	SPOT#2	WideRegion	HugeRegion
Size (km × km)	40 × 40	30 × 30	10 × 10	100 × 100	200 × 200
Resolution (m × m)	3 × 3	15 × 15	1.0 × 1.0	30 × 30	100 × 100
Images per day	375	375	75	150	75
Access region	20–59.5° >600 km	20–59.5° >600 km	20–59.5° >600 km	20–59.5° >600 km	20–59.5° >600 km

per day—corresponding to 1800 radar images—of the Earth's surface. The system operates 24 h per day with a great operational flexibility including: a *spotlight* mode (focusing on an area of tens of square kilometers, with resolution up to one meter for civilian use and under 1 m for military applications), a *stripmap* mode (observing a continuous strip of the Earth surface) with also different polarization on a burst basis (*ping-pong* mode) or a *scanSAR* mode (covering a 200 km—wide region). The response times range from 72 h under routine conditions, up to less than 18 h in emergency conditions where the revisit time is less than 12 h. A summary of the various operational modes is shown in Table 8.1.

The first satellite of the constellation, called *COSMO SkyMed 1*, was launched on June 7th, 2007 at the Vandenberg Air Force Base (California) with a Boeing Delta II. The second satellite was launched on December 9th, 2007 from the same

Fig. 8.3 SAR image (COSMO Skymed), center of Rome (courtesy of ASI)

base with the same launcher. The third satellite of the series was successfully launched on October 25th, 2008. The fourth launch, with the completion of the constellation, was executed at 03.20 on November 6th, 2010 (Italian time). The *COSMO SkyMed 4* signals were acquired an hour and 5 min after the launch and received by the *Fucino* station, managed by Telespazio.

An example of high-resolution image of COSMO-SkyMed is shown in Fig. 8.3.

In December 2010 the Italian government launched the "COSMO-SkyMed Second Generation" (for short, CSG) programme whose main unclassified elements are contained in the ensuing Annex No. 5, kindly written by Francesco Caltagirone from the ASI.[9]

8.1 Annex No. 5—Contribution by Dr. Ing. Francesco Caltagirone

8.1.1 General

COSMO-SkyMed Second Generation (CSG), similar to COSMO-SkyMed *first generation* (CSK), is a remote sensing satellite system for high definition radar imaging and for the exploitation of acquired data either in a stand-alone way or through other systems.

It is designed to generate and manage *dual* (civilian and military) *applications* and to operate—on the basis of purposely defined rules—with a multi-program/multi-function/multi-user approach.

From the performance point of view, the CSG constellation aims at improving the quality of the imaging service, providing the End Users with new/enhanced capabilities in terms of higher number of equivalent images and of increased image quality with respect to the first generation, along with additional capabilities (e.g. full polarimetric SAR acquisition mode) and better operational flexibility in planning and sharing the system resources among different kinds of users requesting images with different characteristics.

Being the heir of the CSK constellation currently in operation, the new CSG constellation will ensure operational continuity of the former CSK SAR capability inheriting the CSK imaging modes but with a greater quality and with increased performances. In addition, CSG will also provide new sensing modes, currently not provided by the operating CSK system, in order to widen the application range of SAR imagery from space and to meet the emerging demands by the users and the operational requirements by customers and institutional users (both military and civilian) as well as by commercial users.

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[9] Francesco Caltagirone (Roma, 1954) is the Cosmo Second Generation Program Manager at the Italian Space Agency (ASI)

CSG will be made up by:

- two new satellites (*Protoflight-PFM* and *Flight Model-FM1*),
- an extended and renewed Ground System to meet the new operational requirements and to allow the seamlessly inclusion and the integration of CSG with the residual CSK satellites.

Like CSK, CSG will be for Italy one of the most important investments in the field of space and, as such, is widely invoked in the Document of Strategic Vision of the Italian Space Agency (www.asi.it) for the 2010–2020 time frame. As in CSK, the elements of greatest technological commitment, i.e. the transmit-receive modules (TRM's) of the phased array antenna (a large planar array, whose area is as large as seven square meters) are designed in Italy.

8.1.2 Objectives of COSMO-SkyMed Second Generation

CSG updates and improves the operational capabilities of the CSK system through significant technological advances and a system architectural design including some key novel elements.

Some of the main points characterizing CSG are:

- A Satellite Platform enhanced from CSK, in terms of:
  - significantly improved reliability of satellite equipment (e.g. more reliable and augmented redundancies in the gyro device) in order to ensure an effective (full performance) the satellite operative lifetime up to seven years;
  - new state-of-the-art Avionics Subsystem (AVS) for a very high satellite agility in attitude manoeuvring, by means of a Control Moment Gyro (CMG);
  - augmented electrical power (i.e. more than 40 % increase, necessary to sustain the imaging performances).
- A brand-new design of the Synthetic Aperture Radar (SAR) sensor, capable of a spatial resolution of the "narrow field images" much finer than CSK, while providing multi-polarization and a new experimental polarimetric operation with alternate transmission of two polarizations and simultaneous reception of two polarisations (*Quad-Pol*);
  The technology necessary to implement such a performance are deeply interesting all SAR elements, with a completely renewed design of active phased array SAR antenna and electronics.
- A Payload Data Handling and Transmission (PDHT) system that, considering the larger band and quantity of the data produced by the SAR, has been designed to significantly improve the performances of the PDHT currently in use in CSK, in terms of on-board data storage capacity (doubled), space-to-ground data transmission throughput (doubled), data reception rate from SAR.
- The Ground Segment (GS) will cope with the increased performances of the Second Generation's Satellites and will enhance the planning, control and

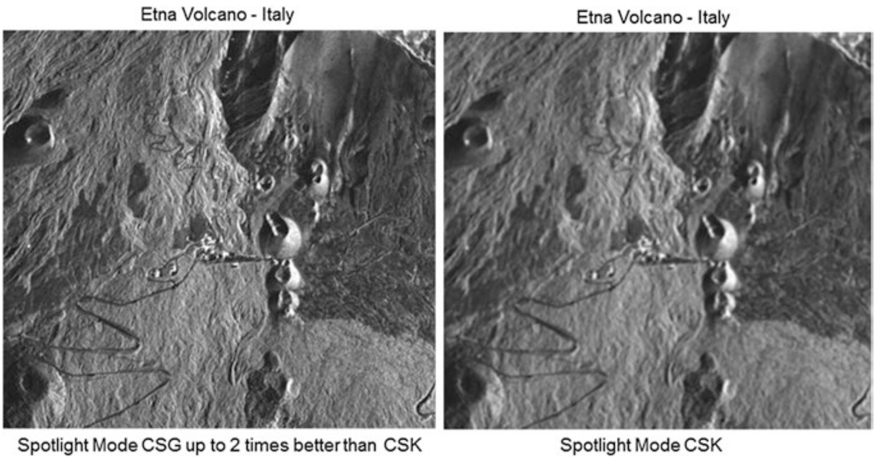

Fig. 8.4 Comparison of SAR images: **a** COSMO Skymed, **b** COSMO Second Generation, (courtesy of ASI)

exploitation capabilities with respect to CSK. In particular, the processing time of raw data will be reduced to about one half with an ability to manage a daily load double w.r.t. CSK. This upgrade is being performed taking great benefit by the IEM (Interoperability, Expandability end Multi-Mission/Multi-Sensor) capabilities already developed in the first generation and further enhanced in the second one. The resulting common first-second generation GS will ensure the full architectural integration of the new CSG capabilities within the "old" CSK ground segment, granting a smooth transition minimising the impact on the operations for the nominal exploitation of the system. The resulting GS will permit to operate CSK and CSG as a unique constellation for the final user during the operation (E) phase.

- The Integrated Logistic Support and Operations (ILS&OPS) segment which is being designed to provide a unique (CSK and CSG) perspective, a unified tools suite and procedures for managing, operating, and maintaining the integrated system that will control both CSK and CSG constellations, with a significant reduction of operational costs.

The different image types by CSK and CSG are shown by examples in Figs. 8.4 and 8.5.

8.1.3 Schedule of the CSG Program

The planning of the CSG programme, whose latest parts are subject to changes on the basis of the incoming allocation of financial resources, is the following (as at the beginning of 2015, and with T_0 = *December 2010*).

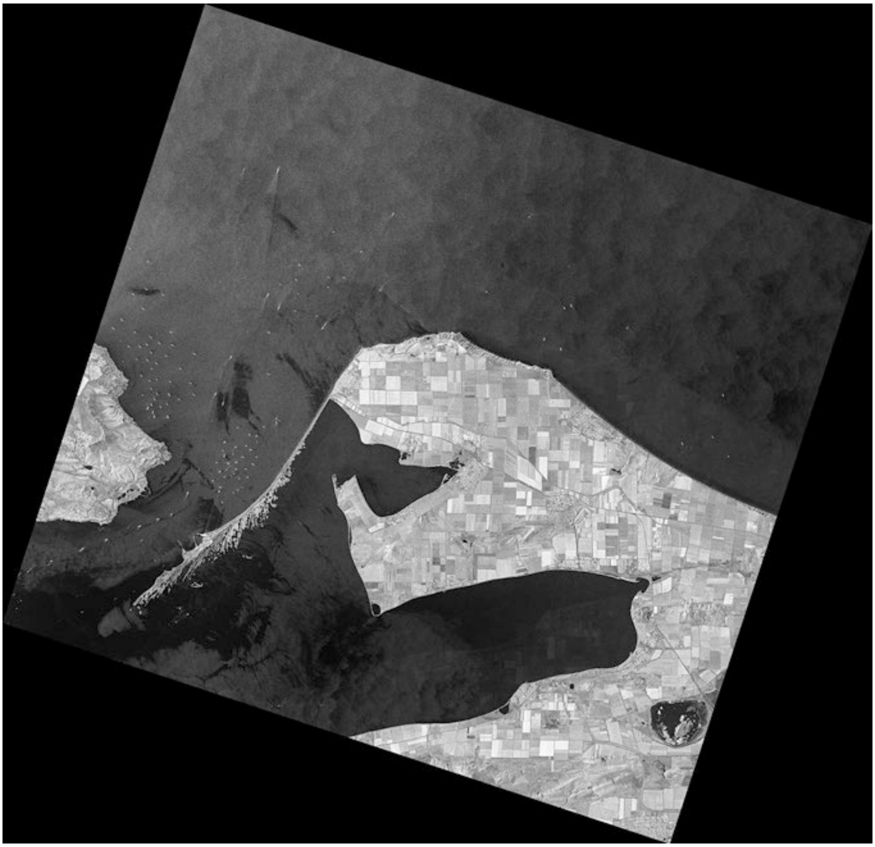

Fig. 8.5 Medium Resolution Image acquired in Kerch strait (Ukraine) "COSMO-SkyMed Product—©ASI—Agenzia Spaziale Italiana—(2007). All Rights Reserved—Image from www.asi.it

- step "B" (Preliminary Design Review): $T_0 + 14$ months,
- step "C"—Critical Design Review: $T_0 + 60$ months,
- step "D"—Implementation of the Protoflight-PFM: $T_0 + 78$ months,
- PFM launch: $T_0 + 80$ months
- step "E1"—Operating System with 1 satellite: $T_0 + 86$ months,
- FM2 launch: $T_0 + 92$ months
- step "E1"—Operational System with 2 satellites: $T_0 + 98$ months.

8.1.4 Deployment of CSG

COSMO-SkyMed—first generation—was deployed between mid-2007 and late 2010 and has entered into operational service since mid-2008 with full capacity by mid-2011.

The CSG satellites will be added to those residual of CSK with a seamless transition, and the ground segment updated to allow the simultaneous command, control and use of CSG an of residual CSK satellites.

With the launch of CSG satellites planned in the second half of 2017 and in the second half of 2018, CSG will ensure the operational continuity at least until 2025.

Chapter 9
Scops Owls and Bats—Recent Radar Developments

9.1 Spallanzani, Bats and Radar Techniques

In Chap. 2 it is shown that to the first operational radar built in Italy the name was given of a nocturnal bird, the *owl*, by inspiration from a famous poem by Charles Baudelaire. About half a century later, Giovanni Pascoli[1] turned his attention to another raptor, the *scops owl* or *chiu*,[1] a small European migratory owl, mainly active at night, whose size is barely that of the blackbird. In the eighteenth century it was found that in another nocturnal creature, the bat,[2] the evolution of species had generated, albeit in the ultrasonic rather than radio electric form, a kind of radar. The first studies on what today is called *echo-location in bats* are due to the abbot Lazzaro Spallanzani,[3] the scientific interest of which with regard to animal vision is addressed first to scops owls, of which Spallanzani wanted to understand the ability of night flight. Spallanzani wrote: “I wanted to know if the *chiu* may see in thick darkness”. For this purpose, he released three scops owls in a tiny room with the windows carefully sealed and illuminated only by a candle. And he could notice that, as long as the candle remained lit, the birds could safely fly. But with

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[1] Giovanni Pascoli was born in *San Mauro di Romagna* (presently, San Mauro Pascoli, Forlì-Cesena) on December 31st, 1855 and died in Bologna on April 6th, 1912. Both Baudelaire and Pascoli paid much attention to the night birds of prey: the first one to the appearance of owls, the second one to the song of the scops owls.

[2] The bats, mammals of the *Chiroptera* order, are very useful to the ecosystem as predators of mosquitoes (a bat can eat as much as one mosquito every 10 s, and thousands per night).

[3] Lazzaro Spallanzani (January 10th, 1729–February 12th, 1799), abbot and professor at the University of Pavia, a great biologist (mostly famous for its research in the field of reproduction), was able to relate the consumption of oxygen with the tissue respiration, worked the artificial insemination in dog, showed the action of gastric juice and did many other discoveries. The most important of them was probably having refuted experimentally the thesis of spontaneous generation. Last but not least, Spallanzani first understood that bats orient, and localize their prey, with ultrasound.

G. Galati, *100 Years of Radar*, DOI 10.1007/978-3-319-00584-3_9

the candle off, the chiu "*took the flight at random, and went to collide with a wall, then fell to the ground like a rag—It is decided that in total absence of light they cannot see*". Having seen that the explanation lies in the high sensitivity of the visual system of the scops owls, just four days later Spallanzani repeated the experiment using three bats and discovered that they perfectly orientate themselves even in the darkness. Spallanzani described his first experiments in a manuscript on 1793 and in the following year published his final research on the orientation of the blinded bats. The paper of 1794 has the significant title "*Letters on the suspicion of a new sense in bats by the Abbot Spallanzani*". He realized that the bats, even when made blind, skillfully steered clear of the walls and some ropes hanging from the ceiling. In a corridor bowed at a right angle, they ran to the corner continuing their flight in the rest of the corridor: the flight was not guided by sight. Convinced, however, that the bats would possess a specialized organ for positioning in the dark, Spallanzani proved that it was not the touch. In fact, having daubed their skin with a thick layer of paint, so as to exclude the sensitivity of the skin, the bats, left flying in a room, flew very close to the walls, but did not collide with them. Discarding then the intervention of view and that of touch, Spallanzani tried to explain the phenomenon.[4] On June 1794, on the basis of similar experiments carried out in Geneva by the Swiss naturalist Charles Jurine (1751–1819), the abbot tried by dropping some tallow from a lit candle into the ear of a bat, and noticed that, under these conditions, the animal was generally unable to fly, and if flying, it collided with the walls. Spallanzani wrote: "*we must say that the bat does not use its eyes, but only the hearing, and the phenomenon can be explained by saying that the motion of the wings, and the body, knocking the air and this being in turn knocked by surrounding solid bodies, it senses, and avoids them*". So, shortly before his death, the brilliant and tireless scholar concluded that, in order to avoid the obstacles, the bats continuously send some sounds that the human ear cannot hear. The echo is perceived by the bat, making its flight possible even in the darkness.

Only 144 years later a great ethologist, Donald R. Griffin (1915–2003), explained in detail how the bats may "see by the ears". In 1938, almost by chance, he discovered the ability of *echo-location* of the bats at the Institute of Physics of Harvard University, where G.W. Pierce (1872–1956) had developed the first ultrasound equipment, with which Pierce and Griffin became aware of ultrasonic cries of bats. In his book,[5] Griffin, who had studied radar techniques, developed an interesting comparison between radar localization (Griffin considered one of the former airborne radars, the AN/APS-10) and the echo-location of bats, showing that, according to some reasonable indicators, the latter is at least two or three orders of magnitude more efficient than the former (see Chap. 5, "Sonar and Radar" in [Gri 59]).

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[4] When Spallanzani caught, in the bell tower, some bats that he had blinded, and then freed, a few days before, he found in their stomach a myriad of insects, just as in the stomach of other (not blinded) bats: the blinded bats could perfectly orient themselves in the dark and succeed in capturing their prey.

[5] [Gri 59] is a delightful book readily available also *on line*.

So, in the Twentieth Century, much later than the experiments of Spallanzani, it was shown that natural evolution produced, well before their invention and use by men, signal types and techniques of detection and localization which even today are of great interest. The bats are the subject of continuing studies[6]; they emit with their mouth (some, with the nose) short ultrasonic signals (with frequencies well above 100 kHz) called *chip* or *click* and listen to the echo due to the presence of objects up to some meters away. Their brain reconstructs the precise position of the object on the basis of the delay of the echo perceived by each ear, its frequency and its intensity. A great sensitivity is required to locate insects, the main food of bats, even at distances of several meters. The emitted signal[7] has both narrow-band i.e. *constant frequency* (CF), and broadband (*frequency modulated*, FM, or *Chirp*) components. The linearly frequency modulated signal called *Chirp* (including its evolutions with non-linear modulation) is one of those emitted by bats, and has been studied for radar applications by both the Germans and the Allied powers since 1942–43. It is remarkable that the first analysis of the signals emitted by bats date back to just four or five years before these years. With respect to a normal rectangular pulse of equal duration and energy, this type of signal allows a dramatic improvement in the capacity of *range resolution*, i.e. of discrimination in the distance measurement, see Fig. 9.1.

Not only signals, but also the processes by which the bats locate obstacles and their preyare of great interest from the radar point of view.[2] According to tradition, the name *chirp* (which identifies the chirping of a bird) is due to one of the U.S. experimenters who developed the *pulse compression* in the 1950s, i.e. B.M. Oliver, who, in an internal Bell Laboratories document, stated that radar should emit "not with a bang, but with a chirp". The theoretical foundations of the *pulse compression* can be found in [Coo 60] and [Coo 67]; for the concept of matched filter, see [Woo 53] and [Tur 60]. A historical discussion of this subject is presented on page 350 of [Bla 04], recalling the first documents of pre-war Germany and some war-time documents,[8] as well as some US patents[9] and the first experiments in the USA on the 1950s, which, once the topic was "declassified", led to publication of the remarkable works [Kla 60] and to [McC 66], the first work in the open literature analyzing bat signals from a radar point of view. Independently,

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[6] The *North America Society for Bat Research* (NASBR) has organized since 1970 an annual Conference, the *North American Symposium on Bat Research*, associated with a prize, the *Spallanzani Award*, which allows the participation of scholars not coming from the United States, Mexico or Canada.

[7] A typical bat signal is available at: http://dsp.rice.edu/software/bat-echolocation-Chirp.

[8] Among them, the patent N. 768068 by E. Huttman dated March 22th, 1940 and the paper by R. Krönert on 1942.

[9] The main patents were by Dicke (January 6th, 1953, N. 2624876) and by Darlington (May 18th, 1954, N. 2678997, entitled *Pulse Compression*).

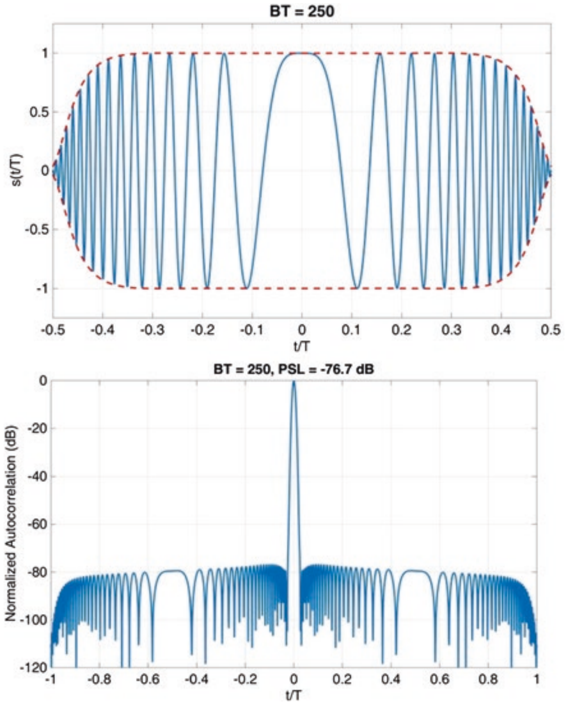

Fig. 9.1 A low-sidelobes, non-linear optimal Chirp (*top*) and the output of its matched filter (*bottom*)

pulse compression was invented and applied[10] in the Soviet Union [Yan 14], thanks to studies by Yakov D. Shirman, and its patents issued in 1955 and 1956.[11] The output of the filter matched to a *Chirp signal* is a pulse with a duration close to the inverse of the bandwidth of the signal, i.e. much narrower than the transmitted pulse (the term *pulse compression* is currently used to denote this process). Figure 9.1 shows an example of *Chirp* signal, before and after the compression process, as studied by Tor Vergata University (2014).

Summing up, the eco-localization techniques of bats are close to the ones of modern radars including: adaptive use of resources; timing and frequency agility of the waveform; pulse compression; tracking with estimation of the Doppler frequency and precise angular measurement by monopulse; Low Probability of Intercept, and probably more.

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[10] In summer 1959, based on the P-12 Radar System, a prototype of VHF-band radar with LFM pulse compression was built and tested under the leadership of Y.D. Shirman, with a pulse duration of 6 microseconds and a spectrum width of 5 MHz. After processing, range resolution improved 30 times without practical decreasing in range performance.

[11] Pat. N. 149134, 146134, 146803 and 152487.

9.2 “Stealth” Targets and New Frequency Bands

After the Second World War the selection of radar frequencies in the western world was oriented to the use of decimeter and centimeter waves (from 23 cm at the L-band to 2 cm at the Ku-band) for the main radar applications. The use of lower (UHF, VHF and HF band) or higher frequencies (mainly in the bands: Ka of 9 mm and W of 3 mm wavelength) was deserved to special applications. On the other side, the Soviets had and maintained a wide experience in metric wave radar (particularly in VHF band),[12] [Yan 14]. The VHF band was useful to the Soviets and their allied at the time of entry into service of to *reduced observability* or “*stealth*”[3] fighter and attack jets, the first of which was the well-known F-117A.[4] For the Soviets, first, and for the Russians, later, the development, by the United States, of *stealth* aircraft (such as the long-range bomber B-2 *Spirit*, likely the most expensive aircraft ever developed) implied the chance to be attacked inside the border of their Air Defense system.[13] As a consequence, they had to develop surface-to-air (SAM) missile systems as well as CVLO (counter very low observable) radar techniques in which the VHF range plays an important role,[5] see (http://www.ausairpower.net/ and http://www.almaz-antey.ru/).

China’s emerging defense industry is strongly considering the threat due to stealth aircraft and missiles: the *East China Research Institute of Electronic Engineering* (ECRIEE) has developed the VHF radar JY-27A Skywatch-V,[14] an active electronically scanned array (AESA) with a tall (about 23–24 m) antenna, unveiled at the Zhuai Air Show (November 2014), see Fig. 9.2.

Farther down on the range of radar frequencies, the HF band (from 3 to 30 MHz) permits radar coverages well beyond the optical horizon thanks to the ionospheric propagation. From the very first experiments of the 1950s, this band has been used for the development of large OTH (Over-The-Horizon) radar systems able to detect

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[12] An example is the P-12 “Yenisei” (NATO name “Spoon Rest”), a Soviet early warning, ground-based VHF radar with a maximum range of 200 km, and altitude up to 25 km, modernized, exported to various nations including Egypt and Serbia, and used in the Vietnam War as well as in several conflicts in the Middle East. It is a three-dimensional monostatic radar, in which azimuth is scanned mechanically by the antenna at 10 r.p.m while the target elevation is determined by phase comparison between upper and lower antenna portions. P-12 has been replaced with the more modern P-18 (NATO name “Spoon Rest D”).

[13] As a matter of fact, the real aim of the large US investment in Stealth aircraft was not so much to directly attack the Soviet, but rather, to force them to sustain huge costs to make their defense systems effective against such threats, leading to a potential economic collapse. In fact, let us consider a reduction of the radar cross section by a figure of a thousand: the radar range in free space is reduced by a figure of 5.6. This means that, in order to maintain an effective line of air defense for the vast Soviet land, the number of surveillance and warning sites (and radars) has to be multiplied by about six, with hardly bearable costs.

[14] The JY-27 (somewhat similar to the Russian 55Zh6ME radar) is claimed to be operational and to have a maximum range of over 435 km, and the following operational modes: omnidirectional surveillance, sector search and missile early warning. The estimated number of antenna elements is 480.

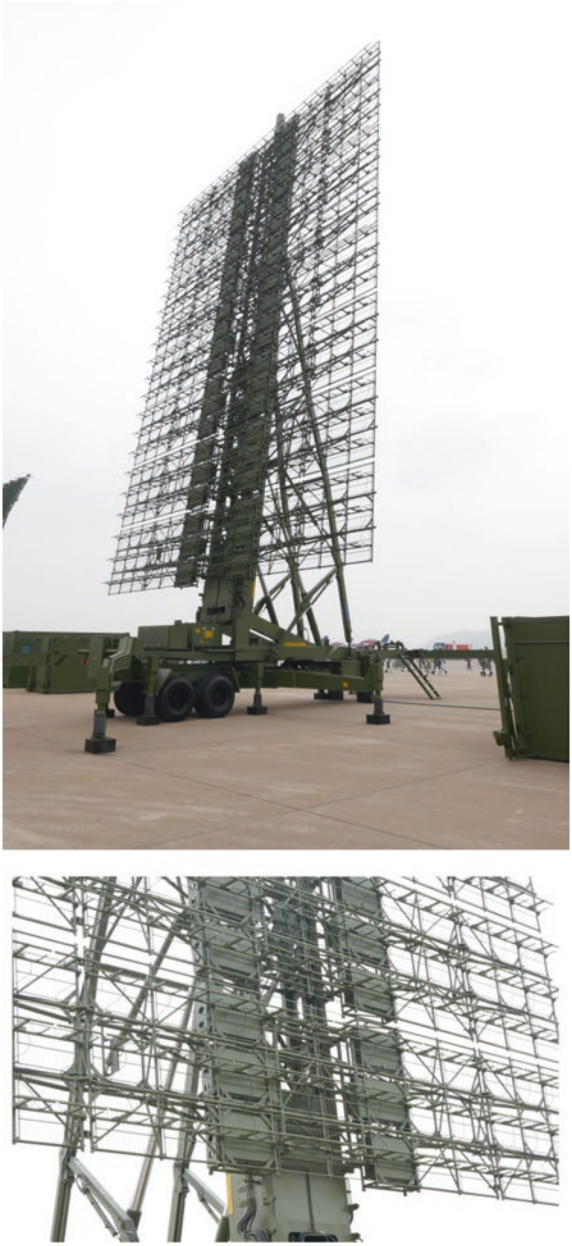

Fig. 9.2 The VHF AESA radar JY-27 A, developed in China (From: Aviation Week and Space Technology, Nov. 17, 2014, pp. 38–39, Courtesy of the Publisher)

air and sea targets at thousands km (http://en.wikipedia.org/wiki/OTH-B_Radar). OTH systems operate in the USA (OTH-B[6] and ROTHR), in Russia and finally in Australia with the Jindalee program.[7]

At the opposite end of the spectrum, the millimeter wave, we have seen (and see) different applications for short distance and/or high resolution, especially when the attenuation due to rain is tolerable. The large amount of bandwidth available at the millimeter-wave frequencies permits very narrow antenna lobes, making it possible to generate radar images that complement, or replace, optical images in conditions of poor (or absent) visibility due to clouds, fog or dust.[15] The mostly used millimeter-wave radar frequencies fall in the so-called *transmission windows* of the atmosphere, at 30/40, 85/96 and 220/230 GHz, in addition to that at 122 GHz, where a 1 GHz-wide bandwidth is available for ISM (industrial, scientific, and medical) applications. However, for low cost applications of radar techniques at millimeter waves, the band of 77 GHz is always the preferred one, because it is standard for automotive applications, thus making available low-cost components and subsystems. An example is the system of small radars [Maz 12] designed to detect and locate the debris (Foreign Object Debris, FOD) that may be present on the runway of an airport and cause very serious accidents, such as that of the Concorde (Air France Flight 4590 from Paris to New York) on July 25th, 2000.

9.3 On the Development of Radar Technologies After the Second World War

It has been shown before that the basic concepts and the main radar (and electronic defense) architectures were developed with the greatest effectiveness and timeliness under the thrust of W.W.II needs. In that wartime they developed concepts and methods such as beam splitting for tracking, which soon originated the *monopulse*, electronic scanning and phased array antennas, bistatic and passive radar systems, frequency agility against jammer, Doppler frequency analysis (and MTI filtering) to mitigate unwanted echoes such as clutter and chaff, cooperation of search and tracking radars, pulse compression,[16] and others, which largely retain their validity today. In addition, some more general results, also essential for the processing of the radar data, were obtained under the pressure of the war. Among them, in addition to the already mentioned spectral characterization of active noise due to Van Vleck and Middleton, must be mentioned those connected to the theory of stochastic filtering starting from the celebrated Wiener filtering,

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[15] Two programs (http://www.darpa.mil/Our_Work/STO/Programs/Multifunction_RF_%28MFRF%29.aspx) of the US Defense Advanced Research Projects Agency (DARPA), i.e. the Multi-Function Radio Frequency (MFRF) and the Video Synthetic Aperture Radar (*Visars*) are in progress in 2012 for radar imaging in the band of 90 and 230 GHz, respectively. MFRF is a intended for guidance, and landing, of helicopters in critical conditions of visibility, while *Visars*, that has to be integrated in the standard electro-optical/infrared head of an aircraft, aims to provide radar images with 20 cm resolution and update rate 5 times per second, fast enough to track a person or a land vehicle in motion.

[16] In reality, pulse compression was used in an extended way only after W.W.II, which was likely due technological limitations.

[Wie 49], first used for prediction of the motion of projectiles of artillery. Kailath [Kai 74] contains a historical review on the topic, while [Sor 70] refers to the wider field of least squares estimation.

In the post-war period, radar concepts and methodologies were *revisited* in view of the new technologies that became available. Of course, the evolution of the threat, very different from that of W.W.II, was the first novelty drive in defense radars. It is not surprising that the United States of America gained most from the knowledge developed during the war, [Cor 03], with the huge advantage arising from being the winners and by not having been bombed. Very few radar systems of that period were truly new, as compared to those developed during W.W.II. Between these few, two are particularly worth notice: the *meteorological* (or, *weather*) radar, which will be discussed later, and the *Synthetic Aperture Radar* (SAR), see also the previous chapter.

An airborne SAR, on board the well-known high altitude reconnaissance aircraft *U-2*, was used by the USA during the Cold War, since the 1950s, to monitor the military infrastructures of the Soviet Union.[17] The operating principle of the SAR itself remained strictly secret until the downing on the Soviet territory, on the first day of May, 1960, of the U-2 of Francis G. Powers from the CIA.[8] To get SAR images without the modern processing means, optical processing was used, by means of conical and cylindrical lenses able to operate the necessary Fourier transforms of the radar signal made visible with an oscilloscope and recorded on a common 35 mm photographic film. Of course, the processing was done on the ground, once the film had been recovered and developed.[18]

The technologies which, in the post-war period, most contributed to the renewal and greatly improved radar systems performance are essentially three: (i) digital signal processing, (ii) highly stable transceiver chains, and (iii) phased arrays with electronic steering of the antenna beam, and subsequently, with digital beam forming.

The evolution of computation means towards digital techniques permitted passage from the completely *analogue* radar of the war and post-war periods, until the 1960s, to the modern ones, equipped with *digital* processors and computers. From the system point of view, this transition has allowed adaptation (radar adaptivity) of the operation of the radar to its environment, with the ability to detect useful targets even in the presence of natural disturbances (clutter due to echoes of land, sea and atmospheric phenomena) and, in the case of military radars, of additional man-made interference (chaff, jammer). With the advent of digital techniques, the decision about the presence of a radar target in a given resolution cell, which was

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[17] The U-2 was able to fly up to 70,000 feet, more than 21 km altitude; according to the experts USA?which were wrong?such a high elevation should have protected it from the Soviet surveillance systems and missiles.

[18] According to some sources, this method, developed for the airborne SAR, has also been applied to the satellite-based SAR. The film was sent to the ground with small rockets and parachutes.

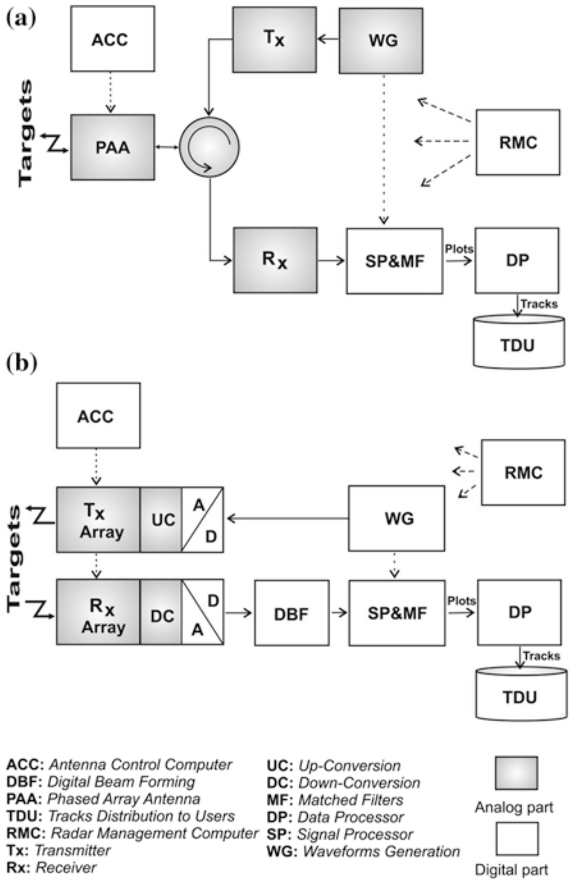

Fig. 9.3 Basic block diagram (**a**) of a *passive* radar phased array and (**b**) of a modern, *active* array radar with digital beam forming

the main task of the war-time radar operator (with the additional task of reading and recording the coordinates of the detected object) is attributed to a machine. This is the so-called *extractor* which, starting from the radar signals (after processing in order to reduce the effect of disturbances and interferences) detects the targets and provides their location, together with any additional information, in the form of messages called *plots*, from whose sequences a dedicated computer creates the trajectories, more exactly, the *tracks.*[19]

In Fig. 9.3 the functional, general schemes of a present and of a next generation phased array radar are shown, where the elements that use digital techniques are highlighted, and prevail in the next generation (full digital radar) case [Gal 15].

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[19] In the technical literature the digital generation of plots and tracks is called *Automatic Detection and Tracking* (ADT); automatic detection involves the definition of a threshold, which must adapt itself to the variations of the disturbance in order to maintain a constant probability of false alarm, that is, a constant false alarm rate, or *CFAR processing*.

9.4 Coherent Chains and Digital Processing of Radar Signals

The most important and long lasting contribution to the evolution of radar is probably the one due to the digital processing of signals, with which the two fundamental radar functions, i.e. target detection in the presence of disturbance and estimate of its position and speed, initially carried out manually, have gradually reached a high level of automation. Digital processing was initially applied to one-dimensional signals, with the only dependence on time being considered, and then to multidimensional signals in the so-called array processing, [Kri 96]. As early as in wartime, they needed to devise suppression techniques of unwanted echoes due to fixed obstacles (mountains, buildings etc.), called *Moving Target Indicator* (MTI). However, only after a transition from the radar transmitters based on the magnetron (which, being an oscillator, has limited stability in frequency and phase) to those based on power amplifiers, using microwave power tubes such as the *klystron* and the *Traveling-Wave Tube* (TWT), the needed stability for a good MTI performance was reached. In a more recent period and for many applications, these high power tubes have been replaced by solid state devices (transistor amplifiers) operating in parallel to get the needed power. Thanks to improvements in the overall transceiver chain, stability has become high enough to ensure a strict coherence of the fixed echoes at many pulse repetition periods, thus guaranteeing an excellent MTI performance, able to permit the detection of small targets in the presence of strong, fixed clutter echoes. The MTI cancellers, initially analog,[20] were then made, starting in the 1960s, with emerging digital techniques, which permitted the delicate and bulky lines of analog delay to be replaced with simple semiconductor memories. In this way were born, nearly together, the former radar applications of *digital signal processing* (for short, DSP) and those of automatic processing of radar data, which have profoundly influenced the developments of all radars, from the 1960s onwards.

In this way, with telecommunication systems still being mostly analogue, the radar designers firstly used digital techniques, without having the time to tell the public what they were doing.[9] So, they paved the way to the use of digital processing not only for MTI but also for more general and effective Doppler filtering. The first of them was the MTD (*Moving Target Detector*), designed and built in the early 1970s[21] to detect small air targets, such as those of general aviation, in

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[20] The MTI cancellers operate with one or more delays of one pulse repetition period each, i.e. of the order of a millisecond, corresponding to a target range about a hundred km. Therefore, to implement the related delay, in the 1940s and 1950s the radar signal was transduced into an acoustic wave, and the delay lines were implemented in water, mercury or quartz: the physical length was thus reduced by the ratio of propagation speeds, in practice by five orders of magnitude. When the total acoustic path length was relatively large, e.g. order of one meter, multiple paths permitted the use of relatively compact structures.

[21] The MTD processor is due to the work, which took place from 1969, of a team from the *Lincoln Laboratory* of the MIT, led by Charles E. Muehe.

the presence of unwanted echoes (clutter) due to ground and rain, and to provide radar data suitable for generating reliable tracks (virtually, with no loss of aircraft tracks and with no false tracks) in the framework of air traffic control [Odo 79]. The operational requirement was, in fact, more difficult, because the detection of small aircraft was required even when the target flew in a transverse direction (with a negligible radial velocity) with respect to the radar station. It was also

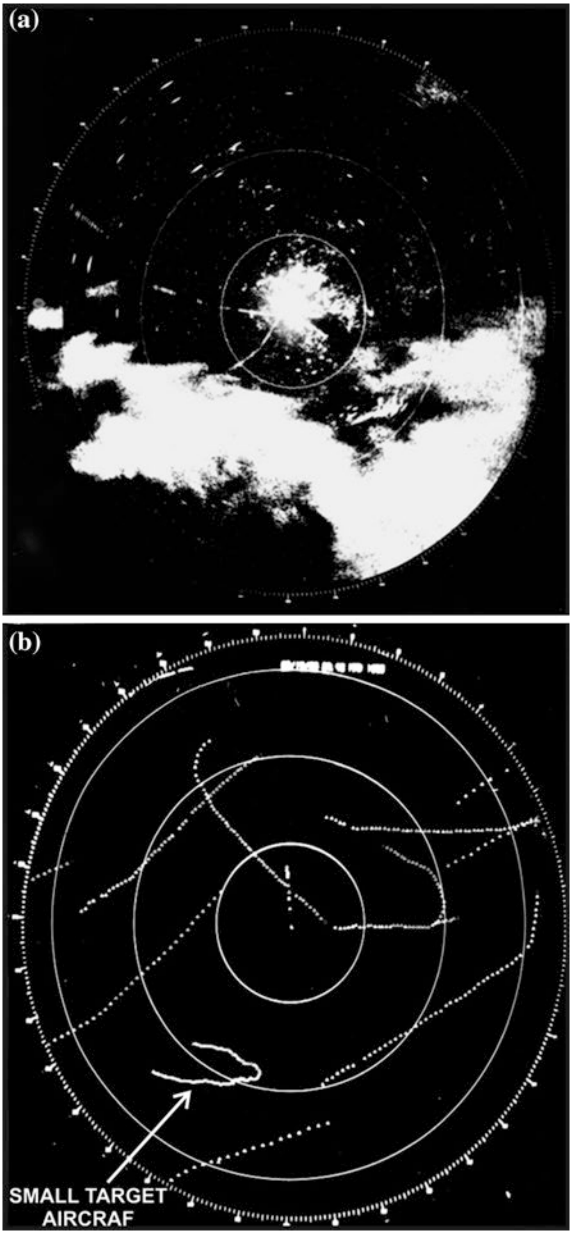

Fig. 9.4 A result of the MTD processing. **a** Raw radar video. **b** Radar video after MTD processing. At “7 h” the trajectory is visible of a small plane (single-engine Piper) in the presence of rain clutter, even when its radial velocity is null

necessary to control in a rigorous manner the false alarms due to clutter, including the nearby road traffic and the *angels* (i.e., the echoes due to phenomena such as birds, swarms of insects and strong turbulence of the atmosphere).

A sample of the results obtainable in air traffic control radar with the MTD processor is shown in Fig. 9.4, from [Pur 00].

In this development, in order to optimize the filtering and the thresholds of the processor, it proved to be essential to estimate the intensity and position of unwanted echoes that could affect the detection of air targets (clutter of various origin: land, rain, *angels*, vehicular traffic and so on) in order to save this information on *Clutter maps*.

In such a frame, today there is a lot of talk about Cognitive Radar, see e.g. [Hay 10] and [Gue 10], a methodology by which the radar is adapted, automatically and in real time, to its operating environment, thus optimizing the processes of transmission and reception. In reality, early in the 1970s, at the time of the first MTD, the radar designers (without feeling the need for so captivating names) used means, often called *maps* of fixed (ground) or varying clutter (rain) to describe the radar environment and to record its relevant characteristics (intensity, radial velocity etc.) on special memories, initially, magnetic drums and then, based on semiconductors e.g. of the RAM type. These maps, organized typically in *range-azimuth bins*, allow the radar to optimize (i) reception (e.g., with the insertion of attenuators), (ii) processing (by Doppler and other filtering), (iii) detection, often with adaptive threshold (CFAR: Constant False Alarm Rate), and in some cases also (iv) transmitted waveforms. The use of *clutter maps* in surveillance radars was widespread in the 1970s and 1980s, particularly in air traffic control (ATC) radar, both in the USA, with the second generation MTD [ATC 95] and in Europe, as well as in Italy [Cor 76], [Gal 83]. Figure 9.5 shows the main drawing of the

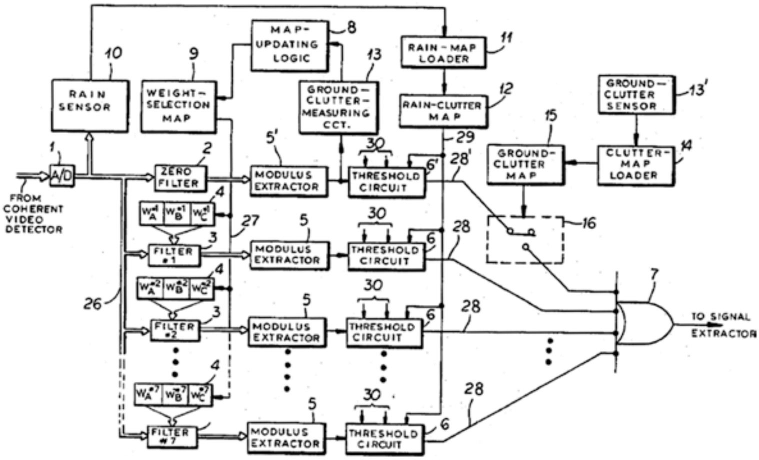

Fig. 9.5 Sensors and maps of clutter in radar ATC—main figure of the US Patent 4636793(A) "Adaptive MTD digital processor for surveillance radar"

patent issued to Selenia SpA (1970s) known as one of the few world makers of ATC radars. Today, even in the era of satellite navigation, they continue to develop new radar for civilian air traffic control, as shown in [Wan 12].

9.5 Phased Arrays with Electronic Scan of the Beam; Adaptivity

A profound effect on radar development was (and is) due to the technology known as *phased array antenna*s, or briefly *phased arrays*. These antennas are replacing (and have substituted in many cases) the reflector antenna in most applications, and are of increasing use in radar systems; see Figs. 9.6a, b and 9.7.

It is clearly seen that while in the case of Fig. 9.6a the beam pointing requires the movement of the antenna, i.e. it is *mechanical*, in the cases of Figs. 9.6b and 9.7 the pointing is obtained by *varying the phase law* on the aperture.

Figure 9.8 shows a more recent architecture of the bistatic, full digital array type, in which the receiving beams are digitally formed (*digital beam forming*, or DBF).

The design and application of phased array antennas goes back to the early studies by Beverage, Friis and Feldman in the 1920s and 1930s, [Mai 07]. The concept was practically applied in the shortwave receiving system called *Multiple Unit Steerable Antenna* (MUSA) and described by Friis and Feldman in 1937. MUSA was equipped with an array of eight elements with electromechanical phase shifters. The same principle provided a base for the *Polyrod Antenna* by the Bell Labs, used in the *Mark 8* artillery control radar[10] in production in the USA (by Western Electric) since 1942.

The receiving system of the Chain Home (http://www.radarpages.co.uk/mob/ch/chainhome.htm) also used an array, but without any scanning, the angular position of the target being derived by goniometry. It is interesting to notice that, in the early years of W.W.II, the Germans (before the Allies) were able to implement the first embodiment of electronic scanning of the beam. Its key element was a kind of phase shifter called *Kompensator*, first applied in 1941 in the *Wassermann L* radar. The Wassermann antenna was made up of four, or six, Freya antennas placed one above the other, which realized a structure up to 36 m tall (see Fig. 9.9), rotating around a large cylindrical pole having an impressive diameter up to 4 m. In the subsequent *Wassermann S* (S for *schwer*, heavy) the Freya antennas became eight, with a total height up to 60 m. The relatively narrow beam formed by this large vertical aperture could be scanned in elevation thanks to the Kompensator: a sort of forerunner of 3D radars as the RAT 31 S[22]!

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[22] The operating frequency of Wassermann, same as the Freya, was in the 125 MHz band. Its 100 kW power permitted maximum ranges up the 300 km.

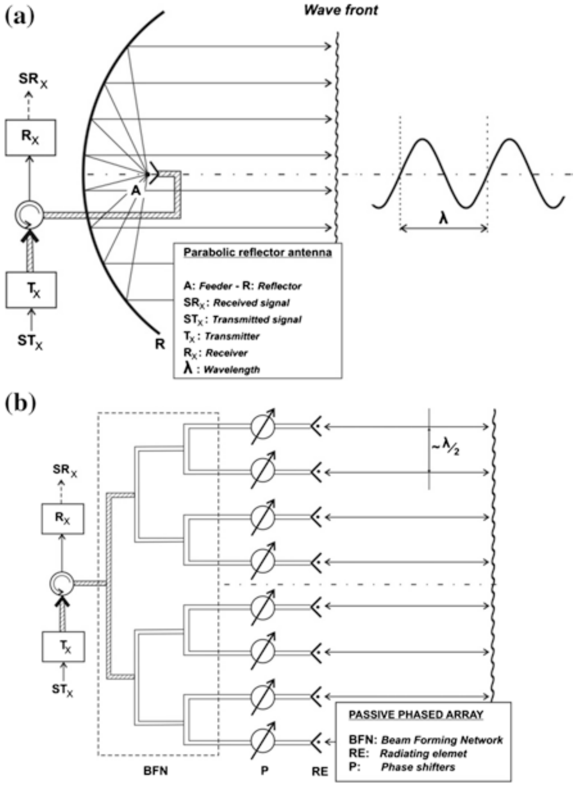

Fig. 9.6 Pictorial comparison between a reflector antenna (**a**) and a passive phased array (**b**) shown in a planar representation. For the sake of clarity the size is 4 wavelengths (typical sizes for high gain radar antennas are 50 to 100 wavelengths)

In the same period the Germans, again using the Kompensator, built radar sets with a non-rotating antenna, i.e. with electronic-only scanning: between 1941 and 1942 they implemented, and installed at several sites for long range surveillance, the giant *Mammut* radar (see Fig. 9.10) in two versions, first, the *Gustav* and then, the *Caesar*. Its antenna, which stayed on the above-ground part of a large bunker, came up to the size of 15 m (or 11 m) in height by 30 m (or 20 m) in width. It was a fixed antenna, of the type that today would be called *passive phased array*, and scanned 100° or 120° via its electromechanical phase shifters; with two array faces (version *Mammut-Friedrich*, for the Luftwaffe) an azimuth coverage of 240° was achieved.[23]

The post-war development of the Phased Array technique was pushed by the need to detect targets at great distances, including possible threats such as ballistic missiles and artificial satellites: an issue that in the USA led, first, to the development of the fixed beams (not phased array) AN/FPS-17 radar[11] described in Chap. 5.

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[23] For both Wassermann and Mammut the transceiver and the radar operators were housed in large underground bunkers, see [Rus 94].

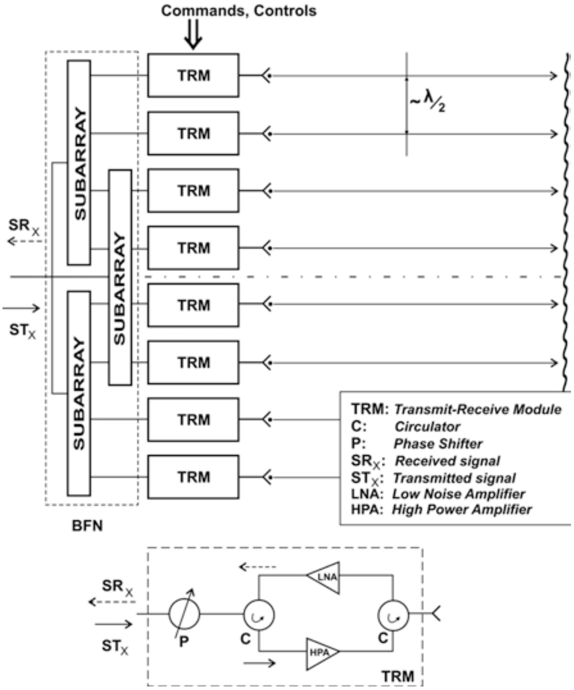

Fig. 9.7 Simplified diagram of an active phased array

After the end of the Second World War, the friction between the USSR and the USA (the Cold War) resulted in the birth of NATO.[24] New, more and more powerful offensive means[25] were developed with an intercontinental range that, in turn, required adequate systems for long range (and low altitude) surveillance. In Canada, in the 1950s, they built the defense line called *Pinetree*, then was followed by the *Mid-Canada line* and the *DEW* (Distant Early Warning) line with coverage through the Arctic, from Alaska to Iceland.[26] The DEW original radars, model AN/FPS 19, were replaced between 1985 and 1994 by the Phased Array—3D L-band radar AN/FPS-117 (with a coverage up to 460 km in range), and the system was renamed *North Warning System*. The DEW also included bistatic radars of the type AN/FPS-23, called *Fluttar* (1950s).

The subsequent developments of these *Early Warning* radars went inevitably to the *full phased-array* solution. In fact, the high power required to achieve the needed coverage could not easily be concentrated in a *feeder* for an antenna

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[24] Atlantic Pact, Washington, April 4th, 1949.

[25] Basically: long-range stratospheric missiles, strategic bombers and nuclear-powered submarines with nuclear warhead missiles.

[26] This defense line was built in less than three years (1955–57) in a particularly difficult environment such as the polar one (beyond the 69th parallel).

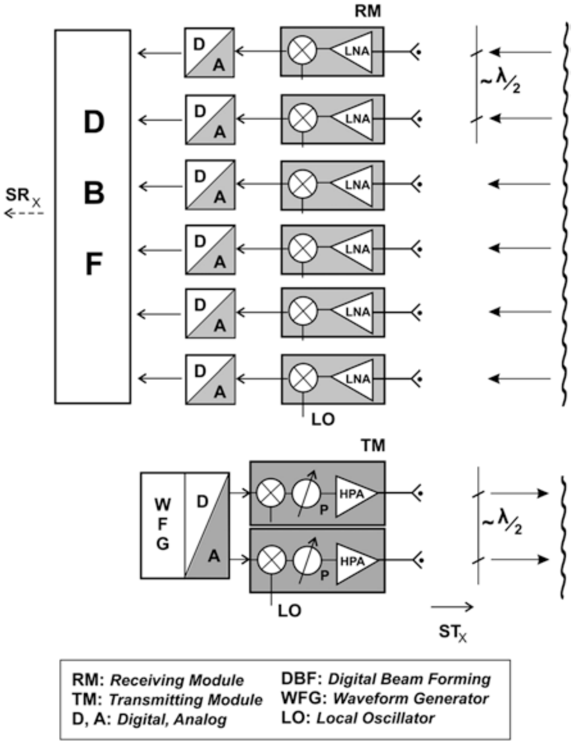

Fig. 9.8 Bistatic array radar with digital beam forming (d-Radar). For the sake of clarity the receiver array size is 3 wavelengths

reflector. Rather, it was compatible with the distributed architecture, typical of the phased array technology. Phased arrays were also suited to implement very large effective antenna apertures, so achieving the necessary very long ranges. In fact, the USA program *COBRA* of the 1970s and 1980s, aimed at monitoring of the launches of missiles and of eso-atmospheric space, produced a number of very large, electronically scanned phased array radars for the surveillance of satellites and ballistic missiles. The *Cobra Dane* radar, also named AN/FPS-108, see Fig. 9.11, is an active phased array radar operating in L-band (1215–1400 MHz) installed in Alaska (in front of the Kamchatka peninsula and the Soviet base of Kura) in 1977 to monitor launches of missiles by the Soviets; between the Cobra Dane aims there was the verification of the SALT II treaty for the limitation of strategic weapons, but the system was also used for defense against missile attacks, and analysis of objects in orbit (satellites, debris).[12]

Another radar from the *COBRA* program is the *Cobra Judy*, or AN/SPQ-11, a passive phased array radar (single-face on a rotating turret, see Figs. 9.12a, b) operating in the S-band (2.9–3.1 GHz), designed in 1967 and operational through 1981, installed on the *Observation Island* ship based in Pearl Harbor, to detect Soviet strategic missiles launched for test purposes in the Pacific area. The

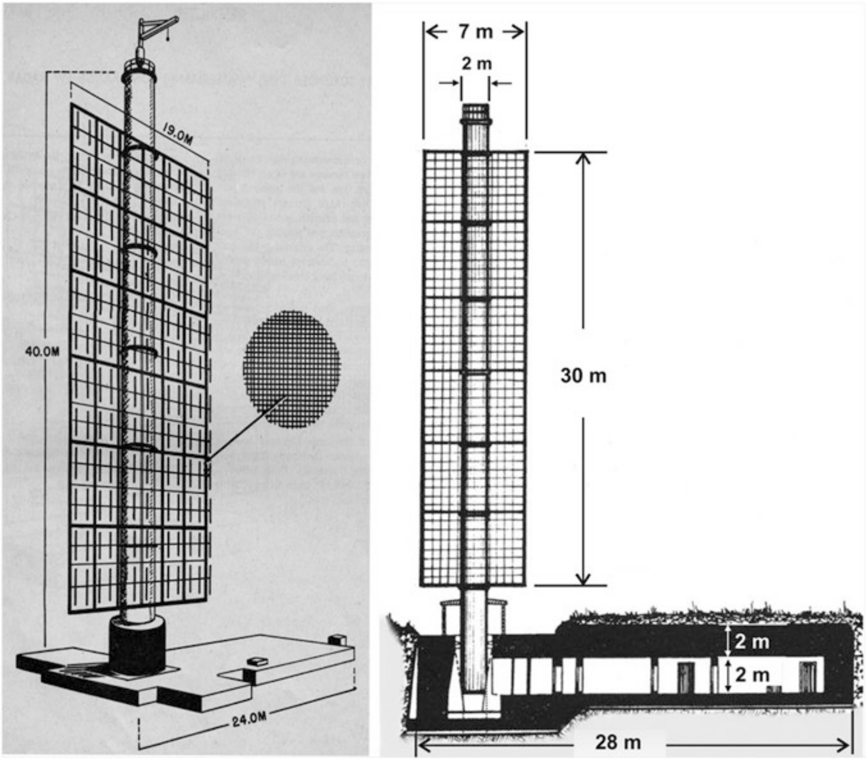

Fig. 9.9 The *Wassermann* radar

octagonal array, Fig. 9.12a, whose diameter is about 7 m, has 12,288 elements, and the system weighs about 250 tons. In 1985, in order to improve the resolution, a radar in the X-band was added, with a parabolic dish antenna to be aimed in the direction of the missile.

Of course, even the Soviets equipped themselves for defense against ballistic missiles. The UHF radar *Don-2N* (NATO name: *Pill Box*), is an element of the defense system of Moscow. The radar building is approximately 33 m high and 130 m long at the base. Each face of the building hosts a phased array antenna with a diameter of 18 m; the overall 360° coverage is obtained by four faces. The reported maximum range is between 1000 and 2000 km. The project started in the 1980s, and the operation from 1990s.

Since the mid 1960s another remarkable possibility was understood to be offered by phased array, i.e. *adaptivity*, hence the term *Adaptive Arrays*, [Mon 04], [How 65], [Wid 67]. Looking at the general diagram of an array, it is readily noticed that, in addition to aim the beam in a desired direction, one can change the shape of the antenna diagram by applying an appropriate weighing (in amplitude and in phase) to the array elements. It was understood very soon[13] that, in military radars, this type of *spatial filtering* was able to significantly reduce the effect

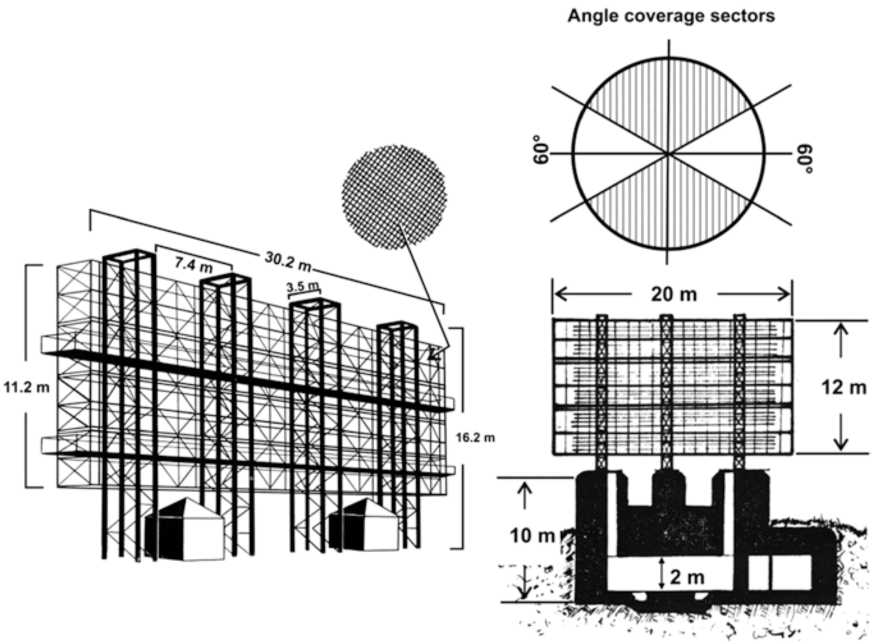

Fig. 9.10 The German electronically scanned radar *Mammut*

Fig. 9.11 The Cobra Dane installed in Alaska—the antenna has a diameter of 28.75 m and aims on the North Pacific area

of active, enemy-generated noise or *jammer*. It is well known that the power of the radar echo is proportional to the inverse fourth power of the distance, while the one of an electronic active noise (jammer) created by the opponent is proportional to the inverse square of the distance, as the active noise propagates on one way rather than on the two ways roundtrip of the radar echo signal. Therefore, with increasing distances the jammer has a growing advantage on the echo signal up to

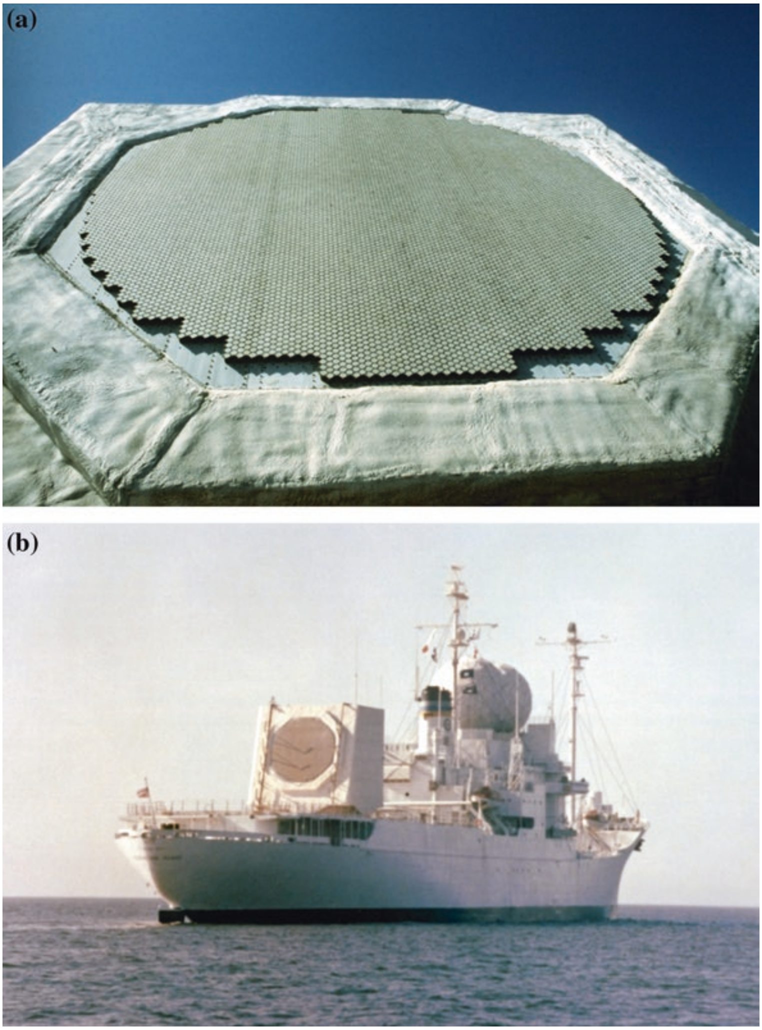

Fig. 9.12 The Cobra Judy radar, **a** detail of the antenna, **b** ensemble view

arrive to overcome it even if the jammer itself is received from the secondary lobes of the antenna. But, if in the direction of the jammer the radar antenna diagram has a so-called *null*, the jamming effect may be drastically reduced: Fig. 9.13 shows a generic array in which a set of coefficients, suitably computed in real time, defines a *beamforming*, i.e. a type of spatial filtering. In *adaptive arrays* this null is automatically created by means of an auxiliary receiving channel, in a kind of spatial filtering in the direction of the active disturbance, which is variable and, a priori, unknown. As more jammers from different directions may be simultaneously present, more auxiliary channels are often needed, see Fig. 9.14 where an adaptive array is shown in which these coefficients are computed in real time. Finally,

Fig. 9.13 Generic array (θ = pointing direction)

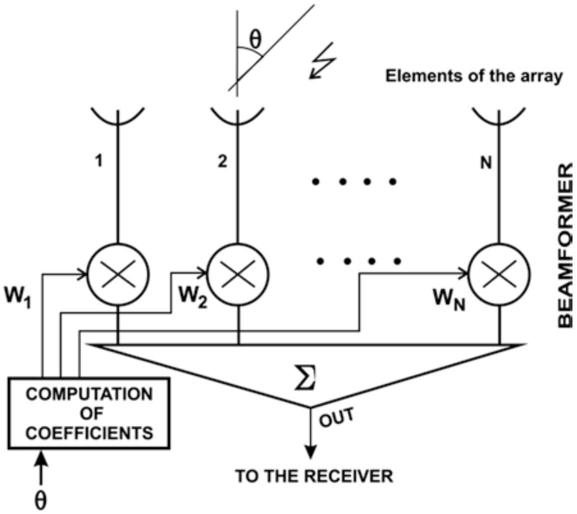

Fig. 9.14 An adaptive array: the *dashed line* shows a possible closed-loop path

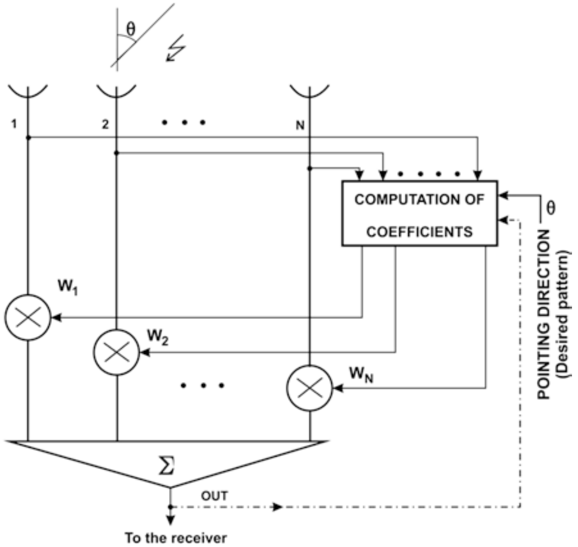

Fig. 9.15 shows the implementation known as MSLC, i.e. *Multiple Side Lobe Cancellation*, using a number of auxiliary antennas, and correlators, equal to the maximum number of simultaneous jammers to be suppressed. Initially this technique was applied with a single auxiliary antenna, and called *Side Lobe Canceller*, or SLC.

Phased arrays quickly evolved in *arrays of subarrays*: subsets of arrays with thousands of elements were arranged in groups of some tens of *subarrays*, connected by a beam forming network, thus making obsolete the auxiliary antennas.

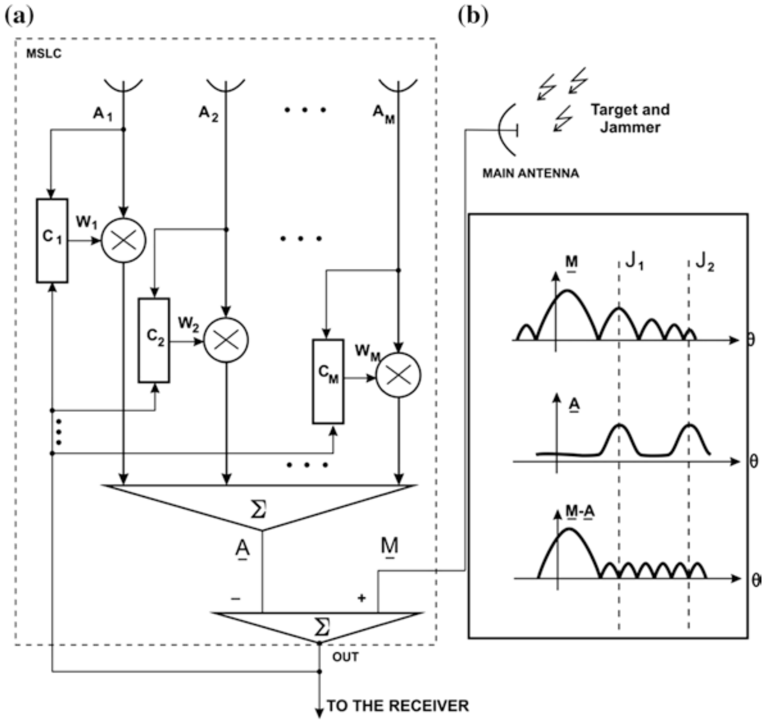

Fig. 9.15 Multiple sidelobe canceller (MSLC) with M auxiliary antennas and correlators (C_1... C_M) for the generation of the adaptive coefficients which minimize the effect of K ($K < M$) *Jammer* spatial sources (*M* main channel, *A* auxiliary channel)—**a** general block diagram, **b** example of operation with two jammers

An example is shown in [Gro 89] that describes the experimental radar ELRA with an antenna made up by 768 array elements organized in 48 subarrays of 16 elements each; the 48 outputs are processed in digital form to implement the adaptive forming of the beams.[27]

The problem of suppressing the active noise (jammer) in the side lobes of the antenna of a defence radar received particular attention in the USA when they learned that the warheads of the Soviet ballistic missiles could release a number of decoys able to disturb the radars of the American ABM (Anti-Ballistic Missiles) defence system by various means, including jammers. The ABM system provides for the destruction of nuclear warheads (once identified as such within the "false" ones, i.e.: fragments, chaff, decoys) by missiles guided by an ad hoc radar, which

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[27] This S band, solid-state experimental phased array radar (ELRA: ELectronic steerable RAdar), built and operated by the German Research Institute FGAN-FFM (now, FGAN-FHR) in Wachtberg, near Bonn, allowed, from the early 1980s, some of the former demonstrations of the concepts of adaptivity in arrays and of digital beam forming. In modern radars, the number of array elements may be of the order of 10000, with a subarrays number in the order of 100.

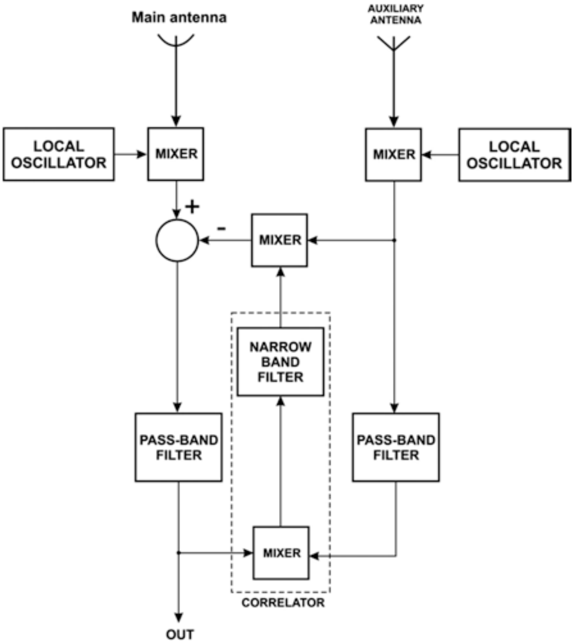

Fig. 9.16 Sketch of the original system for the adaptive cancellation of jammers using an auxiliary antenna (side lobe canceller), from the U.S. patent 3202990 by Howells

could be rendered ineffective by jammers present in some of the multiple heads and activated in the terminal descent phase. Just two of such jammers, with adequate angular separation, would have rendered ineffective the SLC technique, patented in 1965 by Paul Howells from General Electric (see [How 65]), with the patent application filed some years before, in 1959, see Fig. 9.16.

Therefore, the *Syracuse University Research Corporation* (SURC, then SRC) proposed for the ABM radar system a *Multiple adaptive Side-Lobe Canceller*, MSLC, tested in the 1970s on the HAPDAR (*Hard Point Demonstration Array Radar*) in the *White Sands* location.

The 1970s also date the application of adaptive algorithms, born for the arrays, to the *time domain processing* in addition to, or in place of, the space domain. Two parent works in this respect, i.e. [Bre 73] and [Ree 74], appeared in those years. Through the 1980s, the increasingly difficult requirements for airborne radar to detect targets, even at low altitude, in the presence of clutter and jammer[28] pushed the researchers to extend the adaptivity to the space-time domain by new algorithms. In such a context, research and development on *Space-Time Adaptive Processing* (STAP)[14] originated, and developed with a quick growth till the 2000s: see for example [Ran 03], [Gue 03], [Kle 02], [Kle 04], [Mel 04] and Fig. 9.17.

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[28] In an airborne radar the motion of the platform, in combination with the presence of the antenna side lobes, widens the Doppler spectrum of the clutter and shifts its peak on non-null frequency values, making the detection of targets, with the radar antenna pointing down, particularly difficult when they are at a lower altitude than the platform.

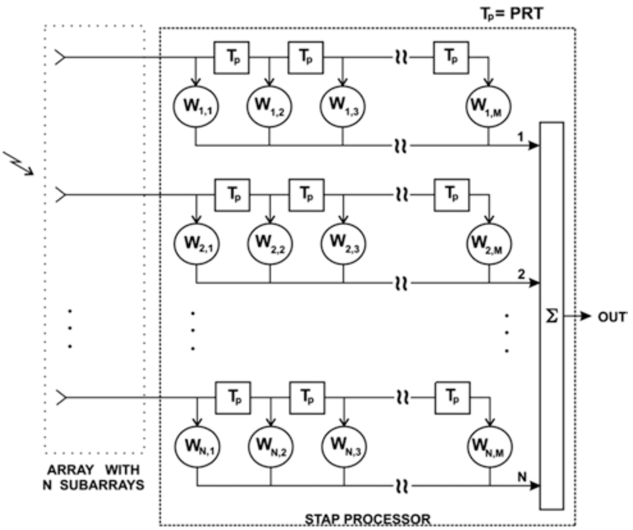

Fig. 9.17 General sketch of the space-time array processing (STAP)

The STAP technique can be considered an evolution of this most ancient *DPCA* (Displaced Phase Center Antenna) technique [Mue 90], [Wen 11] aimed to mitigate, in airborne radars, the harmful effect of the movement of the antenna, which shifts and widens the Doppler spectrum of the ground echoes (land clutter). In 1953 Frank Dickey [Dic 91], a researcher from General Electric, proposed (with no use of the DPCA acronym, yet) to compensate for the translation of the antenna in airborne radars using two monopulse channels. This was, in essence, a compensation for the displacement of the radar antenna between two pulse repetition periods: a very early version of the incoming space-time processing.

9.6 Phased Array Radars for Naval and Aerial Platforms

Phased arrays technology allows the radar industry to produce multifunction sets, such as the airborne AESA described above, integrating the functions of surveillance, air search, surface search, tracking, missile guidance and more.[15] In a mobile platform, such as a naval unit or an aircraft, it is thus possible to greatly simplify the sensors system. In addition to the already mentioned EMPAR, there are several phased array naval radars in production and in operation. One of them is the SAMPSON by *British Aerospace* (BAE Systems) derived from the *Multifunction Electronically Scanned Array Radar* (MESAR), [Sta 07], a program undertaken from 1982 to the 1990s whose tests (MESAR 1) were carried on between 1989 and 1994. In August 1995 the development of the pre-production set MESAR 2 started, from which the SAMPSON was derived for *Type 45* destroyers.

The first SAMPSON set was installed on the *HMS Daring* in 2007, in combination with the long-range radar S1850M. The operational tests were carried on from July 2009.

Unlike EMPAR, the SAMPSON operates in the S-band (its wave length is around 10 cm) and has a pair of antennae (air-cooled, even in this differing from EMPAR) placed "back to back" on a structure rotating at 30 revolutions per minute. In fact, such a pair of equivalent, and independent, radars is capable of renewing the targets information once per second, like EMPAR. Each face of the antenna has about 650 transceiver modules (T/R) each of which feeds four radiating elements for a total of 2600 elements per face. As in EMPAR, the electronic scanning on the horizontal plane permits an increase of dwell time in the most critical angular sectors for the threat. In practice, a beam rotates for a fraction of one second in the opposite direction to the mechanical revolution, resulting in a *slow down* or even stop whenever necessary. The above-deck antenna structure is relatively light as compared to the four fixed antennas systems and therefore can be placed at the top of the highest mast (up to 40 m), with a significant improvement in the radar horizon, while in general a heavy four faces antenna must be placed at a lower height, typically 20 or 25 m. The four-faces approach has been chosen by the U.S. Navy with their AN/SPY-1 system used in *Ticonderoga* class cruisers. The AN/SPY-1A radar entered the service on board of Ticonderoga in 1983 and on the *Arleigh Burke* class destroyers (1991), see Fig. 9.18, as sensor for the AEGIS defense system against missile or aircraft attacks. Lighter versions, called AN/SPY-1F, were built with an antenna diameter of 2.4 m instead of the original 3.6 m, for smaller vessels, such as frigates, and other even smaller (AN/SPY-1K) were built for corvettes. The solution with four fixed faces has also been adopted by Dutch and German Navies with their radar APAR (Active Phased Array Radar), an X-band, medium range (150 km) radar, with as much as 3424 transceiver modules (TRMs) per face.

For the next generation of cruisers and destroyers the USA has planned a new system called AMDR, *Air and Missile Defense Radar*, which will detect and localize aircraft, missiles and even submarines periscopes with an S-band radar (AMDR-S), an X-band radar (AMDR-X) and a Radar Suite Controller (RSC) to manage their joint operation.[29] The S band is dedicated to volumetric search and tracking of air targets and ballistic missiles; the X band, to surveillance on the horizon, to precision tracking, and to the illumination of its own missiles in terminal phase; both radars will have the ability to communicate with the missiles. In essence, the U.S. Navy has understood that the choice of a single frequency band (e.g. the S band chosen by the British or the C band by the Italian Navy with the already described EMPAR[16], or even the X-band selected by the Dutch Navy with

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[29] AMDR will be a successor of the Dual-Band Radar for the DDG 1000 *Zumwalt* class and the forthcoming *Gerald R. Ford* class super-carriers in order to replace several different radars. It is expected that the first AMDR installations will take place in 2019, with orders in 2016, on the ships (DDG 123) of the type now mounting the *Aegis Combat System*.

Fig. 9.18 The destroyer *USS Cole* (DDG-67), *Arleigh Burke* class: two of the four faces of the antenna of the AN/SPY-1 can be seen. The ship is known to have suffered the terrorist attack on October 12th, 2000 in the port of Aden, with 17 casualties among the crew

the APAR) for multifunction radar naval involves operating limitations that may only be overcome by operating in several bands, and accepting the related costs.

There are numerous applications for the active phased array radar technology. The array is often organized into subarrays, with signal processing within each subarray and the possibility of digital forming of the many antenna beams needed at various operation modes. In some application domains the trend is toward fully flexible systems [Adr 10] in which there is an analog-to-digital convertor for each element of the array, and the system is therefore completely digital. The modern phased array techniques allow us to implement multi-function systems[30] self-adapting to the environment, and physical configurations that are no longer planar but, rather, *conformal* to the structure of the platform, [Hol 06]. In [Gal 15] and [Gal 15b] a *conical array* multifunction, full digital radar architecture (d-Radar) for point defence is described with its extensive use of Digital Beam Forming, also discussing its advantages over the *classical* architecture with four flat arrays and its various potentials, see Fig. 9.19.

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[30] The *final multifunction solution*, whose cost/effectiveness is still to be evaluated and whose convenience is still to be defined, is of course the integration into a single antenna of three basic functions: radar, electronic warfare and communications. One may imagine that these new types of sets could be employed, *inter alia*, on future UAV/UAS (Unmanned Aerial Vehicles/Systems) for ISR (Intelligence, Surveillance, Reconnaissance) or strike missions.

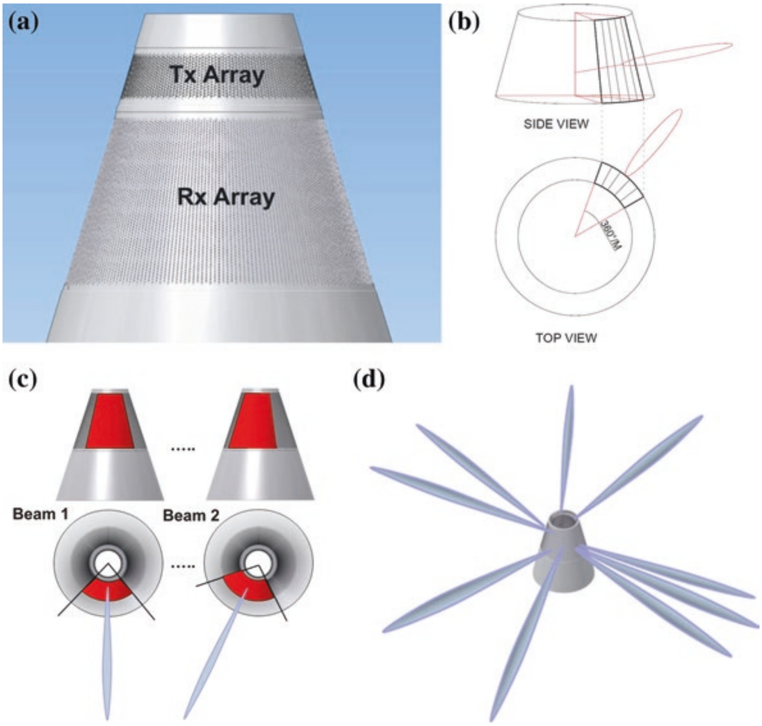

Fig. 9.19 A bistatic, conical digital array radar (d-Radar): **a** transmitting and receiving arrays, **b** forming of a number of transmission sectors, **c** electronic scan of a transmission sector, **d** multiple beams by DBF

9.7 Post-war Civil Developments—Weather Radars

After W.W.II (mainly in the 1950s), in addition to exploit, improve and enhance the so many technologies and system concepts devised in war-time, novel radar architectures were developed to meet, after those of defence, emerging requirements. In addition to those for vessel navigation and air traffic control, the most significant civil radar embodiments have been in the meteorological context,[31] [Whi 88].

During the war, using the microwave radars (in the S and X band) made possible by the magnetron, it was noted that rain and hail generated important radar echoes with increasing intensity (but also with a greater attenuation) at increasing microwave frequencies, and that the PPI images of high radar reflectivity areas can

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[31] The most used terms are: *weather radar*, *meteorological radar*.

represent specific types of meteorological phenomena.[32] It was also sought to establish a link between the rate of precipitation R (in mm/h) and the so-called *radar reflectivity factor* traditionally indicated with the letter Z.[17] Among the many proposed Z-R relationships, the first one, most famous, dates back to 1948: it is due to a Canadian researcher, J.S. Marshall and his doctoral student W.M. Palmer, and is based on the assumption of an exponential distribution for the diameters of the rain drops.[18] In the USA, one of the radar-meteorology pioneers was David Atlas, who worked with the USAF and then with the MIT. In the post-war period (e.g. from 1947 in the USA[33]) various national meteorological services installed weather radars, often derived from the *surplus* of the Armed Forces, to monitor the rainfall on a large scale (hundreds of km) through the display of the radar reflectivity. Initially, the reflectivity map was shown on a Cathode Ray Tube (CRT) display, in the face of which sat the meteorologists, which to record what they saw had the only opportunity to photograph the display. Similar to the surveillance radars for the air defence, the weather radar has been developed where there has been a clear operational requirement. In fact, during W.W.II. the radar echoes due to atmospheric phenomena were considered only a disturbance making the display *dirty*, hence the name *clutter*.

The territory of the United States of America is ravaged, as is well known, by hurricanes and tornadoes whose early detection can save many lives and prevent serious damage.[34] It is therefore not surprising that the early organized radar observations of the atmosphere for meteorological purposes took place in the USA, where the National Weather Service installed, starting from the late 1950s, a number of model WSR-57[35] radar, see Fig. 9.20.

These sets are capable of analysing a single parameter of the rain, namely, the radar reflectivity, which is proportional to the intensity of the echo. This information is valuable in the analysis of the structure of thunderstorms and in small-scale and short-term weather forecasts. Since the 1970s these radars were often

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[32] The first record on the detection of rain echoes dates back to February 7th, 1941 at the Radiation Laboratory (but probably others happened in the United Kingdom in 1940). The first American publication concerning the weather radar is due to Bent, 1943, entitled: “Radar Echoes from Atmospheric Phenomena”. PPI radar images of precipitation obtained in the Second World War were of great interest: for example, it was understood that the "hook" shape indicates a tornado type storm with possible hail.

[33] The so-called *U.S. Basic Weather Radar Network* began to grow in 1947 including the first WSR and other radar sets of the U.S. Air Force and of governmental agencies. In the USA, the first purposely designed radar for meteorological usage was the AN/CPS-9 *Storm Detection Radar*, produced by Raytheon.

[34] On April 5th, 1956 at 14:00 on the display of the weather radar of the *A&M University*, Texas, images appeared of echoes shaped as a hook. The meteorologists of the University called the *Bryan Police Department* and the *College Station School District* to inform them of the imminent arrival of some tornado. The school decided to retain the students to shelter after normal closing hours. This timely action probably saved many lives.

[35] WSR means *Weather Service Radar*, and the two digits following the letters indicate the starting year of the relevant programme.

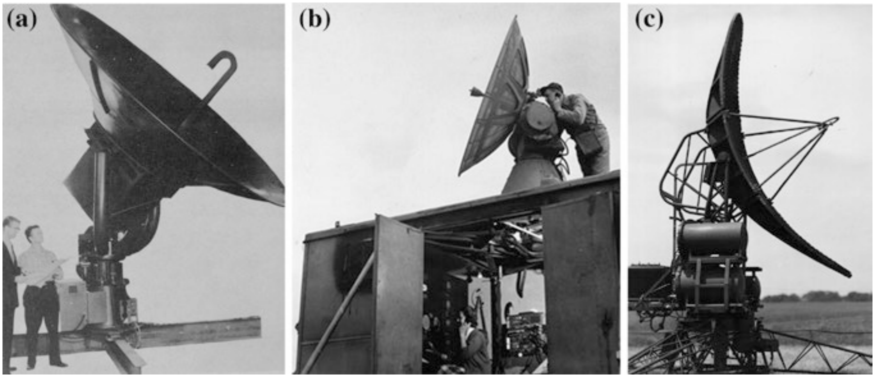

Fig. 9.20 Some early meteorological radars: **a** WSR 57, **b** SCR 584 and **c** AN-TPS 10

organized in a network not only in the USA with measurements being referred to the same standards in order to provide the most complete coverage compatible with orographic masking and with cost constraints of the national territory. Thanks to the research of scholars such as Louis J. Battan [Bat 73], David Atlas [Ama 98], Richard J. Doviak, Dusan S. Zrinc [Dov 93], Henri Sauvageot [Sau 92], Pravas Mahapatra [Mah 86], [Mah 99], Isztar Zawadski [Fab 02], Alexander Ryzhkov, V. Bringi, and many others, the ability to analyse the weather radars signals and data were developed slowly, but with significant steps and achievements. In this growth, the first important step[36] has been introduction of the *radial velocity* information for meteorological phenomena, thanks to the Doppler effect[37] (see for example [Dov 93]). In the 1970s the design of a new family of Doppler weather radars equipped with a coherent and very stable transceiver was finalized. Their usual transmitter power tube was a *klystron*,[19] and the antenna was of the reflector type (the diameter of which, in the case of use of the S-band, could exceed 8 m).

In 1971, at the National Severe Storms Laboratory (NSSL) in *Norman*, Oklahoma, they installed the first Doppler weather radar, followed in 1973 by the second one, at the *Cimarron* airport, Oklahoma; both sets worked in the S-band. In 1976 followed the formalization of the *Joint Doppler Operational Project* (JDOP). At the end of the 1979 the project called WSR-88D (where D stands for Doppler; it is commonly called NEXRAD) started, and saw the first installation after about

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[36] Of course, but non-specific of radar meteorology, another fundamental progress was the application of the techniques of digital signal processing and acquisition, recording and display of the results, often called "products", and finally the control of the radar operation by a computer.

[37] In May 1973 a tornado struck *Union City*, west of Oklahoma City. The experimental S-band Doppler radar of the National Severe Storm Laboratory has allowed researchers to follow the entire life of the phenomenon. In particular it was possible, for the first time, to observe the rotation which characterizes the early forming of the tornado. This fact, along with others, has convinced the National Weather Service of the importance of the information of the radial velocity for the prediction of extreme events.

ten years (Norman, 1990), and the last installation after eight more years (1997). The project led to a network of 159 radars covering the entire USA mainland and some overseas areas. To plan and manage the project, up to the installations and the finalization of the entire system, the *Federal Committee for Meteorological Services and Supporting Research* (FCMSSR) created a special structure called *Joint Systems Project Office* (JSPO). It is remarkable that in this way, the needs of the three federal agencies using weather radar data i.e. the NWS (National Weather Service), the DOD (Department of Defence) and, finally, the FAA (Federal Aviation Administration) were satisfied by a single type of radar, whose data could be processed in different ways to generate *products* suitable to each Agency, with significant savings on both the hardware and the signal processing algorithms.[38]

Since the 1970s, meteorologists have acquired and processed radar images with different elevation angles, or *cones*, analysed during the revolutions of the antenna, permitting one to synthesize the *cuts* of radar detection volume with vertical planes (RHI: *range height indicator*), horizontal at a constant altitude (CAPPI: *Constant Altitude PPI*) or other, facilitating the studies of structure of rainfall, storms and clouds.[20]

In the same period (and by the end of the 1990s), other States organised a network of weather radars. Between them, Canada, whose first Doppler radar (in C-band) was installed in *King City*, north of Toronto, in 1985, and the second (in S-band), at *McGill University*, in 1993; the Canadian network of Doppler weather radar was completed in 1998. In Australia, between the end of the 1990s and the beginning of the 2000s, they built up some research weather radars, and since 2003 started a program for a national network of Doppler radars. Within Europe, between the end of the 1990s and the early 2000s, various countries implemented networks of Doppler weather radars. Among them were Germany and France with the network ARAMIS of Météo-france, consisting of 24 radars, of which, in 2010, 22 were Doppler radar and 10 dual polarisation. Since 2010 many European countries have had national radar coverage with weather radar data made available to the public virtually in real time (with delays between half an hour and one hour) on the Internet. Finally, the situation in India is interesting: since 1970 India had a network of weather radars, particularly necessary in a country that is unfortunately marred by many extreme weather events. Through 2011, India[39] has had a network of approximately 29 radars in X-band, particularly suitable for local measurements, and 11 radars in S-band. Out of the S-band radars, five[40] are Doppler, made operational between 2002 and 2006. A new Doppler weather radar has been

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[38] According to the style of the US Administration, this is an initiative called Tri-Agency involving *Department of Commerce* (DOC), *Department of Defense* (DOD) and finally *Department of Transportation* (DOT); similar programs allow for the development of equipment, systems, services common to different operational realities, with significant cost savings.

[39] See the Web site of the Indian Meteorological Service: http://www.imd.gov.in.

[40] Among them, four are of European design (Gematronik 1500 S) and one of Indian design.

designed and constructed in India,[41] in a cooperative effort between the *Indian Meteorological Department* (IMD) and the *Indian Space Research Organization* (ISRO). The Indian development plans include the acquisition of fourteen Doppler radars, of which twelve are needed to replace obsolete equipment and two for new sites. Future Stages 2 and 3 of the programme include thirty-four more radars with polarimetric (in addition to Doppler) capability that will bring the total of Indian Doppler radars to as much as fifty-five, some of them of Chinese production, others of Indian production.

Following the introduction of Doppler[42] measurements, the second qualitative leap in performance of meteorological radars, studied from the 1980s by Universities and research institutions, has reached operational maturity for applications in the 2000s. This is ***polarimetry***, mainly based on the fact that the large diameter raindrops, i.e., those that most contribute to the radar echo, are not spherical. Their *oblate spheroid* shape results from the balance between three forces: gravity, air drag and surface tension: the latter, prevailing in smaller drops, makes them spherical while the larger drops, which mostly contribute to the radar echo intensity, have an elongated shape in the horizontal direction, see Fig. 9.21.

On the shape of the raindrops there is a huge literature, given that some researchers have devoted a great part of their activities to this problem,[43] assumed most important, particularly in the context of weather radar polarimetry (the polarimetry would not have any real *raison d'être* if drops were spherical). Due to the oblate shape of large drops, the radar echo for a horizontally polarized signal has a greater intensity than in the vertical polarization case. Therefore, the use of both polarizations in a weather radar [Bri 01] allows us to extract more information from the echo of the precipitation by analysing the ratio between the powers of the echo in both polarizations, as well as other quantities (phase shifts, correlations, depolarization ratios and so on) related to the pair of polarizations. In the face of higher cost, the advantages are (i) a better estimate of the rate of precipitation[44] with less dependence on the calibration of the radar, (ii) a better noise suppression, (iii) the possibility of classifying the type[45] of precipitation (rain, snow, hail..), and more,

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[41] It has been operational since 2004 in a site about 100 km north of Chennai; a few other sets have been ordered from the manufacturer, Bharat Electronics Limited (BEL), [Mah 11].

[42] The Doppler measurements of precipitation are basically two: the mean radial velocity, derived from the first moment of the Doppler spectrum, and velocity dispersion, derived from its second moment.

[43] A recent reference with an overview of the problem is [Gor 06]. Until now researchers have made their analytical assessments as if the drops were ellipsoids (of which it is possible to calculate the radar cross-section).

[44] For example, by introducing, in addition to the reflectivity Z (measured in the horizontal polarization), the ratio of the received power in horizontal polarization and that in vertical polarization, called *differential reflectivity* or Z_{DR}.

[45] In fact, snow and hail have ?polarimetric signatures? different from rain, due to the different shape of hailstones, snowflakes and drops. The same occurs for the sources of disturbing echoes, such as swarms of insects, birds and, in the case of pointing to low elevation, surface clutter due to the land features and the man-made ones (e.g. buildings, trellis and various infrastructures, including the particularly harmful *wind turbines* often grouped into *wind farms*).

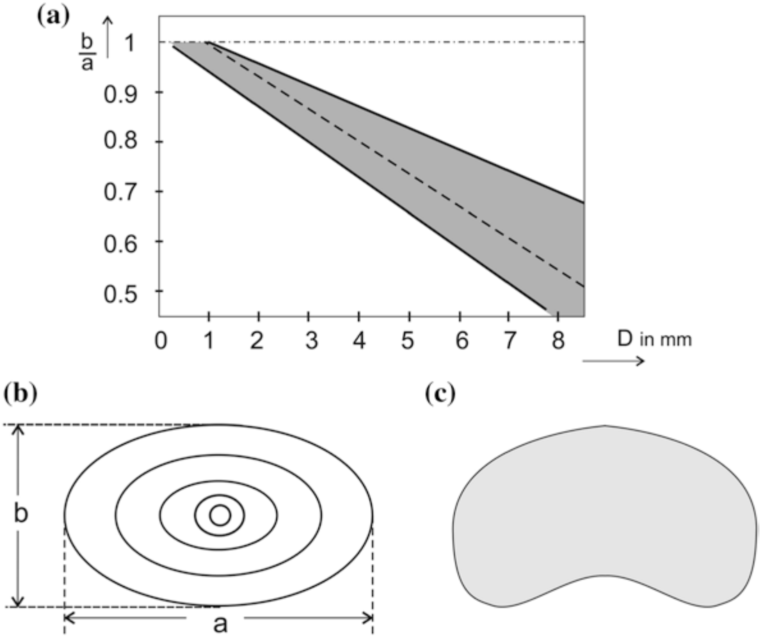

Fig. 9.21 Shape of rain drops: **a** region that contains the different laws for the axial ratio *b*/*a* versus the equal-volumetric diameter D, **b** the ellipsoid: five ellipses (of which the inner is almost spherical) represent the ideal *vertical* sections of drops of 1, 2, 3, 4 and 6 mm equal-volumetric diameter, **c** the real shape of a large drop which, with the diameter increasing, abandons the ellipsoid shape to assume a *parachute* one, up to break-up in smaller drops

with general improvement in forecasts of various weather phenomena, in particular storms and cyclones. An analysis of performance achievable by polarimetry, and related operational advantages, has been conducted in the USA through the *Joint Polarization Experiment* (JPOLE) held in 2002–03 by a prototype polarimetric version of the WSR-88D. The results led the US National Weather Service to decide to add the polarimetric capability to all WSR-88D radars (http://www.roc.noaa.gov/WSR88D/DualPol/Default.aspx).[46]

The third great qualitative evolutionary step of weather radar, still in its infancy, concerns the phased array technology with electronic scanning of the beam, which permits to optimize the time interval between successive measurements through the so-called *beam multiplexing*, as well as to implement multifunction civil radars (in the USA the related programme is known as MPAR: Multifunction Phased Array Radar) for monitoring both air traffic and weather phenomena, [Zha 11]. Also in this area, there are well defined advantages from the cylindrical phased array structure with respect to the one with four flat faces, see for instance [Kar 12].

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[46] The first NEXRAD radar transformed into a polarimetric radar was the one at the Air Force Base of Vance, Oklahoma, fully operational since March 3rd, 2011.

9.8 Developments for the Consumer Market–Maritime and Automotive Radars

The main applications described herein include high technology radar sets with large size and, often, high cost. On the other hand, nowadays the radar has also entered into the consumer market. The first civil application has been, of course, the naval one, which, as already shown, was at the origin of the first radar studies and prototypes, from Hülsmeyer to the ship *Normandie*. The so-called *navigation radar* (or *marine radar*) allows the crew to recognize fixed obstacles and to navigate by following on the radar monitor the coastline, islands and strong echoes of suitable radar reflectors of the *corner reflector* type positioned on buoys or other fixed points.[47] Even more important, it also helps to avoid collisions with other boats even in bad weather, fog, and/or night. Today most vessels, including pleasure and fishing boats, have an on-board radar whose price can be as low as a very few thousand dollars thanks to proven technology with low production costs, such as those of magnetron[21] transmitters, *patch* antennas implemented with printed circuit technology, plastic-made gears, and so on.[22]

Radars for cars, commonly called *automotive radars*, have potential for an even more widespread usage and a greater mass-market opportunities than marine radars. The first studies for the application of radar techniques to road vehicles took place at the end of the 1960s in England, at the *Mullard Research Laboratories*, where they developed a prototype operating on the 10 GHz band, and at the RCA on the beginning of the 1970s.[48] To reduce the antenna size the designers choose, for their prototypes, higher and higher frequencies, namely: 17, 24, 35, 49, 60, and 76/77 GHz. The first commercial sets were available in 1997[49] in Japan, on board of the Toyota *Celsior*, and in 1999 in Europe, on the Mercedes S-Class (*Distronic* system with a 77 GHz radar). Those systems were essentially conceived for the comfort of the driver, who was assisted in maintaining the correct distance from the vehicle ahead. Soon, automotive sets by other brands (BMW, Jaguar, Nissan, Mercedes, Volkswagen, Ford) followed. In the USA a significant application of anti-collision radar at 24 GHz in the 1990s was the installation on 1600 buses of the well-known *Greyhound* line, with a 21 % reduction in the rate of accidents in 1993 (first year of use) over the previous year.

The development of automotive radar has been slowed in all the world by some relevant matters, i.e. (a) legal liability, (b) cost, (c) allocation of frequencies.

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[47] These reflectors also allow the boat to be more visible by navigation radars and coastal radars, see also: http://www.echomax.co.uk/Echomax_Forward.htm.

[48] Some prototypal embodiments were made in the USA around 1970 by *Varian Associates* together with the *Chelmsford MA*, and one of them was shown in Detroit, but the *Detroit Three* (Ford, General Motors and Chrysler) were not interested, probably because of potential liability matters more than because of any technical aspect.

[49] The typical specifications of late 1990s were: pulsed emission in the range 76–77 GHz, with bandwidth up to 500 MHz and effective peak radiated power (EIRP) up to 20 W, mean power less than 10 mW and antenna beam width less than 4° in elevation and 15° in azimuth.

However in 2010 the sector has achieved yearly growth rates up to 40 %. The main purpose (not the only one) of a modern automotive radar is *safety*, on the basis of which two key functionalities have been developed, which can coexist in the same radar set [Sch 05]. The former function is the *Automatic Cruise Control* (ACC) allowing the driver to maintain a given safe distance from the vehicle ahead. This is particularly useful in the motorways and when *stop-and-go* are frequent, and requires a long-range radar (LRR), i.e., one with an operation range up to 250 m. Some trademarks of such a system are: *Active Cruise Control* (BMW), *Distronic* (Daimler-Benz) and *Adaptive Cruise Control* (Jaguar). The second function is Collision Avoidance[23] which warns the pilot of an incoming impact, and if this is unavoidable, prepares the needed actions to avoid or mitigate the damages.[24] A LRR is not strictly necessarily to this end, being sufficient a *short range radar* (SRR), with a range of the order of one hundred metres or even less. These SRR systems have been implemented in the frequency band of 24 GHz, where the technology is much cheaper than at the 76/77 GHz of the LRR. In addition to the collision avoidance (pre-crash sensing), SRR sensors are suitable for: ACC support, parking assistance (radar-based automated parking systems are now available) and surveillance of the *blind spots* not visible by the driver through mirrors.[50] For the SRR, unlike the LRR, measurement of the azimuthal angle is often not required, but, on the other hand, a very high range resolution, order of one cm, is needed, with the result that the radar sensor is of the *ultra-wideband* (UWB) type.

In the European context, the ETSI[51] cares about the standards and recommendations for the working frequencies of both LRR and SRR.[25] The LRR sets of the third generation, based on silicon-germanium rather than on gallium arsenide, arrived to an operating bandwidth of 500 MHz i.e., much wider than the 200 MHz of the second generation. A recent third generation system [Ste 11] has very limited size (in cm: 7.4 × 7 × 5.8) and locates objects distant from half a meter up to 250 m in an angle of 30° in front of the car with a precision of 10 cm in distance and 0.1° in azimuth; it can track up to 33 targets simultaneously. The exploded view of the set is shown in Fig. 9.22.

It is a continuous wave radar with the well-known triangular-law frequency modulation, and has an antenna system with a dielectric lens, with one beam in transmission and four beams in reception. Apart from the dielectric lens and the container with the connectors, the entire radar is housed in only two printed circuit boards, the bottom one containing the processor and the power supply.

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[50] Further functions have been proposed such as assistance to the lane change, alarms to prevent the opening of the doors in the presence of arriving vehicles, proximity alarms for pedestrians and even more.

[51] The *European Telecommunications Standards Institute* (ETSI) is an independent body and a not-for-profit organization responsible for the definition and distribution of standards in the field of telecommunications in Europe. To be mandatory, the standards must be accepted and promulgated by European (European Commission) or by national Authorities.

Fig. 9.22 The third generation automotive radar by Bosch

The extremely small size of such automotive radars can be explained by consider that (a) the wavelength is only 4 mm and (b) due to the modest distances and the need to cover 20° or 30° in azimuth, often without moving parts, the antenna beam widths are of the order of ten degrees, i.e. much larger than those of the conventional surveillance radar. Anyway, the small size is only one of the requirements for a wider diffusion of the automotive radar, the other being, of course, the low cost. According to some experts, a *democratisation* process of the automotive radar is going on with increasing production volumes and reduction of costs, as has happened in a dramatic way for cellular telephony and *smartphones*, among others. On 2011, an ACC system with LRR ago grow the selling price of the car by about one thousand euro, making it difficult to reach the midmarket. However in the following years the situation seemed to be rapidly evolving with production costs lower and lower (non-official sources indicate production costs in the order of fifty euros) and for the first time cars were marketed (Mercedes *B Class*) with the radar (both for *collision avoidance* and *blind spot assist)* being not an optional but provided directly with the car. Of course, the widespread use of automotive radar in the future will to generate mutual interference, a problem common to next-generation, solid-state marine radars and still to be solved.[26]

9.9 Developments for Security: Through-the-Wall Radar (TTWR)

The increasing need to monitor some potentially dangerous human activities, and to rescue people in danger, has led to the development of radar systems working in the ultra-wide band (UWBR: Ultra-Wideband Radar) and capable of detecting the presence and the movements of objects and people through stone, bricks and/or concrete walls. With those *through-the-wall radars*, or TTWRs, ranges of the order of meters and resolutions of centimetres can be achieved, see for example [Ral 10]. Such systems, with separated transmitter and receiver (the MIMO configuration, described in the following chapter, is often used) can achieve accuracies of the order of millimetres in differential mode, with the resulting capability of detecting the vital activity (breathing, heart beat) through a wall, for applications of obvious relevance in the field of security.

9.10 Radar Research Infrastructures

Research and development in the radar area, of course, call for a great amount of experimental activity in addition to the theoretical one. Some universities and research institutions made large investments in order to build their own radar research facilities.

One example is the Doppler, polarimetric radar system named *PARSAX* (Polarimetric Agile Radar in S- and X-band) of the Delft University of Technology, located on the roof of the 92 m high building of its faculty of Electrical Engineering. This experimental radar permits the measurement of the full backscattering matrix by simultaneously transmitting (and receiving) two, digitally generated, orthogonal signals via two orthogonal polarization channels and using two channels (co-polar and cross-polar) in the receiving mode. Its applications are remote sensing (mainly, of the atmosphere), as well as surveillance or tracking; a recent research is the radar analysis and electromagnetic modelling of the Wind Turbines. The PARSAX transmitted signals are fully programmable in amplitude, frequency and code, with a best range resolution of 3 m (signal bandwidth of 50 MHz, duration of the compressed pulse of 20 ns). See also http://radar.ewi.tudelft.nl/.

Another example of experimental facility is the space observation radar *TIRA* (Tracking and Imaging Radar) of the *Fraunhofer Institute for High Frequency Physics and Radar Techniques* (FHR), in Wachtberg-Werthhoven, Germany for the detection and reconnaissance of objects in space, also able to provide support for space missions. The radar is protected by a radome having a diameter of 47 m (the largest of its kind worldwide). With the appearance of a huge, white *ball* (Figs. 9.23 and 9.24) the radome accommodates an antenna with a diameter of

Fig. 9.23 The TIRA experimental space observation radar (Courtesy of Fraunhofer FHR)

Fig. 9.24 The 47-m radome of the TIRA experimental radar characterizes the appearance of the Fraunhofer FHR site in Watchberg, near Bonn (Courtesy of Fraunhofer FHR)

34 m, 360° steerable in azimuth and 90° in elevation at a speed of 24° per second (in azimuth). The TIRA system comprises a tracking radar and an imaging radar. The narrowband, fully coherent, high power tracking radar has a transmission frequency in L-band (1.33 GHz) and the wideband imaging radar has a transmission frequency in Ku-band (16.7 GHz). More details in: http://www.fhr.fraunhofer.de/en/the_institute.html.

Chapter 10
System Integration: A Final (Dis)Solution for the Radar?

Neither Christian Hülsmeyer, the "unlucky" (in the sense that his environment was not ready to accept his invention) inventor of the radar, nor the researchers and the technicians from different nations who, immediately prior to and during the Second World War, have developed the radar and made it operational, could never have imagined the present broad diffusion of radar techniques up to the mass market. And nobody, at least until the 1960s, could ever have imagined that, from the early display of the intensity of the echo on a cathode ray tube,[1] users would enjoy the very rich information of Doppler and polarimetric radars, with the increasingly complex display modes used in radar-meteorology—just to mention one of the so many modern radar applications.

The all-weather and long range detection capabilities of radars are well known, which obviously contribute to complement optical sensors. In addition, radar is a key technology for a number of emerging problems, including:

- personal (body) inspection or imaging for security or medical applications;
- through the wall/ground penetration imaging;
- foliage penetration for ground surveillance or environment monitoring;
- urban or in-house multipath exploitation techniques for non line-of-sight tracking.

It has been shown that pre-war and in the war period the radar operator viewed a simple display of a raw signal, and was supposed to detect by eyes and brain targets embedded in noise and to evaluate their type and relevance. Thereafter, the processing capability of radar systems has gradually led to a greater and greater synthesis and usability of the extracted information. In modern radar such information defines

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[1] In reality, the radar display systems of the early 1940s had, as described before, separated displays for distance, azimuth, and (whenever measured), elevation, with a significant burden for the operators.

G. Galati, *100 Years of Radar*, DOI 10.1007/978-3-319-00584-3_10

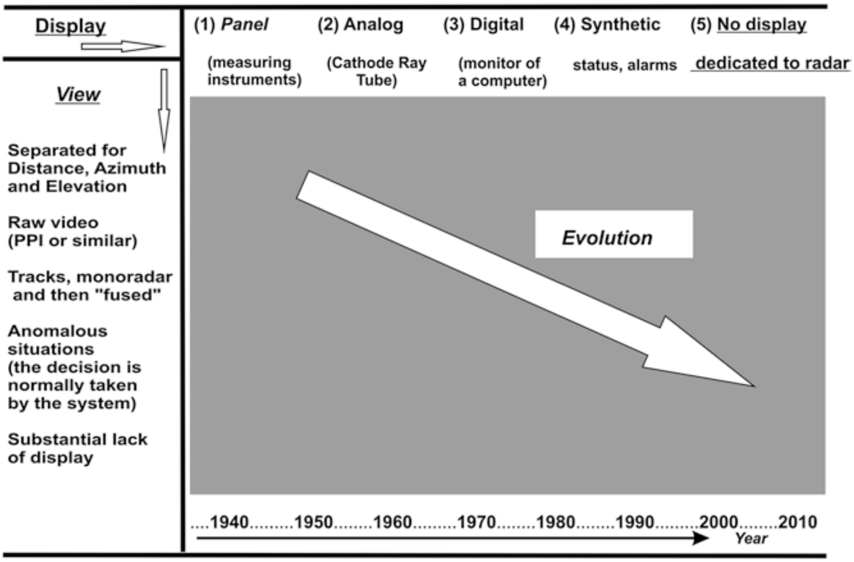

Fig. 10.1 Overview of the evolution by display of raw signals (thirties, beginning forties) to extreme synthesis (years 2000 and beyond)

and highlights facts of operational interest: air targets or naval with their trajectories, the intensity, position and sometimes type of precipitation, reflectivity maps of the ground and even more. So, humans have grown in the hierarchical role versus the radar signal, from the *low level* role of an extension of the sensor to that of a kind of *manager and supervisor* looking—for the decisions to be taken—to the "synthetic" information generated by the radar. Recently (late 2000s) in a significant case, that of *automotive radar systems of the third generation* described beforehand, the process went further, arriving at the automatic decision (in this case, the one to operate the brakes in order to avoid a collision) based on the analysis of radar signals, with no human interve\ntion. Similar situations with the "man out of the loop", at least in principle and in particular cases, could simply lead to suppress the radar display. Such a suppression could happen, for example, when the future widespread use of the increasingly popular UAV/UAS (unmanned air vehicles/unmanned air systems) also in civil aviation will make it necessary to install collision avoidance means, some of which are likely to be based on radar techniques, with some automatic guidance system of the UAV up to its base provided in the case of an interruption of the radio channel between the UAV and its ground-based pilot.

As technology advances, the radar display is going, for short, from a "raw" one, showing the entire radar signal, including noise and disturbance, to a more and more synthetic one, fed by the "fusion" of different sources (or sensors) up, in some cases, to the indication of the only abnormal situations. This evolution is depicted in Fig. 10.1 that only relates to the function of detecting and tracking moving targets, and does not consider remote sensing functions as those of the meteorological radar (even if in the future one should not exclude that the understanding of weather

Fig. 10.2 Console of the meteorological radar meteor 200 mod. RMT 1S–2S (1961)

Fig. 10.3 The new console (2010s) of the kronos defense radar

radar images will be also automated). In this respect, the comparison between the console of the ancient meteorological radar Meteor 200 mod. RMT 1S to 2S—Wind tracker storm analyzed radar—(early 1960s), see Fig. 10.2, versus the one of a modern defence centre, see Fig. 10.3, is self—explanatory.

In the epilogue of [Bla 04], which is part of its chapter on the future of radar, the witty Yves Blanchard puts the question *whether the radar is soluble in the system*, at least for military applications, meaning to point out the possibility of a future disappearance of the military radar as we know it today, and its replacement with multifunction systems (for location, identification, communications, electromagnetic contrast, navigation). The possible reasons are related to the need for: (a) efficient use of spectrum[2] and time resources, (b) integration of equipment and functions and finally (c) integration of the information to be provided to the user, i.e. three strongly related aspects. On one hand, there is a growing demand on the electromagnetic spectrum for uses other than those of the radio-location: everybody knows the continuous spectrum requests for cellular telephony, for mobile networks[3] and for navigation. On the other hand, the coexistence of different radio equipment on the same platform, e.g. a ship or an aircraft, has always been difficult.

While the total of the antennas on a cruiser or an aircraft carrier often exceeds one hundred, on a modern fighter-bomber also there are twenty or more antennas (communications, radar warning receiver, "jammer" …) in addition, of course, to that, under *radome*, of the already discussed airborne multifunction radar (*nose* radar).

The information gathered by the various subsystems of an aerial or a naval platform are combined together, or "fused" at high level, after their processing, and used by the management system of the platform (including of course the human element). The, already discussed, advent of active phased array antennas, whose elements may be distributed on an assigned surface, connected in a flexible manner with appropriate networks and dedicated, in time and/or in space division, to different functionalities, may permit the sharing of the radio frequency modules for different aims. A considerable effort in this regard started in the USA from 2000 with activities of prototype development and experimentation for a future use on aerial [Hug 00] and naval platforms, [Tav 05]. The latter work describes a *Test Bed*, operating from 6 to 18 GHz, with functionalities of:

- Communications (*Tactical Common Data Link* in the Ku-band and satellite communications in the commercial Ku-band and in the military X-band);
- Defence Electronics (both active, through Jamming or Deceiving Noise, and passive—ESM—with analysis and precise location of the emitters), and finally;
- Navigation Radar (which operates from 7 to 16 GHz).

The tests began in the summer of 2004. In the embodiment of the Test Bed the American administration, via the Naval Research Laboratory, involved the main defence industries of the USA.

A parallel program of the American DARPA, called MFRF (Multi-Function RF) and aimed at the airborne context, considers, as a first application, the need for a helicopter to operate in different light conditions, avoiding collisions with

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[2] The *International Telecommunication Union* which is devoted, through its *Radiocommunication Sector* (*ITU*-R), to define the use of the electromagnetic spectrum on a global basis, indicates the radar applications with the term *Radiolocation*.

[3] For example the introduction of the transmission technology known as WiMAX (*Worldwide Interoperability for Microwave Access*) in Italy has caused, in the second half of the 2000s, the replacement of the radars for the national air defense operating in the S-band (i.e. just above 3 GHz) with the latest radar in L band, i.e. the FADR (RAT-31 DL) type.

other aircraft with the ground and with the suspended cables, and furthermore, to keep clear of stormy areas and to build a map of the underlying land. Other functions will include detection, recognition and identification of the targets, control of weapons and finally digital communications. Using software defined architectures, the focus is onto a "plug and play" multifunctional system capable, through the flexibility of the waves and of the RF apertures, to meet the requirements of the existing aircraft (in the case of substitutions, or retrofitting) and of the future ones including UAV/UAS.

Concerning the non-military applications, there have been proposals and some implementations of a prototypal multifunctional radar for civil use, first of which is the MPAR (Multifunction Phased Array Radar). This is an active Phased Array radar in the S-band for the surveillance of air traffic and for meteorology, able to replace, with a single modular technology, at least eight types of radar operating in the USA. In this frame, notable is the USA program called NWRT (National Weather Radar Test Beds) [Yea 11], carried out in cooperation between federal agencies, universities and the private sector. This programme has led to the availability from 2003 , for the community of researchers, of a prototypal multifunction radar in Norman, Oklahoma, whose antenna is taken by the AN/SPY-1 (Aegis) of the US Navy, see Fig. 10.4.

Other developments build on the already described multi-static systems, i.e. with distributed transmitters and receivers. Of the modern MIMO (Multiple-Input Multiple-Output) [LiS 09] radar there is a "statistical" version, with antennas arranged on a wide-area, very much different from the "coherent" version in which the antennas are usually within the backscatter main lobe of the target. The MIMO architecture was brought forward many years ago by Bernard Steinberg with his *Radio Camera*, illustrated in various technical-scientific papers as well as in three volumes of which the most ancient is [Ste 76], and more recently by many other authors including V. Cherniak, [Che 88].

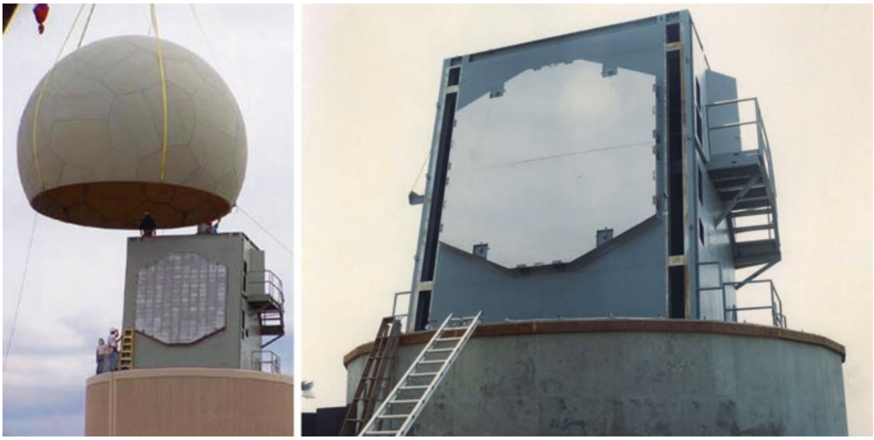

Fig. 10.4 The MPAR test bed

The bistatic operation (and the ensuing multistatic one) is as old as radar itself, because the separation of the transmitter from the receiver greatly simplifies the implementation of the set. In military applications the bi- and multi-static radars show potential operational advantages, mainly consisting in the difficulty, for the enemy, to detect the receiving-only radar stations which are located in the area of operations and cooperate with one or more transmitting stations placed in protected areas. Sometimes, as in the already seen case of *Klein Heidelberg*, the transmitting stations are transmitters of opportunity, outside the control of whoever manages and uses the system, such as broadcast stations, either analogue (FM radio in the range 88–108 MHz) or digital (DVB-T, DAB) or radio communications stations (WiFi, WiMAX) or cellular ones (GSM/GPRS//UMTS/HSPA/LTE), giving rise to the *passive coherent location*(PCL) or *passive radar* technology, studied and experimented in many Research institutes and Universities.[4]

The localization of targets in the multistatic radar case (or in the PCL case) is quite different from the classic "distance—angle" of the monostatic radar: it is necessary to determine the intersection of at least two ellipses (two ellipsoids in a three-dimensional localization)[5] as shown in Fig. 10.5. The technical evolution of the receiving antennas, thanks to the electronic scanning of the beam and the creation of multiple beams (digital beam forming) has, of course, made obsolete the method already described for the Klein Heidelberg, see Fig. 10.6.

The availability of coherent and stable receivers and of fast signal processors makes it possible to process the radar echo, maintaining its phase information even without controlling the transmitter section and even if the echo signal is not known nor predictable, but, rather, is only acquired by an antenna and a receiving reference channel. On this matter, Fig. 10.7 shows a case in which the source and a noise generator (the most used term is *Noise Radar Technology*) which makes the radar hard to be intercepted and exploited. These applications use the information of the time delay and of the Doppler shift which are obtained from the so-called

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[4] In over fifteen years the PCL systems, however, have not yet reached a significant diffusion or usage, not even as "*gap filler*", and perhaps never will reach due to the heavy limitations which are intrinsic to a loss of control of the emitted signal. In fact, the earliest manufacturer of PCL, Lockheed Martin, has closed this line of products. Likely, better commercial chances will be reserved to military systems using PCL and PET (Passive Emission Tracking, or Passive ESM Tracking) on the same target, see [SPV 13]. In this case, the target is located by the intersections of ellipsoids (PCL) and hyperboloids (PET). On the other hand, PCL has some potential for specific applications, e.g. the use of WiFi signals to passively monitor moving objects and persons out of the line of sight. In an indoor application, the movements of people were monitored through the Range-Doppler profiles of the WiFi signals reflected by their bodies. Moving hands above the keyboard of a PC also generate Range-Doppler profiles characterising their movement, with the interesting potential for a new human-computer interface based on 3D movements of the hands.

[5] This operation is made possible by modern broadband transmission networks and by satellite navigation systems, which allow the precise location and the synchronization of radar stations across a country. The name *statistical MIMO* is also used.

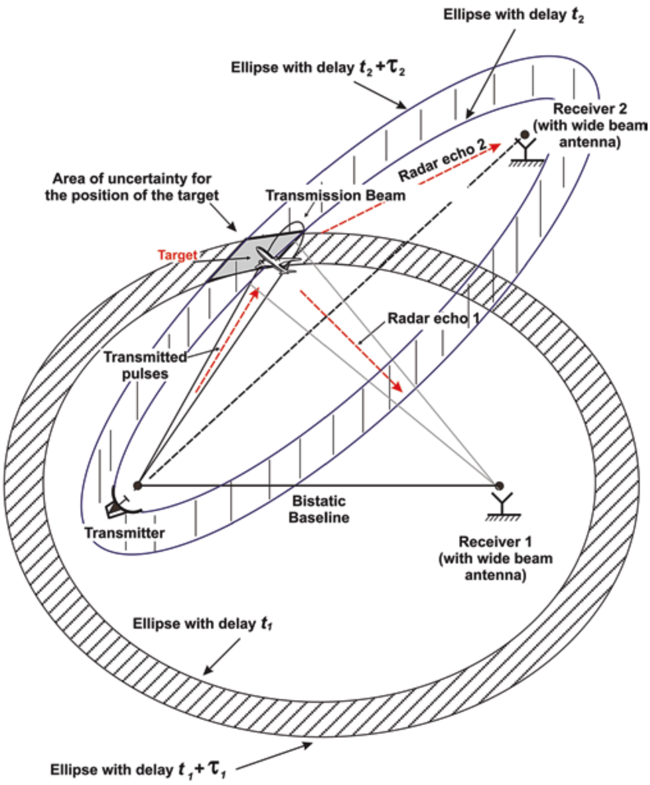

Fig. 10.5 Geometry of a multistatic radar with two fixed, wide beam receiving antennas; the target is located by the intersection of two ellipsoids. The uncertainty is related to the duration of the transmitted pulses (i.e. τ_1 and τ_2) and to the geometry

Cross Ambiguity Function, a generalization of the correlation function used in the optimal reception.[6]

Systems with *multiple inputs and multiple outputs*, also known as MIMO, have received a considerable interest, with some prototypical developments, in

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[6] *Noise Radar Technology* was discussed in the international conferences since the beginning of the century (the first event was the NRTW 2002—First *International Workshop on the Noise Radar Technology*, September 2002, Yalta, Crimea, Ukraine, see http://nrtw2002.lndes.org/downloads/contents.pdf). This technology is discussed, among others, in the NATO working group SET 184 (2012–2014) and in its follow-on SET 225 (2015–2017).

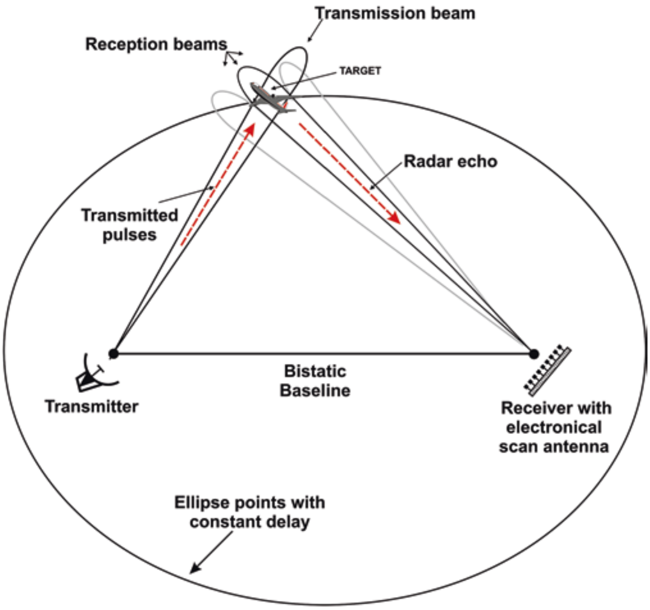

Fig. 10.6 Geometry of a modern bistatic pulse radar, from [Gal 93]. The difference between the time of arrival of the transmitted signal and the one of the eco defines an ellipsoid on which the target is located; the position on the ellipsoid is derived from angular measurements. If, unlike the *Klein Heidelberg*, the transmitter scans the surveillance volume with a narrow antenna beam, the receiving antenna (a phased array) must scan at very high angular speed the pointing line of the transmitting antenna, so implementing the so-called *pulse chase*, or it must synthesize a sufficient number of beams to cover the entire illuminated volume

the early 2000s: the concept was born in the radio communication sector, where the processing of multiple spatial simultaneous channels has allowed significant improvements to the quality of the transmission and its capacity (throughput). This is possible, basically, because MIMO uses channel diversity: the transmitter and the receiver operate according to those channel modes that optimize the signal to noise ratio.

The application to the radar of MIMO concept[7]—that, at the research level, dates back to the early 2000s—is quite different from that of telecommunications. The different MIMO radar configurations (but the most correct term should be

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[7] Also applied in other areas such as sonar systems and biomedical imaging.

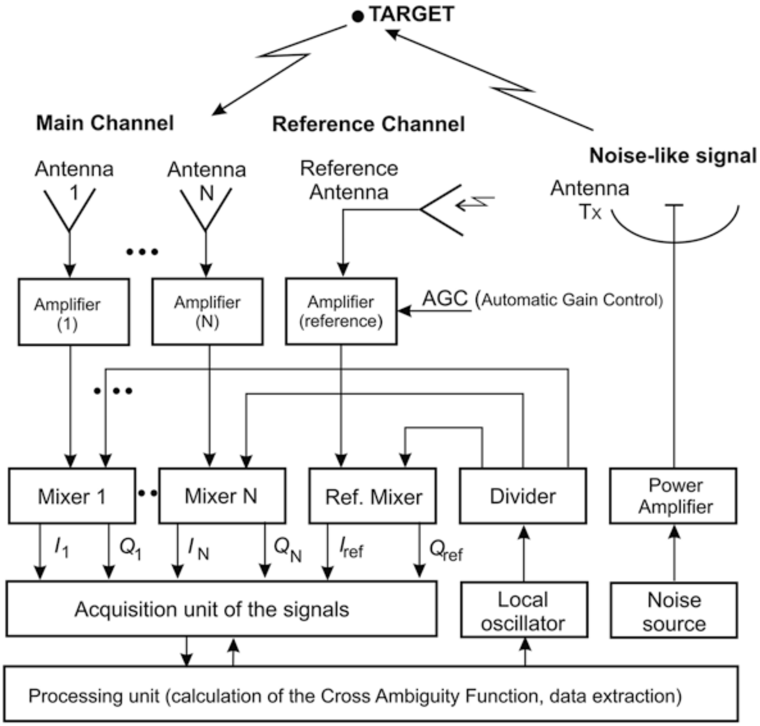

Fig. 10.7 General diagram of a Noise Radar

multi-static, preferred by some authors, see [Che 88]) may be divided into two classes. The first one has antennas very distant from each other,[8] see for example [Hai 08]. The second one, also called “coherent MIMO”,[9] has closely spaced antennas within the main lobe of the target’s backscattering. The reception-transmission

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[8] As an example, in the 2010s the *University College London* (UCL) and the *University of Cape Town* developed a multistatic system called NeXtRAD (follow-on of the previous NetRAD by UCL) with three nodes (one transmitting and two receiving), multi-frequency (X band, S and L bands being planned), variable pulse duration (0.5–20μs), dual polarization, fair power (400 W peak at X-band), large bandwidth (greater than 100 MHz; 50 MHz for the NetRad) to be used for multiband characterization of (mainly, sea) clutter and targets as well as for micro Doppler and MIMO radar trials.

[9] The region in which the antennas are located is smaller than the diffraction lobe of the radar target, therefore the different antenna signals may be combined in amplitude and phase, i.e. coherently.

between different pairs of these antennas synthesizes a virtual array whose dimensions which may be significantly greater than the physical ones of each antenna [LiS 07].

In principle, nothing prevents us from combining the advantages of the two approaches in a multistatic system (MSRS: *Multisite Radar System*) of "*coherent MIMO*" radars, as proposed in [XuD 11].

The embodiment of a MIMO radar is made possible by the intrinsic flexibility of the active phased array antennas whose elements can be organized into a number of sub-apertures. Different waveforms may be transmitted by the different sub-apertures; in reception, the outputs are combined to synthesize a number of simultaneous beams. The case of a single transmitting beam is shown in Fig. 10.8.

On the other hand, coherent MIMO permits a fine angular resolution, equal to the width of the main lobe of a very large virtual antenna being synthesized as a convolution between the illumination of the transmitting section with that of the receiving section, see Figs. 10.9 and 10.10.

The advantage is clear: by transmitting from a linear array with M elements and receiving from a linear array with N elements, the radiation pattern of a "full" rectangular array with N·M elements is obtained. The shape of the beams thus obtained can be defined, as a function of the operational requirements, by suitable weighting, providing "beam forming" in both transmission and reception. The greater information content allows for a better interference suppression by means of the STAP (Space-Time Adaptive Processing) [Che 08].

The MIMO radar techniques also fall into two time-scale categories. One of them is *time division* (sometimes called *switched*) *MIMO*, useful when the radar environment is stationary and the time is not a critical element. With this

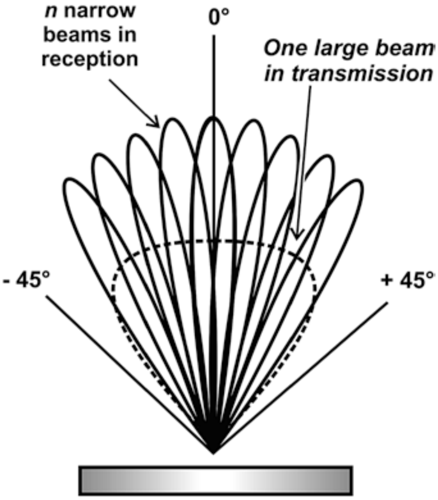


Fig. 10.8 Pictorial view of the digital beam forming concept, with simultaneous antenna beams in reception

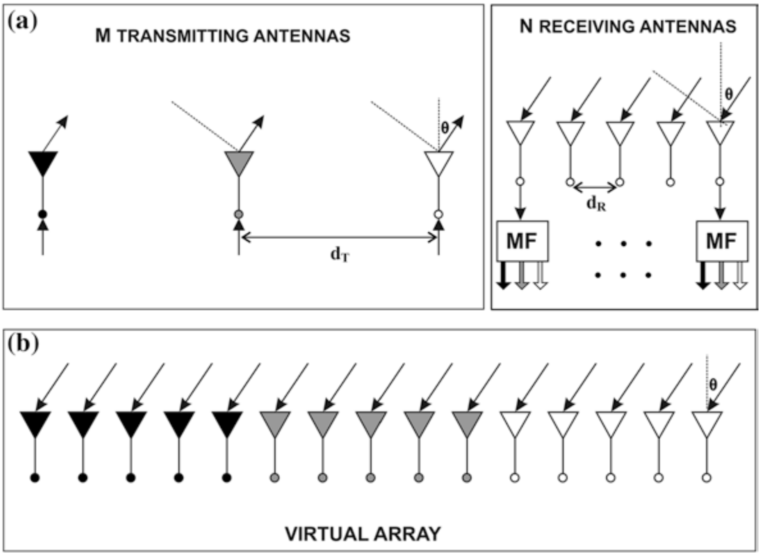
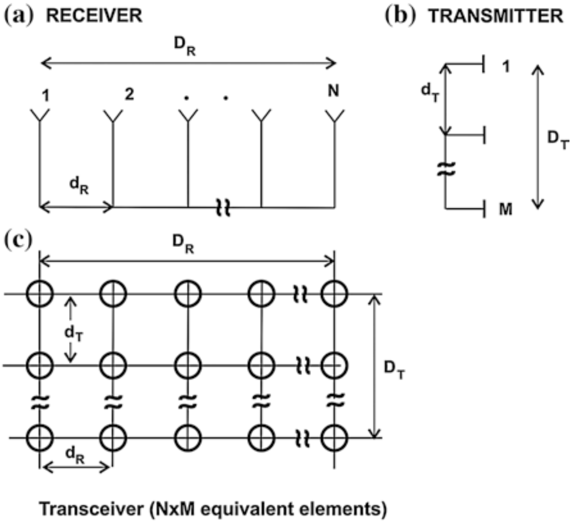


Fig. 10.9 **a** Schematic diagram of a MIMO radar with M = 3 transmitting antennas and N = 5 receiving antennas; **b** Equivalent virtual array, with M × N elements. *MF* Matched filter

Fig. 10.10 Example of application of the MIMO concept to a pair of linear arrays, a (receiving) *horizontal* and a (transmitting) *vertical* one. **a** Reception **b** transmission **c** reception-transmission (N × M equivalent elements)



technique,[10] transmission starts with the element number 1, with reception and acquisition by the elements 1, 2, … N of the receiving array; then the process repeats itself transmitting from the element number 2, and so on up to the Mth. Another technique is code division, with generation of M orthogonal signals[11] [Fri 07], [vGe 12] and their transmission by the elements 1, 2, … M respectively; these orthogonal signals will be separated in reception by a bank of M filters within each of the N receiving elements. From similar arrangements (in which, incidentally, the greater dwell time compensates, via the integration of signals, the reduced antenna gain) the name of "ubiquitous radar" was born [Sko 01a]. These architectures are not necessarily of MIMO type, but may be a more simple SIMO (Single Input-Multiple Output) [Fri 09], or Phased Array radar in which the transmission occurs "wide-beam" by a *subarray* (or by a dedicated antenna).

In addition to the MIMO radar, researchers are studying, still at the basic research level, applications to the radar of the "sparse" representation of radar signals and the related *Compressed Sampling* [Can 06a], [Can 06b], [Can 08] with an aim to overcome, for targets detection and resolution, the concept of matched filter and of ambiguity function [Bar 07], [Str 09], [Her 08], [Her 09]. The *Compressed* (or *Compressive*) *sampling* (or *sensing*), for short, CS, is mainly due to Emmanuel J. Candes who in 1998 received a Ph. Doctor degree in statistics from Stanford University with a thesis on "*Wavelets able to capture higher order structures in signals*". In radar, the CS is mostly aimed to improve the resolution and/or to reduce the usage of hardware resources. It is based on the a priori definition of signals to be acquired and of a sampling base; the detection of the signal (target echo) is the result of an optimization process trying to minimize the number of coefficients which represent it and agree with the measurements. A critical aspect of the CS applied to the radar is the possibility of generating false targets due to disturbance (noise, clutter). In the course of the EuRAD 2012 conference [Eur 12], thirteen papers on MIMO radar (including detection and tracking of objects behind a wall and ultra-wideband (UWB) techniques) and three papers on Compressed Sampling were presented out of 91 papers dedicated to radar. These limited and partial data, are an early indication of the evolution and the interest in some modern radar topics. Ongoing applied research will better define the applicability of similar new concepts to operational radar systems.

To the surprising novelty of radars capable to operate the brakes of a car without, or before, any human intervention, many other ones will be added in the coming years, continuing to keep alive and interesting the wide and varied radar area about which, without any pretence of completeness, some facts and facets

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[10] A real case, presented by the Dutch TNO at the EuRAD Conference (EuMW, Manchester, October 13th–14th, 2011), has been the monitoring of civil structures (mainly, buildings), by a radar with MIMO *through the wall* operation, positioned on a van, moving on the road in front of the buildings to be monitored.

[11] Those signals have theoretically null, practically negligible mutual correlation.

were reported in this volume. In more general terms, it should be pointed out that various indicators (number of employed, of published works, of attendees in Conferences …) show that the development of radar in Europe and in the rest of the world continues to be very relevant and growing.

Perhaps this can be explained by some *Darwinian* aspect of radar, which is capable of continuously evolving in order to adapt itself to changing needs, without forgetting the teachings that have marked over a hundred years of its history.

End Notes

Chapter 1

[1] Of course, there have been *unlucky inventors* also "in the absolute sense". Perhaps, the most popular of them in Italy, is Antonio Meucci (Florence, April 13th, 1808—Staten Island, October 18th, 1889), whose paternity of the invention of the telephone, stolen by A.G. Bell, was recognized even in the USA (resolution 269 of the United States Congress, June 2002) although very late and only thanks to the enormous work made by Dr. Ing. Basilio Catania, documented on http://www.chezbasilio.org/. Many other clever inventors were unlucky, such as Eli Whitney, who at the end of the Eighteenth Century invented a machine to cleanse the cotton, known as a *cotton gin*, with which a good part of the South of the United States was enriched, or another American, Christopher Latham Sholes, to which the mostly used model of typing machine is due (and even the current QWERTY keyboard), or even the English colonel Henry Shrapnel, who has named a type of ammunition well, and sadly, known even today.

[2] Born in Eydelstedt, a small village south of Bremen, on December 25th, 1881, Hülsmeyer was baptized with the name Johann Christel; as a student of the local school (1887–1895) he was immediately noticed for the vivacity of its intellect; on the advice of professors, he entered the College of Bremen in 1896 aiming to become professor of physics. The College had a laboratory for experiments on the waves of Hertz, which probably attracted much of the interest of the young Christian. Encouraged by the direction of the College, he made experiments for the reflection by metal surfaces of the radio (Hertzian) waves generated by spark discharge. For never clearly explained reasons, he let the College in 1900. Between 1900 and 1901 he lost both parents, and by the decree of the royal court, he was declared "independent adult" in September 1901, before being 21 years old; his profession, reported in the decree, was *Mechaniker*, mechanical engineer, the activity he carried out at the Siemens-Schucketr in Bremen. In April 1902 he left the Siemens-Schucketr and joined his brother Wilhelm at Düsseldorf. His daughter Annelise recalls (but her memory may have been

G. Galati, *100 Years of Radar*, DOI 10.1007/978-3-319-00584-3

distorted by her feeling) that on that occasion Christian had only two marks in his pocket. His first patent was filed on March 20th, 1902 for an invention, whose description is not too clear, and is called *Telephonogram Apparatus* in the patent application to the USA (October 13th, 1902). Numerous patent applications followed, not all transformed into a patent. One of them is the application No. H 31 800 dated November 21th, 1903, of which only the title is known: *Telemobiloskop*, that makes us think of the radar; however, it was dismissed. After the episode of the patent on the radar (1904–1905), and the failed attempt of marketing it, Hülsmeyer applied his undoubted and multifaceted capacity to other fields. In the course of his life, including the extensions abroad of his patents and the not-accepted applications, has produced over 150 between patents and patent applications! He got some success with an anti-limestone filter for boilers and heating machines. In 1910 he founded in Düsseldorf-Flingern an industry which was operating until 1953, with some difficulty during the crisis in 1923 and also in 1934, when the Nazis put Hülsmeyer in prison for some time. He married in 1910 with a girl from Bremen, Luise Marie Petersen, and he had six sons between 1911 and 1924. As already said, he forgot the radar, but not for ever: at the beginning of the 1950s in Germany they rediscovered this 70-years-old scientist who had built an "Ur-radar" (prehistoric radar). In April 1954, on the fiftieth anniversary of the "Telemobiloskop" patent, the German Institute of Navigation (DGON: *Deutsche Gesellschaft für Ortung und Navigation e.V.*, with headquarter in Bonn) organized a Conference which included a meeting between Hülsmeyer and Sir Robert Watson-Watt, the creator of the Chain Home and father of British radar (but according to him: *British father of radar*). It is said that on that occasion Watson-Watt had some difficulty in acknowledging that he had, at least, to share the paternity of the radar with Hülsmeyer! Christian Hülsmeyer, unlucky inventor as far as the radar is concerned but, probably, lucky and happy man, and certainly enterprising and brave, died of a heart attack on January 31st, 1957 in Ahrweiler near Bonn, at the remarkable (for those times) age of 75 years.

[3] The radar community reminded Hülsmeyer on different occasions, including the "*Colloque international sur le radar*—Radar 2004", a conference organized by the French cultural and professional association *SEE* in Toulouse, October 2004, which opened with a historic session (similar meetings took place in the same year, in Germany and in the Netherlands) dedicated to the centenary of the radar. The session was based on the work of a special committee including both radar experts (i.e. Yves Blanchard, president; Marc Lecomte, secretary; Jean Claude Boudenot; Arthur O. Bauer, Jean Marie Colin, Hermann Rohling) and an historician (Pierre—Eric Mounier-Kuhn). On that occasion many, new elements on the invention of radar emerged. The author has particularly appreciated the publications, and the painstaking work of documentary investigation, by Arthur O. Bauer and Yves Blanchard, on which his chapter is mostly based. In this respect one should not forget the previous research by David Pritchard, author of the probably most complete work on the German contribution to the origins of the radar, [Pri 89].

[4] Two of these patents are most noticeable. The first one is the DE 111578 (October 14th, 1898) by Karl Ferdinand Braun (Fulda, June 6th, 1850—New York, April 20th, 1918—the well-known inventor of the cathode ray tube, which made possible the first display of radar signals). The patent by Braun included—like, in reality, what O. Lodge had done a few months before—a tuned circuit by inductive coupling on the primary of the transformer between the spark generator, or spark gap, and the aerial, which increased very much the power transfer to the antenna itself. The second one is the patent No. 7777 (well known as *syntony patent*) by Marconi (26 April 1900) developing a similar solution, however, with tuning of both the primary and the secondary circuit of the transformer. Marconi himself recognized "having borrowed" this idea from the patents by Braun on tuning.

[5] On the other hand, the priority of the invention of the radio is still disputed: in Russia, (and before, in the Soviet Union) Aleksandr S. Popov [Sus 62] is known by everybody as the inventor of the radio. In the U.K. they celebrated, in 1994, the centenary of the invention of radio telegraphy (wireless telegraphy) attributed to the physicist Oliver Lodge (1851–1940) together with George M. Minchin. Others indicate the Indian physicist Jagadish Chandra Bose, and finally in 1943 the Supreme Court of the United States of America recognized the priority of the patents by Nikola Tesla over those by Marconi. Tesla, as it is well-known, was an American-naturalized Serbo-Croatian. He is another example of "unlucky inventor", and died, poor, in the same year 1943 as the Decree of the U.S. Supreme Court. The U.S. Patent 645.576 by Tesla presented the September 2, 1897 and assigned on March 20th, 1900, "*…comprises a system of four circuits, with each of two circuits transmitting and receiving, and is operated so that all four circuits are tuned to the same frequency [… He] Knew (in the patent) that his apparatus could, without any change, be used for wireless communication…*".

The IEEE celebrates the person of the Canadian scientist Reginald Aubrey Fessenden (1866–1932), since 1892 professor of electrical engineering at Purdue University, who, according to the historical section of the IEEE itself, http://www.ewh.ieee.org/reg/7/awards/fess_bio.htm, in his laboratory at Cobb Island on the Potomac River managed to transmit by radio a voice message on December 23rd, 1900, at a distance of fifty miles. The well known transatlantic transmission by Marconi came only a year later. On the very controversial issue, which is now centennial, of the fatherhood of the invention of the radio (or *radio-telegraphy* or *wireless*) the interested reader is addressed to the well-documented article [Gar 11]. Prof. Gardiol from the Swiss Technical University ETHZ (EPFL), a scholar who has written nine books and is author/coauthor of more than 300 scientific works. Being free, maybe even for his "neutral" nationality, from every preconception, Gardiol is one of the very few authors who narrates objectively the basic education by Marconi, who "… picked up a few concepts of physics and mathematics at Livorno, under the guidance of Vincenzo Rosa, a professor in the Liceo Niccolini; … However, his scientific education had many shortcomings. Therefore both the

Naval Academy in Livorno and the University of Bologna refused his application (contrary to what is commonly believed, Marconi was never a student of Righi, even if he was present at some of his lectures)".

[6] In various documents it is possible to find the text of the speech by Marconi: "…as shown by Hertz, the electric waves can be completely reflected by conductive bodies … In some of my experiments I noticed reflection effects of these waves by metal objects at a distance of miles… It seems to me that it should be possible to design apparatus by means of which a ship might radiate or project in any convenient direction a divergent beam of rays which, if they impinge a metallic obstacle, for example another vessel, would be reflected to a receiver located on the ship that carries the receiver (being protected by a shield from the transmitter), thus revealing the presence and position of the other ship, in fog or in bad weather, even if these ships were deprived of any type of radio".

[7] It is found, once again, the whistle (hissing sound) that could not be generated by a vehicle at the relatively low speed of the car by Marconi, except in the case that Marconi used the frequency-modulated continuous-wave technique (FM-CW) of the first radar by Tiberio, which is described in Chap. 2. But this is not compatible with the fact that the transmitter and the receiver were in two different places. Moreover, it should be noted that the book [Sol 11] Solari itself makes no reference at all to these experiments, while he describes in detail the visit to the radio equipment in *Torre Chiaruccia* operating on 55 cm on November 26th, 1936 to analyze the interference with the Daventry station. Anyway, nothing remains: Marconi's equipment was removed or destroyed during the Second World War and even the building (the old tower known as *Torre Chiaruccia*) was completely destroyed on February 1st, 1944.

Chapter 2

[1] The eyes of the Owl, as in all nocturnal birds of prey, are extraordinarily sensitive. It is well known that the eyes of humans and of many animals have an almost spherical symmetry; this geometry allows a scan (without head movements, therefore, fast and with minimum energy consumption) within an angle of nearly 180° in all directions with respect to the usual, nearly frontal "pointing direction". Vice versa, from the optical point of view, the eye of the Owl is a system with cylindrical symmetry, i.e. it is similar to a photographic lens allowing a high *relative aperture* (ratio between optical aperture and focal length, the *f/number* of photographers), granting the excellent brightness of the image formed on the retina, which is required for night vision. On the other hand, the eye of the Owl cannot move with respect to its head, which is small and very mobile. From these two characteristics, the great relative aperture and the lack of mobility, the stillness of the gaze and the apparent red color of the eye of the Owl originate: "*Dardant leur oeil rouge*". The latter is due to the abundant blood vessels on its bottom, which in the humans is perceived only if illuminated directly from a flash, creating, on some photographic images, the annoying "red-eyes" effect.

[2] Born in Campobasso, Italy, on August 19th, 1904, Ugo Tiberio graduated with honors in civil engineering in 1927 from the University of Naples, and worked at his father's study from 1927 to 1931. He obtained in 1932 a specialization diploma in Electrical Engineering at the Engineering School in Rome, and in 1933/34 he was lieutenant [*sottotenente di complemento*] of the Corps of Engineers. Once finished his military service, he remained at the Military Higher Institute of Transmissions (ISMT) in Rome as engineer and lecturer of Radio Techniques. By winning a competition, he was appointed in 1935 Lieutenant of Naval Weapons in the Italian Navy (Regia Marina) remaining at the ISMT until 1936. He held research activities from 1931 to 1936 at the ISMT, and from 1936 till the Armistice in 1943 at the R.I.E.C. (i.e. the Electro Technical and Telecommunications Institute of the Navy) in Livorno, where, at his request, he was transferred in 1936. In 1937 he received the University teaching qualification in Radio engineering and from 1937 he was professor at the Naval Academy. Within the Italian Navy, during his long recall in W.W.II, he had two promotions for outstanding scientific merits, arriving, finally, at the rank of Lieutenant Colonel of Naval Weapons. He won the competition for the chair of Electrical Engineering at the Naval Academy in 1941, and in 1948 he was included in the list of possible winners [*ternati*] for the chair of Electrical Communications at the University of Rome, where, anyway, he could not be appointed professor for bureaucratic reasons. Then in 1953 he was still in the list of possible winners of the competition for the chair of Theory of Electromagnetic Waves banned by the Naval University of Naples, and finally was "called" to the chair of Radio Techniques (Radiotecnica) in the University of Pisa in 1954, where he was full professor until 1979, the year of his retirement. In Pisa, in the late '50s, he founded the Institute of Electronics, which, time after time, has become the present Department of Information Engineering. He died in Livorno on May 17th, 1980. The area where he was mostly engaged, with significant results that make him always remembered in the scientific fora, was that of the radar techniques. His research in this field began in 1934 by the construction at the R.I.E.C. (in spite of the scarcity of means and technologies) of the first prototypical Italian radar used by units of the Italian Navy during the Second World War. His name is also linked to some theoretical aspects of the radar, such as the "fourth power formula" for the radar range, the concept of radar equivalent area (radar cross section) of the targets, the visibility factor etc. In the post-war period prof. Tiberio continued his research in the field of electronics, telecommunications, electromagnetic propagation and bioengineering [EDM 15].

[3] The shift of the frequency when the source of the waves is moving with respect to the receiver (or the observer) was analyzed for the first time in 1845 by Christian Andreas Doppler (Salzburg, 1803—Venice, 1853) who made well-known experiments with acoustic waves. This shift is called "Doppler frequency", and is equal to the ratio between the radial speed and the wavelength (for the normal situation of radial speeds very small as compared to the propagation speed). In radar this effect is present in both the transmitter-target

path and in the return path; if the transmit and receive antennas coincide or are close to each other, the shift resulting from the target motion is twice the ratio between the radial speed and the wavelength. In a coherent radar the Doppler effect permits the detection of moving objects even in the presence of strong echoes due to fixed objects (i.e. the well known *moving target indication*, or MTI, function).

[4] Nello Carrara (1900–1993) was full professor at the Naval Academy in Livorno from November 1st, 1924 to January 16th, 1954, founder of the Research Institute on Electromagnetic Waves, *IROE* (former Microwave Center) of the National Council of Research (CNR) in Italy and director of IROE from 1947 to 1970, and finally President of the company SMA [*Segnalamento Marittimo ed Aereo*]—Florence. Prof. Carrara was responsible for the paternity of the term *Microwave,* used in his paper "The detection of microwave" published in the *Proceedings of the Institute of Radio Engineers*, vol. 20, (10), pp. 1615–1625, (1932). In Italy, the first issue of the scientific magazine *Alta Frequenza*, founded in 1932, contains the paper entitled: "La rivelazione delle microonde" [Detection of microwave] by Carrara, showing for the first time, in the Italian scientific literature, the term "Microonde". In the field of radar, we should remember that Carrara made the important contribution of designing a valve, realized in collaboration with the Italian firm FIVRE [*Fabbrica Italiana Valvole Radio Elettriche*], which allowed one to reach a peak power of 10 kW. Inserted into a cavity resonator with a high quality factor (Q), which is also of Carrara's design, this valve could overcome the difficulty of obtaining high power levels in the ultra-short waves (70 cm) region.

[5] In the pulse technique the measure of the distance R is derived from the total transit time (forth and back) of the signal, which—if the transmitter (Tx) and the receiver (Rx) are located in the same place—is equal to $2R/c,$ with c is the speed of light (in practice every microsecond of delay between emission and reception corresponds to a distance of approximately 150 m). The above expression is valid in the usual circumstances of a target speed much smaller than that of propagation. In radar, the "instrumented range" is the distance (equal to $cT/2$) that corresponds to a round-trip time equal to the pulses repetition period T; for example Tiberio's "radiotelemetro" E.C.3 of 1940 sent 5000 pulses per second ($T = 200$ µs, $ct/2 = 30$ km); the following E.C.3-Ter *Gufo* (1941), with ten times more transmitted power and a more sensitive receiver, sent 500 pulses per second and had a instrumented range of 300 km. Note that if the Tx and the Rx are located in different positions, and the target is R_1 m from the first, R_2 m from the second, the delay is $(R_1 + R_2)/c$ seconds and the target is on an ellipse whose foci are Tx and Rx.

[6] Giancarlo Vallauri (Rome, October 19th, 1882—Turin, May 7th, 1957) after attending the Naval Academy in Livorno, graduated in electrical engineering in 1907, and devoted himself immediately to university teaching, first at the University of Padua and Naples, and from 1916 in Livorno at the same *Accademia Navale*. He was promoter of the birth (on June 11th, 1916, with

daily activity beginning on December 1st, 1916) and director (1916–1926) of the Institute of the Navy that today has his name (*Istituto per le Telecomunicazioni e l' Elettronica "G. Vallauri"*, generally known as Mariteleradar-Livorno, since 2007 a part of the CSSN [*Centro di Supporto e Sperimentazione Navale*], that also includes *Mariperman* and *Marimissili*). In the period between 1920 and 1923, the Institute designed and built in Coltano[1] the first major radio station in Italy, one of the most modern facilities of that time, also used to ensure the links with the Italian colonies *Eritrea* and *Somalia*. In 1926 Vallauri was called to the Technical University of Turin (*Politecnico di Torino*), of which in 1935 he became chairman [*rettore*]. In Turin he created the conditions for the birth (started in 1934) of the IEN [*Istituto Elettrotecnico Nazionale*] Galileo Ferraris. In March 1932, he founded the magazine *Alta Frequenza*, whose authors were Ugo Tiberio, Nello Carrara, Francesco Vecchiacchi, Guglielmo Marconi and many others (unfortunately, the last issue of *Alta Frequenza* was the N. 6–November/December–2001: this historic magazine, unique in Italy of its kind, was suppressed for budget reasons). Moreover, Vallauri was the successor of Pietro Badoglio from 1941 to 1943 as President of the National Research Council. Vallauri is also well known for his equation that allowed the analytical definition of the properties of electron tubes (the so-called *equation of the triode*).

[7] For example in Europe, companies such as the Spanish INDRA have an entire family, called ARIES, of CW military radar with a solid state transmitter for naval (navigation, surface search, search of air targets) and coastal applications, including a version for submarines. From this family, INDRA derived a civilian product, a CW radar for airport surveillance, i.e. a "Surface Movements Radar" (SMR).

[8] It is known that in the first years of the Twentieth Century, a fruitful period to which we will return in Chap. 3, the first active electronic devices, called *valves* (and sometimes *electronic tubes* or simply *tubes*), were born. John Ambrose Fleming (1849–1945) invented the *diode* in 1904 and Lee De Forest (1873–1961) invented the *triode* (at that time called *Audion* or "De Forest's valve") in 1906 and patented it in 1907. The *triode*, together with the successive types of valves, allowed the development of radio communications at a large distance and, of course, of radar. About fifteen years later, through the work of many researchers, first of them Albert Wallace Hull (1880–1966) from the *General Electric Research Laboratory*, the *magnetron* was invented. The main purpose of the research on tubes controlled

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[1] The area of *Coltano*, between Pisa and Livorno, is historically well known, [Bac 89], [Cia 96], for the fields of imprisonment [Pwe 336, 337 and 338] in which, at the end of the Second World War, the US Fifth Army kept soldiers from defeated Germany and the *Repubblica Sociale Italiana*, and their supporters, in inhuman conditions. Anticipating Guantanamo, the military prisoners were declassified from *Prisoners of War* (PoW), to which the Geneva Convention must be applied, to *Disarmed Enemy Forces* (DEFs). In another field near Pisa, the *Metato* one, the poet Ezra Pound was segregated in a cage, like a beast in a zoo (May to June 1945).

by a magnetic field, such as the *magnetron*, was to overcome the protection by patents of De Forest and by those of the inventor of frequency modulation, Edwin H. Armstrong (1890–1954). The magnetron by Hull worked as amplifier in radio reception and even as a low frequency oscillator. It shall not be confused with the ensuing *cavity magnetron* of the 1930s, a power oscillator which today is called briefly *magnetron* having made obsolete the other types.

[9] Alfeo Maria Brandimarte (Loreto, January 31st, 1906—Rome, June 4th, 1944) served with the initial rank of captain in the *Regia Marina* during the Second World War. He collaborated with Tiberio and Carrara to implement the first operational Italian radar, the E.C.3 (*Gufo*). From the first days after the Italian armistice (September 8th, 1943) he operated in the ranks of clandestine opponents to the nazi-fascists [*Resistenza*] where he, with self-developed means, implemented various radiotelephone links with national and allied authorities of liberated Italy. He was actively sought by the Germans; as a result of spying, he was captured on May 23rd, 1944 and kept in Roma, in the *Via Tasso* prison. On the evening of June 3rd, 1944, with allied forces just entering Roma, he was loaded by the Germans on a truck together with other Italian and foreign prisoners, in a convoy to northern Italy. On the morning of the next day, together with 13 other prisoners including Bruno Buozzi, he was executed by a firing squad (Massacre of La Storta, whose motivation has never been fully clarified). His adventurous life, and his almost incredible contempt of danger, is narrated in the book "*Ricordi di un marinaio*" [Memories of a sailor] by the Admiral Franco Maugeri, Nursia editions, Milan, 1980.

[10] The Radar Cross Section, usually indicated by the letter σ, is the ratio between the incident power on the target (W) and the power density (W/m^2) backscattered in the considered direction per unit solid angle; therefore it is measured in m^2. At the time of Tiberio it was preferred to use the intensities (effective values) of the electric field (and of the current) rather than the power values. Hence, the equivalent concept of *Forzacimomotrice* (from the Greek *kyma*, wave), which represents, in the wave emitted by a source and measured at a given distance from it, the product of the field intensity by the distance, a product that in free propagation remains unchanged at distances from the source large enough with respect to the radiator (i.e. in the so-called far-field). By applying this concept to the field backscattered from a target, Tiberio arrived to the radar equation [Tib 39]. According to it, the field strength (V/m) backscattered from a target at a distance R is given by the product of the "equivalent length of re-radiation" of the target [m] by the transmitted *Forza cimomotrice* [V · m] divided by the square of the distance, R^2 [m^2], a result fully equivalent to the modern formulation. Tiberio considered, in the first instance, a target made up by a metallic wire (for complex targets, Tiberio considered their decomposition into many wires).

[11] SAFAR, a company manufacturing radio sets, was founded in Milan in 1923 to produce headphones for radios and phones. In 1927 the firm expanded its

activities, with 375 employees, and in 1931 SAFAR started to produce radio equipment in large quantities, having obtained orders from the Air force and from the Navy, and was responsible for establishing new radio stations in Addis Ababa, Harrar, Mogadishu, Asmara and Massawa. A new specialization was achieved by SAFAR with the production of cathode-ray tubes for different uses. SAFAR produced the first Italian television system that worked briefly in Rome and Milan before the Second World War. During the war, in its Milan plant (Via Bassini 15) about 4600 employees and workers were employed. After the armistice on September 8th, 1943 the company continued to operate for the armed forces of the *Repubblica Sociale Italiana* and for the German command. In 1946 its laboratories were ready for mass production of television sets, derived from the "Gufo" radar receiver, with the European standard of 625 lines; however, soon after the war SAFAR, which had tied his interests to the past regime, received virtually no orders and had to cease all activities in 1948. A part of the SAFAR archive, acquired by Luigi Carilio Castioni, is preserved at the National Museum of Science and Technology *Leonardo da Vinci* in Milan.

[12] Arturo Vittorio Castellani (Gorizia, 1903—Milan, 1968), graduated in 1928 in engineering in Zurich and was only 28 years old when his first book on television was published by *Hoepli*. After a first period with *Magneti Marelli*, a company he left around 1929, in 1932 he became Central Technical Director of the SAFAR, and he was a shareholder of this company with 25–30 % of the shares.

Castellani filed numerous patents in the fields of television and radar and had installed in his house in Milan a well equipped laboratory; being a kind of electronics genius, he greatly contributed to the development of the Italian radar. In a paper dated 1939 Castellani foresaw the coming of television as a public service, which could be extended to Italy as a whole within 1945. In 1941/1942 within SAFAR he was the designer of the prototype of the RDT/5 *Veltro*, an Italian *Flak* radar with fire control capabilities. During the war he took care of the industrial production of other radar sets (E.C.3-bis, E.C.3-Ter *Gufo*). After the closing of the SAFAR he hold consultancy positions for the major electronic industries, manufacturers of radio and television sets. In 1952 he tried to install in Milan the first private Italian television.

[13] A fierce debate—to which Ugo Tiberio was always, and wisely, entirely unrelated—arose in Italy one or two decades after the Second World War between those who accused the high-ranking officers of the Italian Navy not to have encouraged, and in some instances, to have hindered the development of the radar, and those who defended the Navy. It should be recalled that, according to the accusers, Tiberio had to work virtually alone and at the same time was teaching at the Academy (and in fact, he did never stop teaching), while from [SMM 98] it results that "at the radar project two sections worked, connected respectively to Prof. Tiberio and to Prof. Carrara who ….also had to ensure the teaching at the Naval Academy", and that "each section included a maximum of two NCOs and some workers who

worked in close contact with the two professors who, in addition to the development of theory and calculations, also liked to participate directly in the practical phase of equipment construction".

[14] During the war, the R.I.E.C. had to deal with the *Electronic Counter Measures* (ECM, *jamming*) and *Electronic Counter-Counter Measures* (ECCM): in addition to the activity on *Radiotelemetri*, the R.I.E.C. researchers also had the responsibility to investigate the means to prevent the interception of radar signals by the enemy and to limit the effects of radar interference generated by the enemy with the use of suitable transmitters. In short, the Institute treated the problems connected with the "electronic warfare", paying particular attention to naval applications. The development of radar counter-countermeasures at the R.I.E.C. engaged very much the team of Tiberio, who, however succeeded once again to give effective answers, either by reducing the wavelengths used by the naval radar, or by making them suitable to operate on multiple frequencies, a forerunner to the modern "frequency agility". At the same time, research was initiated at the R.I.E.C. to use new techniques of emission of radar signals based on *pulse compression* with the use of dispersive networks that permitted advanced solutions to improve the anti-jamming characteristics. Of course, there was a substantial end of any activity with the armistice of September 8th, 1943.

[15] In Chap. 3, paragraph (3) of [Tib 51b] the method of coating of the targets to implement the "interferential absorption" is rigorously analyzed and described. It's not easy to find in the technical and scientific "open literature" of the following four decades such a thorough discussion on the "stealth" targets through what today is called *Radar Absorbing Material*. During the war, under strict secrecy, this technique was used by the Germans to mask the snorkel or the emerged part of a submarine against the radar allies at the 3 and 10 cm wavelength by covering them with a mixture of rubber and graphite.

Chapter 3

[1] This *Exposition Universelle* was held from May 6th to October 31st, in the centenary of the French Revolution and, as it is well known, saw the inauguration of the tallest building in the world (at that time): the big Tower, initially 300 m high (with the addition of antennas in 1957, it reached 320 m and exceeded the height of the Chrysler Building) built by Gustave Eiffel (1832–1923). Soon the *Tour Eiffel* proved useful for telegraphy: since 1898 Eiffel had allowed experiments of wireless telegraphy between the Tower and the Pantheon, and soon General Gustave-Auguste Ferrié (1868–1932) succeeded in the first communications of this type: in 1897, a year after Marconi's experiments, Eugène Ducretet (1844–1915) made his trials of radio broadcasting from a mast on the third level of the Eiffel Tower. Ferrié supported the preservation of the tower against its demolition, scheduled within twenty years after its construction.

[2] During the *Belle Époque* they begin to “think big”: for instance, in previous times anything similar to the Eighth Symphony in C minor by Anton Bruckner (1824–1896) would have been unthinkable. This work, monumental for its duration and its huge orchestra, was performed for the first time in Vienna on December 18th, 1892, conducted by Hans Richter. In those times people could succeed in the arts, sciences and professions while being still young, as well as Christian Hülsmeyer, who filed his first patent (1902) at the age of 21, and his famous patent on radar (1904) soon after, and at Guglielmo Marconi himself, who filed in London (where he went with his mother and received the assistance of his cousin Jamieson Davis), the first patent on the radiotelegraphy on June 2nd, 1896 at the age of 22. Ludwig Boltzmann (1844–1906) was awarded the title of Ph.D. when 22 years old and become Professor of Mathematical Physics at the University of Graz at the age of 25. There were also early music composers. The 25 years old Arnold Schönberg (1874–1951) wrote the celebrated *Verklärte Nacht* (Transfigured Night), Opus N. 4, in 1899; this string sextet was published and performed in 1902. Richard Strauss (1864–1949), composed the symphonic poem *Don Juan* in 1887–1888. Sergej Rachmaninov (1873–1943) being not yet 24 years old, wrote his Concert N. 2 in C minor for piano and orchestra at the age of 27. This concert, performed for the first time in Moscow in October, 1901, quickly became so famous that it threatened to overshadow other equally extraordinary works by Rachmaninov.

[3] Electricity and magnetism are quite old names. The use of a compass in China dates back to the third millennium before Christ, and in the *Magnesia* town (Asia Minor) they discovered the particular properties of the natural stone known as *magnetite.* On the other hand, the ancient Greeks, who were impressed by the strange properties of amber, called it ἤλεκτρον.Michael Faraday (Newington Butts, London, 1791—Hampton Court, London, 1867), one of the greatest experimenters in the history of science, studied the magnetic field produced by an electric current, discovered the magnetic induction and the diamagnetism, and put the technological basis for electrical motors. Together with him one must mention at least Hans Christian Ørsted (1777–1851), who as early as in 1819 noticed that a wire with an electric current moved the needle of a compass, and the Italian Francesco Zantedeschi (1797–1873) who in 1829–1830 published the results of his experiments on the production of electric current in closed circuits to which a magnet was approached.

[4] Most of the scientific life of James Clerk Maxwell (Edinburgh, 1831—Cambridge, U.K., 1879), a brilliant British (more exactly: Scottish) scientist, was devoted to electromagnetism. His greatest contribution was the mathematical formulation, submitted to the Royal Society in 1864, of the laws of electromagnetism by means of a set of differential equations in 20 variables. They were then reduced to four equations in four variables and formalized more effectively in 1884–1886 by Oliver Heaviside (1850–1925) by means of the differential vector operators still used today. A combination of

Maxwell's equations provides the so-called *Wave Equation* whose solution is an oscillation of the electric and magnetic fields in space and time, which propagates with a speed that depends on the electrical and magnetic properties of the medium but not on the frequency: this speed is the same for any electromagnetic wave, including, of course, light.

[5] In his brief but intense and very productive life, the German physicist Heinrich Hertz (Hamburg, February 22nd, 1857—Bonn, January 1st, 1894) experienced the phenomena of reflection, refraction and propagation of radio waves and showed their equivalence with the light. It is worth to notice that the experiments were conducted by Hertz at wavelengths of 6 m, 3 m and 60 cm, i.e., up to a frequency of 450 MHz, which is higher than that of the first British radar. Hertz used a spark gap with two spheres made by brass to generate the waves, and a *coherer* to detect them; the first "radio connection" between a transmitter and a receiver took place in Hertz's laboratory on November 13th, 1886.

[6] Temistocle Calzecchi Onesti (December 14th, 1853—November 22th, 1922), an Italian physicist, is known as the inventor of the *coesore* (a term which was later translated into English by Sir Oliver Lodge as *coherer*). This apparatus consists essentially of a tube of glass containing powders of nickel and silver placed between two electrodes, possibly with small quantities of mercury. The *coesore/coherer* can act as detector of electromagnetic waves, since the conductivity of the powders increases in the presence of electromagnetic radiation. In order to repeat a detection, the conductivity must be set back to the previous values by shaking or shocking the tube. Calzecchi Onesti published the results of his experiments on the Review "*Nuovo Cimento*" in 1884 and 1885. The *coesore*, subsequently developed in different versions by various researchers, including Sir Oliver Lodge and Edouard Branly, was used by Guglielmo Marconi and resulted a key element to the development of radio.

[7] The property of the ionosphere explains the success of the experiment of transatlantic radiotelegraphy made by Marconi in 1901 (but according to somebody, no signal was actually received in 1901) and repeated, with undisputed success, in 1902. In spite of the fact that in 1902, Oliver Heaviside and A.E. Kennelly had suggested that the ionosphere propagation may explain the success by Marconi in transmitting signals across the Atlantic, Marconi does not seem to have understood the reason of the success of his experiments. In fact, on two occasions (London, June 12th, 1902—Memorandum presented to the Royal Society, and Stockholm, December 11th, 1909—Speech to the Royal Academy of Sciences on the occasion of the Nobel prize) Marconi gave some "peculiar" explanations, see the Appendix of [Mus 90] and the Complement B of [Gal 12], available in http://radarlab.uniroma2.it/stscradar/marconi.pdf. Briefly, in these *Marconian* documents the stupefied reader will find explanations such as the "diselettrification" of the antenna by the light of the sun and the fact that "concerning the *alleged* effect of Earth curvature, I believe that the

connections with the Earth, for both transmitter and receiver, generate *conductive* effects… It seems clear that wireless telegraphy… depend on the *conductivity* of the Earth. The fact remains that the clear light of the day and the blue sky act as a *kind of fog* on … short waves, such as those used in ship to ship communications".

[8] In [Bla 04], at page 60, the differences between the contents of the report by Taylor and the speech by Marconi at the IRE a few months before are analyzed: the latter barely proposes to use the superposition of the direct signal and the reflected one, i.e. the beats, while Taylor indicates the need for shielding the receiver from the transmitter. Therefore, Blanchard remarks that "… the proposal by Marconi was only a basic hypothesis, limited to the purely intellectual field, while in Taylor the inventive idea takes shape… with the awareness of a real problem not yet solved…".

[9] Considering the fact that the issued patents are public, it is amazing that in 1935 Guglielmo Marconi (Chap. 1) had invited some of the highest italian authorities to see the "top secret experiments" related to a system not only already demonstrated in the USA for five years, but even patented for a year!

[10] The Dutch scientist Hendrik Antoon Lorentz (Arnhem, 1853—Haarlem, 1928) received the Nobel prize for physics in 1902 along with Zeeman. His name is linked to the famous transformations of the theory of special relativity (initially called "Lorenz- Einstein" transformations), published together with Poincaré in 1905. In a paper dated 1904, Lorentz showed the increase of the mass of fast moving objects, confirmed experimentally in 1908. Another contribution by Lorenz, relevant in this book, is the analysis of the force that an electromagnetic field exerts on an electrical charge in motion.

[11] This technique, which looks very rudimentary today, worked well, indeed. When associated with the use of projectiles with proximity fuze, (another top secret technique), the SCR 268 radar made the antiaircraft artillery very effective in many occasions. During the Pacific war in New Georgia (Solomon Islands), on July 1943, a battery of Marines equipped with the SCR-268 and 90 mm guns downed 12 Japanese aircraft, out of 16, by firing only 88 hits.

Chapter 4

[1] The development of bombers reached its maximum at the end of 1943, with the entry into service of the B 29, equipped with the ground mapping radar capable of producing maps of the terrain. It had a maximum takeoff weight of 67 tons, a pressurized cabin and could carry up to about 3 tons of bombs at a distance of 2700 km. At the end of the Second World War, the best bombers by the Allies, i.e. the B-17 (USA) and the Lancaster (United Kingdom), reached 55 tons at full load. Among the English light fighter-bombers, the twin engine *Mosquito* excelled. It was equipped with the H2S radar (Chap. 6), and capable of operating at 12 km altitude and with maximum speed of 635 km/h; the Mosquito was only surpassed by the German fighter Me 262 which operated for a very short period.

[2] Appointed Reich Chancellor by President Paul Hindenburg on January 30th, 1933, Adolf Hitler (Braunau, April 20th, 1889—Berlin, April 30th, 1945) assumed quickly the control of Germany: full power on March 23rd, 1933, shortly after the fire of the Reichstag (February 27th, 1933) and “Fuehrer and Chancellor of the Reich” on August 2nd, 1934. Leaving the League of Nations (1933) and setting the mandatory conscription (1935) were some of the stages of the rearmament of Germany, culminating with the attack to Poland and the beginning of the Second World War.

[3] In 1959, when the history of the birth of radar and its development during the Second World War was in the public domain, the sixty-five years old Watson-Watt insisted on holding the title of inventor of radar. In the course of a seminar at Cardiff University in Canada, having been fined (for the modest amount of twelve Canadian dollars and a half, that perhaps for a Scotsman is still too much) for excessive speed by the traffic police using a radar as speedometer, Watson-Watt recited the following poetry, entitled “A Rough Justice” (from http://www.microwaves101.com/encyclopedias/616-a-rough-justice):

Pity Sir Watson-Watt, Strange target of this radar plot	Oh Frankenstein who lost control Of monsters man created whole
And thus, with others I can mention, The victim of his own invention	With fondest regard sympathy One more hoists with his petard
His magical all-seeing eye Enabled cloud-bound planes to fly	As for you courageous boffins Who may be nailing up your coffins
But now by some ironic twist It spots the speeding motorist	Particularly those whose mission Deals in the realm of nuclear fission
And bites, no doubt with legal wit The hand that once created it	Pause and covered let’s counter plot And learn with us what’s Watson-Watt

Chapter 5

[1] The Versailles Treaty (1919) imposed on Germany the loss of the colonies and of important territories (Alsace-Lorraine, Northern Schleswig, city of Gdansk, and parts of the Posnania, of western Prussia and Silesia), and economic losses, with a debt of as much as 33 billion dollars. Paying such a huge amount, equal to about three times the value of all national goods, would have left Germany indebted for decades. The subsequent inflation, the highest in the history, is often cited as the main cause of the end of the Weimar Republic and of the rise of Adolf Hitler into total power. In fact, when Hitler came into power, 20 % of the workforce was unemployed and the German monetary reserves were almost zero.

[2] Between 1933 and 1938 Germany saw one of the largest economic growths in modern history, even more significant than the “New Deal” by F.D. Roosevelt. This development was trailed by building, automobile and metallurgy industry thanks to large-scale projects on public infrastructures such as the motorway network. Hjalmar Schacht (1877–1970),

president of the central bank of the Reich and ministry of the Economy (1934–1937), devised a non-inflationary monetary mechanism able to provide the needed resources to the German industry, with the issuance of MEFO [*Metallurgische Forschungsgesellschaft*] bonds guaranteed by the Reich bank. In January 1933, when Hitler came into full power, the unemployed Germans were over 6 million; in January 1934 this figure almost halved and in June decreased to 2.5 million; in 1936 they fell down to 1.6 million and in 1938—with Germany being the most powerful European industrial nation—the unemployment virtually disappeared, being reduced to less than four hundred thousand.

[3] In the Second World War, the situation with respect to anti-aircraft artillery was very different than the First one. The speed of the attack planes changed from about 190 km/h of the Fokker DR.1 (with operating height up to 3 km) to 540 km/h of B-17 (with height about 7.5 km), and an artillery round fired at 700 m/s in the direction of the B-17 needed approximately 11 s to reach the target, which in the meantime advanced more than one km and a half. In German guns as the 88 mm "Flak 18" and "Flak 36" the impact point was determined by optical means and the fuze of the projectile was graduated prior to the loading. To improve this aiming system, the new 88 mm called "Flak 37" had a point (with a different color for the pointer in elevation and for the pointer in azimuth) which moved on a graduated scale of a central electromechanical computer which managed the whole battery of (generally four) nearby cannons. The year of 1943 entered in service the 88 mm Flak 41 with a new 72 calibers barrel, with which the output velocity of the projectile arrived at 1000 m/s and the anti-aircraft fire was effective up to an altitude of 10 km.

[4] The towers were built in Berlin (in three locations: *Zoo*, *Humboldthain* and *Fredrichshain*, (all three with 105 mm Flak 38/39 artillery, some of which were replaced later with the 128 mm), Hamburg (two towers, 128 mm guns) and, surprisingly, Vienna (three towers, 105 and 128 mm). Vienna was devoid of the high strategic value of Berlin and Hamburg, but was considered worthy of maximum protection because of its extraordinary cultural value. These interesting Flak buildings are thoroughly and vividly shown in [Foe 98], while the radars of the Luftwaffe are illustrated in [Mül 98]; these buildings suffered a few damages during the war. The attacks of the Allies against the German territory released over a million tons of bombs, with the direct killing of over three hundred thousand civilians and the destruction of about 3 million and a half buildings. However, in these attacks the units in the Flak, responsible for the loss of more than half of the Allied aircraft, were essentially ignored. This is rather strange, as their presence forced the bombers to fly at higher altitudes, where the precision of the bombing was strongly reduced as compared to the low altitudes.

[5] Some antennas survived the events of the war, becoming museum items or antennas for radio astronomy or, as in the case of the one shown at the Deutsches Museum in Munich, both: it was used as a radio telescope in the Netherlands (observatory in Dwingeloo) from 1946 to 1990, was donated

to the Deutsches Museum in 1991, and finally restored and shown there from 1993 till September, 2011. In the occupied France, at *Douvres-la-Délivrande*, Calvados, the Germans built a large Air Defense center, with (at North) the long-range radar *Wasserman* by Siemens, and (in the South area) two *Freya* and two *Würzburg Riese* radars, operated by about 230 units of the Luftwaffe, including 36 radar controllers of the airspace. The center was disturbed electronically before the landing in Normandy, and made inoperative by the bombing on June 6th, 1944 (the "D-Day"). Two bunkers of the center are now currently a museum, the "*Musée radar*", whose scientific executive is Yves Blanchard, showing the evolution and the role of radar; the museum hosts a rare specimen (one out of three not destroyed) of the Würzburg Riese, which after the war was transported to Britain to be studied, and then returned to France where the antenna was used for a while for a radio telescope. Finally the radar set was restored and placed in Douvres-la-Délivrande on the fiftieth anniversary of D-Day.

[6] The German radar engineers did understand at first that the angular resolution improves with the dimension of the antenna increasing (referred to the wavelength), and so does the maximum range. The wartime technologies, before the magnetron, allowed Germans to obtain the needed high power levels only at relatively large wavelengths (order of one meter) and therefore, in order to improve the resolution and increase the maximum range, it was necessary to increase the size of the antenna of the ground based radars, as it happened when passing from Würzburg to Würzburg-Riese. This trend was exacerbated in the spring of 1942, with the entry into service of the *Mammut*, a huge radar built by Telefunken and derived from the Freya, with a non-rotating antenna—obtained by means of a combination of Freya antennas—up to 28.5 m wide and 15 m high in the 4 pylons (Luftwaffe version), with electronic scanning in azimuth within ±50°, capable of detecting air targets at high altitude (8000 m) up to about 300 km, and up to 35 km for a plane flying at 50 m of altitude. The subsequent height finder *Wasserman*, produced by Gema/Siemens, had a tall antenna 6 m wide and 40 m (according to some, up to 57 m) high and mounted on a rotating tower. The Wasserman was capable of measuring distance, azimuth and elevation of air targets up to 280 km (according to others, the range was 210 km for 8000 m high targets). The measurement of the height of the target was accurate within ±300 m, a value comparable to some modern Air Defense radar. Wasserman and Mammut operated at 120–150 MHz with peak power levels around 100 and 200 kW respectively. In the last months of the war (1944) the *Jagdschloss* was added to the German air defense system for ground-directed intercept, using the panoramic display (PPI: *Plan Position Indicator*) which is common today.

[7] The Allies used *Window* in many other occasions, including the Normandy landing (*Operation Overlord*) on June 6th, 1944 (D-Day): the Operation *Taxable*, one of the many organized to deceive the German defense, consisted in simulating a fleet attacking the area of *Cap d'Antifer*, far from the

one of the real landing. The chaff release was cleverly organized in order to create clouds of *Window* able to simulate a huge fleet covering a sea area of about 26 km × 23 km advancing at 7 knots. Because of the limited resolution of the *Seetakt* radar (15° in azimuth, 500 m in range) the *Window* packages progressively released by the many aircraft of the squadron 617 in their rectangular-shaped flight paths appeared as continuous echoes to the operators of Seetakt and Freya radars, [Pri 09]. The needed computations were performed by Joan Currain from the T.R.E.

[8] Sixty years later this method became rather *fashionable* as a new "green radar technology" and "intercept-free radar" with the name PCR, *Passive Covert Radar*, or PCL, *Passive Coherent Location* with illuminators of opportunity. However, despite the fashion and a lot of advertising of this non-emitting "green radar" and despite fifteen years of study from about the beginning of the present century, no passive radar has been sold through 2014 for operational applications in the Western world (in spite of glamourous names such as "Silent Sentry" or "Aulos"). Only two or maybe three sets have been sold for research or experimental purposes. The main producer of passive Radar, Lockheed Martin, has closed the related activity. Maybe a counter-example of the "not-announced revolution" of digital signal processing?

[9] The imbalance of air forces was evident: on July 1st, 1940 the RAF had 900 fighter aircraft of which 114 twin-engine (Blenheim) and the remaining, single engine (Spitfire, Hurricane, Defiant), while on July 20th of the same year the Luftwaffe had 2784 aircraft, including 1330 twin-engine bombers (Do17, Ju 88, He111). On the other hand, the losses of combat aircraft between July 10th and August 12th, 1943 unbalanced in the opposite direction: 127 losses for the RAF, 261 for the Luftwaffe, [Pri 10]. Thanks to their national radar coverage, the British could operate their Air Force more effectively and with smaller losses than their enemies.

[10] The Tizard Committee's members were:
Sir Henry Tizard (Mission Leader); Brigadier F.C. Wallace (Army); Captain H.W. Faulkner (Navy); Group Captain F.L. Pearce (RAF); Professor John Cockcroft (Army Research); Dr. E.G. Bowen (Radar); A.E. Woodward Nutt (Secretary). The counterpart in Washington was by the U.S. Navy and U.S. Army delegations. The former was led by the admiral Harold Bowen, director of the Naval Research Laboratory, the latter was led by the general Mouborgne, chief signal officer of Signal Corps. Other fundamental points of contact for the *Tizard Committee* were the National Defense Research Council directed by Vannevar Bush, assisted by Karl Compton, rector of MIT, and by James B. Conant, president of Harvard.

[11] Much has been written about the *Tizard Mission* in various papers and volumes where sometimes the *Anglo-Saxon pride* prevails on the needed sobriety, among them: [Bud 97], [Fis 06], [Phe 10], [Zim 96] and others. However the main, and probably, best book on the *Tizard mission* is [Bow 87], written by one of the protagonists of the development of radar, in particular, of airborne radar, and bearer of the top secret cavity magnetron to the

United States. Finally, to know an important aspect of the *Tizard Mission*, i.e. the visit to Canada, one should read [Red 01], one of the few articles giving an account of the results obtained from nations other than Britain and, in the rich, above-mentioned literature, probably the "less romanticized tale".

[12] The name initially chosen for the Radiation Laboratory (*Rad Lab*) was *Microwave Laboratory*. To avoid revealing the actual activities, they selected the final name that led people to think about research in elementary particle physics, not in radar or microwave. Its first director, Lee DuBridge, was a nuclear physicist from the University of Rochester, while the vice-director was Isidor I. Rabi, a future Nobel prize from the physics department of Columbia University. In autumn 1940 MIT hosted an annual Conference of applied physics and nuclear physics, areas in which the interest in microwave was growing. During the Conference, as usual, many bilateral or small groups meetings took place. So, at the end of the Conference, DuBridge and Rabi succeeded in the enrollment of the needed qualified people to start the business of the *Rad Lab*. In December 1940 on the roof of the building 6 of MIT, two parabolic antennas showed the test activity of a former microwave radar.

[13] The MEW was a sort of *Berta* in the radar world. The complete system weighed over 65 tons and absorbed 23 kW supplied by an ad-hoc electric generator. Eight trucks were required for the transport; the displacement of a MEW to a new site required three days of work by a hundred people. The antenna was made up by two co-rotating sections placed back-to-back. A section (2.4 m high) covered low altitudes, the other one (1.5 m high) covered the higher altitudes. Each section, of cylindrical reflector type with a linear feeder, was long 7.6 m, and at the radar wavelength of 10 cm, generated a main lobe wide only 0.8° in azimuth, with an excellent resolution, but without the ability to measure the height of targets; therefore the MEW was often associated with the British *AMES Type 13 Mk III* height seeking radar. The large antenna area and the high transmitted power of 750 kW permitted a remarkable maximum range up to 320 km for high flying aircraft. A MEW was transported to England in the summer of 1944 to detect and track the V1 attacks to London, providing an early warning and the possibility to reconstruct the position of the launch base. Another MEW was transported in Normandy, where its parts arrived on June 12th, 1944, to help, with the radar display of the air situation, the operations of the Allies after the beginning of landing operations in June 6th, 1944.

[14] The *No. 3 Mk 2* supplied continuously the three coordinates of the target: distance, azimuth, elevation, and had four operators: technical operator, range operator, bearing operator, elevation operator. The angular measurement technique of No. 3 Mk 2 was very ingenuous. The *feeder* of the receiving antenna, a dipole with reflector, was rotating around the antenna axis at 105 revolutions per second thanks to a synchronous axial motor; this revolution was in phase with the emission of the pulses. The *feeder* was about 2 cm off-axis with respect to the focal axis, or *boresight*, of the antenna

reflector (a dish with a diameter of one meter and twenty cm) causing an offset of 2° of the antenna main lobe (about 10° wide at half power). The pulse-repetition frequency (PRF) of the radar was exactly 420 pulses per second, hence, every four successive pulses were received from the directions: top, right, bottom, left respectively. The azimuth and elevation operators observed the cathode ray monitor and moved the antenna system up to make equal the relevant pair of signals (right/left and up/down). The system was very precise, within ±20 m in Range and ±0.17° in angles, up to the maximum operational range of 36 km. The ensuing model with automatic target tracking, No. 3 Mk 2/3, never went into production, probably because of the success of the SCR 584, which became soon as the "N. 1" between the fire control radar of the Allies, see: http://www.anti-aircraft.co.uk/index.html.

[15] The Battle of Cape Matapan was fought on March 28th and 29th, 1941 in the maritime area south of the Peloponnese, between the small island of Gaudo and Cape Matapan, were a squadron of the Italian Navy (*Regia Marina*) under the command of the admiral Angelo Iachino, had in front the *Mediterranean Fleet* led by the British admiral Andrew Cunningham. The battle consisted of two phases: one fought near Gaudo on the morning and the afternoon of March 28th, and a second near Cape Matapan on the night between March 28th and 29th. Rivers of ink and numerous and lengthy disputes were paid after W.W. II on this battle, on the role of radar, on the aversion to the radar by the admiral Cavagnari, [Pet 96], [Iac 46], [Tri 52].

[16] Taranto, the most important Italian naval base, equipped for the repair of damaged units, had, however, serious gaps concerning antiaircraft and anti-torpedo protection. Since radar (already operational in Germany and in the United Kingdom) was completely absent in Taranto, the protection was entrusted to old projectors and to thirteen aerophonic stations, dated back to the Great War, which anyway could not provide the direction of the attacks, nor could coordinate the projectors and the artillery. In the autumn of 1940 the admiral Andrew Cunningham organized an ambitious operation to attack Taranto by some torpedo bombers from two aircraft carriers. On November 10th the British units reached Malta and on November 11th at 20.30 the first torpedo bombers from the carrier *Illustrious* flied in the direction of Taranto. At 23:00 six torpedo bombers *Fairey Swordfish* began the attack on the battleship *Conte of Cavour*, the destroyers *Pessagno* and *Libeccio* and the fuel depots, damaging all of them seriously. At 23:15 two more torpedo bombers attacked successfully the battleship *Littorio*. Five minutes later the first team of aircraft retired, and at 23:30, a second attack squadron avoided the Italian barrage and hit the warships *Caio Duilio* and *Littorio* and the heavy cruiser *Trento*. At the end of the attack, at 0:30 on November 12th, the Italians suffered from 58 casualties (according to [Sad 06], 52 casualties) and 581 injured, six damaged ships (the *Cavour* could never return into service) and various types of damage to the land installations. The Italians fired over thirteen thousand rounds but could destroy only two British aircraft: with

an adequate antiaircraft artillery with radar control the Italian losses would have been much less.

[17] According to some sources (see Chap. 2), before the armistice of September 8th, 1943 thirteen "Gufo" and four "Folaga" sets (in addition to the prototypes) were delivered to the Italian Navy, and on September 8th only twelve operating units of the Italian Navy were equipped with the *Gufo*. Six *Gufo* radars were installed in the month of August of the same year. Some documents refer to projects which included the installation of the *Gufo* on all large units and on all new vessels under construction or under design up to the Torpedo Boats. Italy was late in the radar implementation and operation but did some advanced research. For example, the patent application N. 3340, October 27th, 1942 by SAFAR/Castellani describes a target location method with an electronic scan on two orthogonal planes, in a manner similar to a television scan (441 rows), with the aim to generate images of the target and of the surrounding environment.

[18] The DSSE [*Direzione superiore studied esperienze*] was established on April 27th, 1935 (in the same day, exactly ten years later, and in the same place where the Lieutenant General of Air Force Alessandro Guidoni died during an experiment) in *Montecelio*, near Roma, where the *Regia Aeronautica*, through the period after W.W.I, collected the aeronautical research activities and facilities, to which greatly contributed the aviation and space pioneer Gaetano Arturo Crocco (1877–1968). In the years before W.W.II the DSSE was a centre at top level, where all technologies related to the flight could be experimented, including radio, fluid mechanics, optics and photography, weaponry etc. up to the aeronautical medicine. The results of DSSE activities were a patrimony of the Italian aeronautical industries (Savoia-Marchetti, Caproni, Fiat, CANT, etc.) maintaining and increasing their leadership. The new town of *Guidonia* grew around the DSSE. After the Armistice of September, 8th 1943 the centre was destroyed and any attempt to restore it after the war was unsuccessful; a recent (November, 2013) proposal by the "*Comitato per la salvaguardia dei Ruderi della DSSE e dell'Aeroporto Alfredo Barbieri*" to restore the ruins of DSSE and Guidonia Airport for display and museum purposes is described in http://guidonia.romatoday.it/comitato-ruderi-aeroporto-barbieri-guidonia.html.

[19] In parallel with the national developments of ground-based and airborne radar, mostly not concluded due to the Armistice of September 8th, 1943, Italy got from Germany a dozen of airborne radars *FuG 202 Lichtenstein B/C* (see next chapter) of which two were installed in July 1943 on the *BZ 303* night fighters, derived from the fast, two-engines medium bomber *CANT Z-1018*. However, there are no indications on operational use of the DSSE airborne radars, and more generally, no indications of usage of radar in W.W.II by Italian aircraft.

[20] Ernesto Montù (Alessandria, 1893—S. Margherita Ligure, 1981), engineer, radio-amateur, was a pupil of Galileo Ferraris and cofounder of the *Istituto Elettrotecnico Nazionale Galileo Ferraris, IEN,* in Turin (from 2006 the

IEN is part of the *Istituto nazionale di ricerca metrologica*, INRiM). In May 1921 he became co-director of the *Industrie Telefoniche Italiane* and responsible for the radio production by that firm; from April 1924 he worked with *Ansaldo Lorenz*. On January 31st, 1936 Montù got the patent no. 338,834 which was also granted in France, Germany and—as N. 2,174,350—in the USA (filed on December 24th, 1936). This patent, as from its Claim No. 1, describes a partial form of radar (without the measurement of the distance) derived from the former television techniques being studied at that time. However from the Description of the patent it results that the invention could receive a radar echo: "*…such a … radiation which, for instance, can be emitted by stations suitably installed on ground and received by the apparatus after reflection from the aircraft…*"

[21] According to some sources, at the beginning of 1936 the engineer Agostino del Vecchio, technical manager in the Italian branch of the firm *Philips*, built a pulsed RDT (radar) based on a magnetron whose anodes were cooled with distilled water, and provided with an oscilloscope. More likely, the patent by del Vecchio does not describe a complete radar prototype, but, rather, a magnetron transmitter.

[22] Francesco Vecchiacchi (1902–1955) obtained in 1925 the degree in mathematical physics at the University of Pisa, and in 1927 moved to Livorno to teach at the Naval Academy. In 1932 he joined the firm *Magneti Marelli* in Sesto S. Giovanni (Milano) which created the Radio Central Laboratory, particularly active in the development of radio bridges. In 1937 Vecchiacchi became full professor at the *Politecnico di Milano*. Some sources mention his studies on Radiolocation with *Magneti Marelli* just before W.W.II, but supporting documents are missing. After the war he became famous for its design (1953) of the Milano-Palermo radio bridge (the longest in Europe) for the distribution of television programs in the whole nation.

[23] According to (http://www.cisi.unito.it/marconi/radar.htm) the *Lince* radar originated by a group of three firms, i.e. *Borletti* in Milan, *Galileo* in Florence and *San Giorgio* in Genoa and Pistoia, called BGS. The alleged *Lince* prototypes were called "small" *or near* and "great" or *far away* on the basis of the maximum distance at which they operated, up to 60 km and up to 120 km, respectively. Again according to (http://www.cisi.unito.it/Marconi/radar.htm), the construction schemes were taken from an English ground-radar kept after having taken the Libyan city of Tobruk. A low-definition, barely readable photo of the 48-monopoles antenna of the "great" *Lince* can be found in (http://www.cisi.unito.it/marconi/radar.htm) and in other unofficial documents, where it is added that the *great Lince* production was interrupted by the Allied bombing raids in Pistoia in January 1944 that destroyed the San Giorgio plan. In a subsequent transfer by the Germans in the north of Italy, the *great Lince*, because of its size, was not moved and was reduced to ruins.

It should be clarified that (http://www.cisi.unito.it/marconi/radar.htm) is not in agreement with the official sources of that time, such as the Minutes of the Technical-Scientific committee of the Italian Armed Forces on December

23rd, 1942 (see the Appendix E, page 510, of [Gal 12]), where the following Italian radars are mentioned with the German operational equivalent: *Veltro* (Würzburg), *Folaga* (Freya), *Razza* (Riesen), *Gufo* (no German equivalent) and *Lepre* (no German equivalent). These top-level Minutes do not mention, not even as a prototype, the "*Lince*". This fact can be explained in two ways: either the *Lince* was not an Italian radar, or the decision to start the *Lince* development has been taken at a later date, in practice, in 1943, i.e. only seven months before the fall of the fascist regime: a too short period to arrive at working apparatus.

[24] However it is well known that Germany, at the beginning of September 1943, invited [Ger 10] an Italian scientific delegation made up by professors *Giorgio Barzilai* and *Gaetano Latmiral*, the main Italian experts of very high frequencies. The aim was to analyze the parts of a radar, likely the *Rotterdam* (i.e. the English H2S) recovered from a downed British aircraft. This mission saw a different fate of the Italian scholars. Barzilai declined the invitation stating that he was sick, and—also considering the Italian situation, which seemed to him to prelude an upheaval—suggested that Latmiral not accept. However Latmiral, for his misfortune, accepted the invitation and then found himself in Berlin on September 8th, 1943, assuming immediately the status of "enemy holder of important military secrets" and then being liable to execution. Luckily he was "only" interned in the military prison of Tegel Airport (which was managed by the Army, not by the commands of the SS: it is likely that the German scientists tried to save his life). Latmiral escaped in 1945, at the end of the war, with the III Reich being disrupted. Worse was the fate of the Lutheran theologian—and opponent of Nazism—*Dietrich Bonhoeffer* (1906–1945) who was a prisoner at Tegel Airport in the same period, and knew Latmiral there (as he wrote in his celebrated letters [Bon 70]). Having conspired against Hitler, Bonhoeffer was hanged in the concentration camp of Flossenbürg at the dawn of April 9th, 1945, a very few days before the end of the war. The collaboration between Barzilai and Latmiral was witnessed, among others, by the patent No. 420709 dated July 14th, 1946 and signed Latmiral/Barzilai, concerning radio receivers.

[25] The Zoltán Bay's experiment was interrupted by German occupation and subsequently (1945) by the arrival of the Red Army: it was carried out successfully only on February 6th, 1946. The very weak echo of the radar signal, a pulse of 0.06 s duration repeated every 3 s, with a peak power 150 kW, was detected with an ingenious system. One thousand pulses were "integrated" (i.e. a fifty minutes integration time was achieved) by measuring the amount of hydrogen from electrodes connected to the receiver and immersed in an electrolyte solution.

Even the Americans, in an independent manner, had a similar project, significantly called *Project Diana*, which began in September 1945 and was directed by John H. DeWitt Jr., from the Signal Corps. A modified *SCR 271* radar (similar to the one of Pearl Harbor) transmitted 0.25 s long pulses at 3000 W. The receiver bandwidth was fixed at 57 Hz, and given that the Moon's relative motion (about −1700 km/h to about +1700 km/h) produces a Doppler shift up to 350 Hz at the working frequency of 111.5 MHz, it was necessary to tune the receiver for each observation. The first echo was recorded in the presence of John H. DeWitt and E. King Stodola on January, 10th, 1946 at 11:58 a.m. local time, only three weeks before the Hungarian experiment. For those experiments, see also: http://www.ok2kkw.com/eme1960/eme1960eng.htm and for the reflections of very powerful radar signals from the moon: Melvin L. Stone and Gerald P. Banner: "Radars for the Detection and Tracking of Ballistic Missiles, Satellites, and Planets", Lincoln Laboratory Journal, Volume 12, Number 2, 2000, also available in http://www.ll.mit.edu/publications/journal/pdf/vol12_no2/12_2detectsatellitiesplanets.pdf.

The above descriptions help to critically review the claim by *Adelmo Landini*, a technician who worked with Guglielmo Marconi, see (a) http://www.radiomarconi.com/marconi/landini.html and (b) ESA/ESRIN, Meeting of AMSAT (Radio Amateur Satellite Corporation) Italia, 5 December 2008. Landini, a technician on the Marconi's *Elettra* laboratory ship, writes that on July 27th, 1930—according to (a), or July 26th, 1927—on board of the *Elettra* in Civitavecchia port at 17:00 UTC, during a radiotelegraph reception from Rio de Janeiro "… suddenly the signal became widespread, showing a pronounced echo clearly delayed of about 2 s… Marconi offered this explanation: "There is no doubt, we must suppose an extra-terrestrial reception. More precisely, a reflection of the Moon. Two seconds are just the time the wave travels a distance earth-moon and back." Neither Marconi nor Landini did the simple computations showing that this explanation was not correct because of the too low signal-to-noise ratio after that long travel of the signal (even considering a 100 kW transmission, neglecting ionosphere attenuation and receiver noise), see for instance: email message (and its annexes) by prof. Piero Tognolatti to the author on August 22nd, 2014—19:08. Tognolatti and his students experimented earth-moon-earth transmission in 2001 at 1296 MHz and in 2005 at 10 GHz, using a high-gain antenna and a low noise amplifier.

[26] The main aim of this radar was the control of anti-aircraft artillery. The antenna, of about 3 m × 3 m, was an array with 4 rows of 8 dipoles each (in a later set there were 12 × 8 dipoles) on a ground plane made with a thick wire mesh; the width of the main lobe was about 15°. It was of a rather modern apparatus, characterized by the use of a single antenna. In fact, before many other nations, the Dutch designed and realized the *duplexer*, a remarkable device with a switching time of only 1.5 μs (i.e. permitting a minimum distance for detection as low as 450 m). The display, based on the tube of Braun, was " type J", as in the *Gufo*. Another interesting characteristic of the Dutch radar was the azimuthal revolution of the antenna, implemented with pedals and a transmission chain, in a manner very similar to a bicycle (only in the Netherlands could this be conceived!).

The main architect of the Dutch radar was prof. ing. J.L.W.C. von Weiler, who in 1946 held the first chair of Radar at the Delft University of Technology (TUDelft). The group led by von Weiler included S. Gratama and Max Staal. After the German invasion, von Weiler and Staal escaped by sea from the Netherlands to the United Kingdom, where von Weiler worked at the *Signal School* in Portsmouth.

[27] This fear originated, among other things, the constitution of USAF (U.S. Air Force) in 1947 and the establishment of NATO in 1949. The Soviets developed promptly a long range bomber, the *Tu-4*, conceived, according to a precise order by Stalin, as a perfect copy of the well-known *B-29* "Superfortress", a plane that the USA. refused to provide to the Soviet Union within the *Lend-Lease Act* dated March 11th, 1941. However, four of these bombers came into Soviet hands in 1944/1945, after bombing the Japanese territory. The new Tu-4 first flew on May 1947 and become operational on a large scale through 1949. The plane could carry 8000 kg of bombs, and with the modified version Tu-4A in October 1951 the Soviets did their first nuclear test, launching a 30 k Tons bomb. In those years the Soviets were able to reach Europe and the USA with the Tu-4's, which in 1952 were produced in over eight hundred units, armed with nuclear bombs.

[28] The implementation of the *Rotor*, the successor of the Chain Home, first of all led to the selection of sites (28 sites along the coast were adapted from those of the Chain Home, and more 38 sites were used for functions such as the *Ground Controlled Intercept*—GCI—and the *Low Altitude Surveillance*). Moreover, a new radar in centimeter range (Centimeter Early Warning, CEW) was engineered. The research and development activities to replace the old Chain Home radars led to implement the GCI *Type7/Type11* and the centimeter wave radar *Type13/Type14*. In the same period, at the *Radar Research Establishment* (RRE) they studed the new *Green Garlic* radar, later known as *Type 80* and operational since 1953. The main characteristics of this huge S-band surveillance radar—from http://www.radarpages.co.uk/mob/mrs/type80.htm—are listed below.

- Operating Frequency: from 2850 to 3050 MHz.
- Coverage: 360° in azimuth, from 0 to 30° in elevation (*Cosec*^{2} antenna pattern).
- Scope: acquisition and tracking up to 200 nautical miles (370 km) of an aircraft type *Canberra* at 13.5 km (45 kft) altitude.
- Antenna: cylindrical reflector 23 m long and 7.5 m high, with linear waveguide feeder, horizontal polarization, azimuth beam width 0.3°. Four antenna revolutions per minute.
- Transmitter: magnetron, with a transmitted power of 1 MW (models *Mk.1* and *2*) or 2.5 MW (*Mk.3*)
- Length of the transmitted pulse: 5 μs (2 μs selectable)
- Pulse repetition frequency: 235 to 300 Hz.
- Receiver: with a linear channel and a logarithmic channel.

The Type 80 had considerable success so much so that the radar stations of *Rotor* equipped with it became Master Radar Stations and continued to work even after the *Rotor*.

[29] After target detection by the *acquisition radar*, its designated range and azimuth data are transferred to the *target tracking radar* (TTR) and to the *target ranging radar* (TRR), feeding the computer with the target position data. The continuous target position data supplied to the computer system consists of azimuth and elevation data from the TTR system and range data from either the TTR or the TRR system. The use of two radar systems for range tracking is preferred against enemy electronic countermeasures (ECM). The computer systems send azimuth preset data through the launching control group to the designated missile on a launcher, in order to provide a stable reference that enables the missile to roll automatically to a predetermined attitude, after launch, related to the predicted intercept point. While the target is being tracked, the computer system sends steering orders to the *missile tracking radar* (MTR) system. The MTR system converts the steering orders to guidance commands, consisting of coded pulses of RF energy, that are transmitted to the designated missile on its launcher. A transponder in the missile responds to the guidance commands by transmitting RF response pulses. The transmitted missile response pulses enable the MTR system to "lock on" the designated missile prior to launch and to track the missile after launch. After the missile is launched and has separated from the rocket motor cluster, the missile rolls to the altitude determined before launch by the setting of the roll amount gyro and heads in the direction of the predicted intercept point. The computer system, receiving continuous target position data from the TTR system and continuous missile position data from the MTR system, determines the necessary maneuvers for the missile to intercept the target and sends the appropriate steering orders to the MTR system. The MTR system converts the steering orders into guidance commands that produce the required missile maneuvers. The missile continues to transmit response pulses which enable the MTR system to track the missile and supply continuous missile position data to the computer. When the missile is within its lethal range of the target, the computer system sends an order to the MTR system, which transmits a radiofrequency burst command which detonates the missile.

[30] The main characteristics of a channel of the AN/FPS-17 are:

Frequency	175–215 MHz
Peak power (per beam)	1.2 MW
Duration of the transmitted pulse	2000 μs
Repetition rate of the pulses	30 pulses per second
Compression ratio	100:1
Width of the antenna beams (degrees)	2.5 × 1.8 and 1 × 2
Minimum detectable signa	130 dB below 1 mW

Chapter 6

[1] The company *EMI* (*Electric and Musical Industries Ltd.*) was established in 1931 by the union of the *Columbia Graphophone Company* and the *Gramophone Company*, known for its trademark "His master's voice". In addition to producing phonographs and vinyl gramophone records, EMI developed electronic sets: during the Second World War, in the EMI laboratory at Hayes (Hillingdon) they produced radar and guided missiles. The brilliant designer Alan Blumlein (June 29th, 1903—June 7th, 1942) worked at the EMI and was one of the key figures in the development of the airborne radar H2S. He died in an air accident on June 7th, 1942 when the Handley Page *Halifax* bomber used by the *Telecommunications Research Establishment* (TRE) for flight tests of the first H2S prototype caught fire and fell down. By an order of Churchill the circumstances of the disaster were kept secret, even to the relatives of Blumlein, for over two years.

[2] Admiral Karl Dönitz (1891–1980) was the leader and the commander of the submarine fleet of the German U-Boots during the Second World War. In the Battle of the Atlantic, Germany tried to block convoy ships with their vital supplies from the United States and other countries to the United Kingdom. The strategy was conceptually simple: if the U-Boot succeeded in sinking a number of merchant ships greater than the Allies could build, the United Kingdom would have been reduced to dealing for the peace.

As noted in the title of the autobiographical book "Ten years and twenty days", Dönitz was also president of the Reich between April 30th, and May 23rd, 1945 following the suicide of Adolf Hitler.

[3] In October 1940 the U-Boot reached the highest efficiency level of the entire war with 920 tons of enemy shipping sunk per day for each unit in combat. Among the U-Boot commanders perhaps the most famous is Otto Kretschmer (1912–1998), who reached the top figure of 44 (according to other sources, 47) naval unit sunk. Known for his human behaviour despite the ferocity of war, in addition to his professionalism and courage, Kretschmer received in 1941 the *iron cross with oak leaves and swords*. After the war he made his career in the Navy of the federal republic of Germany, achieving the grade of Admiral.

[4] The Battle of the Atlantic was finally very expensive to the *Unterseewaffe*; at the end of the war four men out of five from the crews of the U-Boots were killed or dispersed, i.e. 27,500 human losses out of the approximately 35,000 enrolled on the U-Boots. The Germans built about 1150–1200 U-Boots between 1935 and 1945; about 800 of them were sunk in combat action or for allied air bombing.

[5] The history of the crypto analysts group in *Bletchley Park* is well known: they succeeded, with the fundamental contribution by the unfortunate genius*Alan Turing* and his machines called "bombs", to break the codes of German force. Among the many volumes in this regard it is to be noticed [Hod 06] and, for the general history of cryptography, [Sin 01]. Of course,

the *Bletchley Park* group could only start after the British had kept at least one set of the *Enigma* crypto machine used by the Germans. Two of these sets were taken by the British on May 9th, 1941 on board the U-110, which was damaged, more slightly than the commander believed, by two destroyers.

[6] The *schnorchel* (or *snorkel or schnorkel*) technology was acquired by the Germans when they occupied the Netherlands. It was originated by former experiments in the 1920s by an Italian, the captain of the naval engineering ing. Pericle Ferretti (1888–1960). Basically, it was a long pipe with a system of pumps, valves and filters to blow air on board allowing Diesel engines to operate at periscope depth. It was (and is) placed in a horizontal position during the navigation at height deeper than periscope depth, when not used. Used by the U-Boots (the first was U-539) from January 1944, allowed the navigation at 12 knots for a long time, versus the 5–7 knots permitted by electric motors only for a limited time due to the capacity of the batteries. Among the problems of the navigation with a *schnorchel* must be mentioned the noise that prevented the use of the hydrophone, so the submarine had to stop every quarter of an hour to listen and detect any ships in the vicinity. Moreover, the greater magnitude, with respect to the periscope, of the emerged part of the *schnorchel* increased the possibility that the submarine was detected by radar. Despite these drawbacks, the Germans, before the end of the Second World War, launched over 220 submarines equipped with the *schnorchel*.

[7] According to [Bow 87], six thousand sets of the *ASV Mk. II* were ordered in Great Britain (1940–1941) and seventeen thousand abroad, mainly, in the USA and in Canada. This is probably the radar produced in the largest number of sets during W.W.II. The version *Long Range* ASV (LRASV) was also developed with side looking antennas. The transmitting antenna was an array of ten dipoles on the top of the fuselage, about five and a half meters long, while the receiving antennas system used the *Sterba array* (see the U.S. patent No. 1885151 dated November 1st, 1932, by E.J. Sterba) installed on the sides of the fuselage, with a length of three and a half meters. These higher gain antennas, in addition to improvement of the angular resolution, allowed an increase of the radar range, with ability to detect emerged submarines up to the distance of 18–28 km. In practice the configuration LRASV amounted to about half of the overall ASV Mk.II production, and was the only one really effective against submarines. The first success due to the ASV was the damage of the U-71 in the Bay of Biscay on November 30th, 1940, by a *Whitley* Mk.VI.

[8] The official name of *Metox* was "FuMB 1- R600A" but it was preferred to use the name of the French factory in which it was produced. The receiver, of the super heterodyne type to ensure the maximum sensitivity, analysed the range of frequencies from 79 to 333 MHz. The *Metox* was installed on most U-Boots through September 1942, which drastically reduce their losses.

[9] The allies' S-band microwave radar was operational from March/April, 1943 but only in September did the U-Boot command realize that 10-cm radar was being used against them. The "*Rotterdam Gerät*," i.e. the British H_2S radar working in the 10-cm band, was kept at Rotterdam by the German Air Force in March 1943, and German scientists had soon determined its characteristics; however, the first really effective S-band radar warning receiver, the FuMB7-*Naxos* (covering the 8–12 cm band) was put in service only in the fall of 1943, and fully operational only in the spring of 1944. Other sets followed, including the FuMB10-*Borkum* (of the crystal detector type, hence, free from any radiation, and covering the 7–300 cm), the FuMB24-*Fliege*, the FuMB 25-*Mücke* and the FuMB 26-*Tunis*, with two back-to-back manually rotating antennas, i.e. the *Mücke* horn for the X-band, and the *Fliege* parabolic reflector for the S-band, whose installations started in the late spring of 1944. *Tunis* was very effective against 3 cm ASV Mk.VII radar (bearing accuracy in the 9 cm range was ±10°, in the 3 cm range ±3°) and was used through the end of war. The last, more sophisticated and watertight systems introduced at the end of the war were the FuMB-29 *Bali* and FuMB-35 *Athos.*

[10] The main parameters of the U-Boot radars are synthesized in the following table.

Type	Frequency (MHz)	Output power (kW)	Approx. Range (km)
FuMO 29	368	8–10	6–15
FuMO 30	368	8–10	7–15
FuMO 61 *Hohentwiel U*	556	30–40	7–20
FuMO 84 *Berlin*	3300	20	20–30
FuMO 391 *Lessing* (range-only)	125	125	30 in emersion (12 @ periscope depth)

[11] The ***Ferranti*** Company, established (London 1896) by *Sebastian Ziani de Ferranti*, became *Ferranti Ltd.* in 1901 and operated first in electro-technics, then in weapons, radars, missile guidance, computers (Ferranti developed and sold one of the early *minicomputers*, known with the name of the firm itself and very popular in the 1960s and 1970s) and, later on, in microelectronics and airborne systems. In the 1980s, the company employed about 18,000 people in more than 40 factories and offices. Its Defence Systems Division, acquired by GEC Marconi and then by BAe Systems, in 2007 was transferred to Finmeccanica, as Selex Sensors and Airborne Systems Inc., and then as Selex Galileo Inc. On January 1st, 2013, SELEX Galileo became Selex ES when it merged with its sister companies SELEX Sistemi Integrati and SELEX Elsag. Most of UK airborne radars history—and present developments—is related to the Ferranti site of *Crewe Toll*, near Edinburgh, Scotland, where, during W.W.II, they developed *gyroscopic gun sights* (GGS, that equipped most British fighters in the last years of W.W.II,

a product still maintained by the Company today!). Decades later this expertise led to products as diverse as navigation systems for *Ariane* rockets and devices for plotting oil well drills.

The Ferranti has given some sets of its airborne radars, produced in Edinburgh in the post-war period, to the *National Museum ofFlight*, located in East Lothian, Scotland. At the Museum operates a group of volunteers, organized in the *Aviation Preservation Society of Scotland* (APSS), http://www.apss.org.uk/index.htm and http://www.apss.org.uk/projects/APSS_projects/radar/index.htm. In one of the projects of the APSS, volunteers have made—on the basis of some rare photographs—a 1:500 mock-up of a site (Drone Hill) of the Chain Home, with its transmitting and receiving antennas, buildings, fences and roads.

[12] The name H2S looks deliberately obscure for very likely reasons of security, exactly as the name *Window* for the anti-radar strips or the names of German radars such as *Freya* and *Würzburg*. Its origin could mean "*Height to Slope*" or "*Home Sweet Home*", to falsely mean that this apparatus was created for landing or carry the members of the crew to their home. The letter "S" may be related to the transmission band. Finally, the formula of hydrogen sulphide H2S, might have been a response, aimed to be witty, of the project team to the scientific adviser of Churchill, Lord Cherwell (Prof. Frederick Lindemann). In fact they say that, during a meeting, the angered Lord Cherwell, who looked to have been convinced that they are hiding something to him, said "the project stinks".

[13] The working frequency of the *Lichtenstein B/C* was about 500 MHz; the four groups of antennas (top/bottom and left/right) were switched cyclically in a capacitive manner, with a sort of electronic scanning of the beam *ante litteram*, and the corresponding signals being equal indicated the correct aiming at the target. The range for a target such as a bomber B 24 was about 4 km; the full scale of the distance was 8 km but the indication of the azimuth and elevation stopped at 2 km. The designers managed to provide a minimum distance of only 250 m, which was essential for night operations. The transmitted power was 450 W, and the PRF was 2700 Hz.

[14] The meaning of the symbol *B/C* remains obscure, such as that of the abbreviation SN-*2*, sometimes reported as *SN2*. The *Lichtenstein SN-2* is derived from a previous model, the *FuG 213* (Telefunken, 1942/43); the reasons for the choices made in the design include the fact that from 1943 it became crucial for the Germans to fight against the allied bombings which were gradually eroding their productive capacity, particularly in the field of weaponry. The night fighters were an essential element of the defence from the night bombing; the pilot of a night fighter had to acquire the target and move into a favourable position to shoot. In practice, the fighter had to fly in the back of the bomber staying aligned with the target at its same level and speed: a radar support was essential. The *Lichtenstein B/C* operated on about the same frequencies as the *Würzburg* (from 480 to 580 MHz) on which the Allies had already developed anti-radar devices. In addition, a radar with a

wavelength of about 4 m was more difficult to disturb with the *Window* than the 60-cm *Lichtenstein B/C* or *Würzburg*, for which thin strips of aluminium were only 30 cm long. Finally, the longer wavelength permitted a significant increase of the radar range, according to the radar equation with the antenna (half wave dipole) gain fixed. In fact, the range of the *SN-2* was about 7 or 8 km on a *Lancaster* or *B 24* target, twice as the B*/C*. The *Lichtenstein SN-2 FuG 220* was developed with an accelerated program, which led to operational sets in the second half of 1943. It operated in the 85–91 MHz (later to be extended to 70–91 MHz) band, where it was possible to use the popular tubes *RV12P2000* said "Wehrmacht Pentodes", produced in tens of millions of units. The principle of the azimuth-elevation display obtained with pairs of antennas was common to other airborne radars operating in metric wave. This radar, that for the large antennas was called *Hirschgeweih*, was only suitable for aircraft rather large as the twin engine ones. Within February 1944 two hundred sets were built and a thousand more within May 1944. The technical data are: peak power, 2 kW; sensitivity of the receiver, −90 dBm; antenna gain, 5 dB; dipole antennas long 1.15 m (with the resonance frequency lowered from 130 to 80 MHz by load inductances); pulse length, 1 μs; instrumented range, 8 km; antenna beam width (both in azimuth and elevation) about 60°, centered on the prow of the aircraft.

[15] The name "Berlin" did not refer to a particular type or set of radar but, generally, to a radar operating at a wavelength around 9 cm. In the last days of the war the *Berlin FuG 240 N1* (where "N" probably was for *Nachtjagd*) with a dish antenna was operational. The *Berlin N1* had the following characteristics:

- Peak Power: 15 kW (then increased to 20 kW).
- Scan angle: ±55°.
- Antenna with rotary feeder and parabolic reflector, diameter: 70 cm.
- Frequency range: from 3250 to 3330 MHz.
- Pulse Duration: 1 μs, with a PRF of 15 kHz.
- Range coverage: from 500 (according to some, 350 m) to 5000 m (according to some, 9000 m).
- Magnetron Type: LMS 10.

[16] Each antenna element, of the *endfire antenna type,* was a bar of polystyrene (of dielectric constant $\varepsilon \approx 2.5$) of such a shape and size to be adapted to the free space impedance, and energised to one end. Each element had a main lobe width of about 40°. The array of four elements brought the width of the lobe to 10°, about the same as a dish antenna with a diameter of 70 cm (in the same S-band). However the *polyrod antenna* had the great advantage of a much smaller size, hence could be housed in a low-thickness ventral *radome*. In addition, the reduced mass and the small size allowed a very high revolution speed for the antenna, i.e. over ten revolutions per second, which, by exploiting the phenomenon of persistence on the retina, permits to avoid the use of a high persistence phosphorus on the plan-position indicator (PPI) display. This method said *Bright Display,* allowing the vision in

normal light, was also used in the post-war period, until the advent of digital monitors. An example of *Bright Display* is that of the first of airport surface movements radar (SMR), called ASMI (*Aerodrome Surface Movements Indicator*) built by Decca and operating at 34–35 GHz (Ka band). During 1952–1953 Decca's 'Radar Lab' designed and supplied a radar, which significantly increased take-off and landing capacity at London's Heathrow Airport. The set was also installed at Paris-Orly, Rome-Fiumicino and Milan-Linate to provide tower controllers with an image of the aircraft traffic on the ground. The system had a high speed rotating antenna (720 r.p.m. i.e. 12 revolutions per second) which allowed the display of the echoes in the control tower using a cathode-ray monitor with high persistence phosphors. The monitor had a fixed coil display from 0.5 nautical miles to 2.5 nautical miles (about 4.5 km) with an off-centre capability.

[17] Technical data of the *AN/APQ 13*:

- Wavelength: 3 cm (frequency: 9375 MHz)
- Pulse width: 0.5 μs
- Pulse repetition frequency: 1350 Hz
- Scan rate: 13 rpm in search mode; 50 scans per minute in sector scan mode
- Power: 1 kW
- Range:
  15 nautical miles on harbour buoys
  40 nautical miles on 5000-ton vessels
  95 nautical miles on a large coastal city
  Minimum range: 180 m
- Antenna: Parabolic
- Display: PPI
- Accuracy: Range accuracy 1 %. Bombing accuracy 400 m
- Weight: 168 kg

[18] It is known that a company with its headquarters in a given State must be established according to the laws of this State: the multinationals industrial organizations are aggregations of national companies with a centralized control. In these cases, the Finmeccanica style to use the same corporate name, for example, Selex + *something*, followed by *s.p.a.* or *Inc.*, or *Ltd.* or *GmbH*—certainly does not contribute to the clarity. In one case, they *almost* deleted a renowed and historical name (brand), that of *Gematronik* in Neuss (Germany), a well known and ancient manufacturer of weather radars. In July 2005, acquired by Selex Ltd (U.K.), *Gematronik* became *Selex Sistemi Integrati GmbH;* on December 30th, 2009, newly acquired by the Italian firm *Selex Sistemi Integrati SpA,* became *Selex Systems Integration GmbH.* After the acquisition, *Gematronik* continued to design, produce, and sell exactly as before, and anyway, the "real" name of the company remains, thanks to the web site: http://www.gematronik.com which is evidently managed by Neuss, not Rome, as well as in the colloquial term *Selex Gematronik.*

[19] In a *Phased Array* radar the angular scanning to different directions leads to a widening of the main lobe and a loss of gain, which become important beyond at 45° and more. In some cases, for example for the missile guidance during evasive maneuvers of the own aircraft, a more extensive coverage is provided by a mechanism for angular positioning of the antenna, sometimes called *repositioner*, a swivel base which allows the radar to cover a wider portion of the area of interest, by significantly increasing the performance in high angles of incidence or against off-axis targets.

Chapter 7

[1] The initial USAF *Starfighters* had a basic *AN/ASG-14T* radar (operating frequency from 9000 to 9600 MHz, tuneable magnetron transmitter with peak power 140 kW, PRF: 1000 ± 25 Hz in search, 1300 Hz in tracking, parabolic reflector antenna with beam width 3.9°), a TACAN, and an *AN/ARC-34* UHF radio. In the late 1960s, Lockheed developed a more advanced version of the Starfighter, the *F-104S*, for use by the Italian Air Force as an all-weather interceptor. The F-104S had on board a *NASARR R-21G/H* radar with moving-target indicator (MTI) capability and a continuous-wave (CW) illuminator for semi-active radar homing missiles, including the AIM-7 *Sparrow* (some claim that the S following F-104 stands for Sparrow) and the Selenia *Aspide*. In the mid-1980s, surviving F-104S aircraft were updated to ASA standard ([*Aggiornamento Sistemi d'Arma*] or Weapon Systems Update), with a much improved, more compact *FIAR R-21G/M1* radar.

[2] Now manufactured by *Telephonics* (USA), the Bendix/FIAR *RDR-1500B* is a multi-mode, X-band, 360° radar for helicopters and fixed-wing aircraft in low and medium altitude maritime missions, the primary mission being airborne search and surveillance for sea operations. Secondary missions include terrain mapping, weather avoidance, beacon navigation and navigation. Main technical data: Transmitter Frequency: 9375 MHz; Transmitter Power Output: 10 kW nominal; Pulse Repetition Frequency: 1600/800/200 Hz; Pulse Width: 0.1/0.5/2.35 μs; Antenna Gain (1 m × 0.23 m array, stabilized): 31.5 dBi with an azimuth beam width of 2.6°.

[3] With the proliferation of electronic equipment (radio, radar, electronic warfare…) during W.W.II, the United States forces had to establish a unique *naming and numbering*. Army and Navy introduced the "*JointCommunications-Electronics Nomenclature System*"—called "Army-Navy" or briefly "AN System"—and formally approved on February 17th, 1943; when the US Air Force separated from the Army (1947), they continued to use this system.

In the sequence **AN/(1)(2)(3)-xy**, where xy is the progressive number of the specific apparatus, the three letters after AN indicate:

1. the installation (examples: A—Piloted Aircraft, F—Ground, Fixed, P—Portable (by man), S—Surface Ship, T—Ground, Transportable),

2. the type of apparatus (examples: L—Countermeasures, M—Meteorological, **P—Radar**, Q—Sonar and Underwater),
3. the purpose (examples: G—Fire Control or Searchlight Directing, N—Navigation Aid, Q—Special or Combination, S—Detecting, Range and Bearing, Search, X—Identification or Recognition, Y—Surveillance and Control).

   For example, the long range radar (400 km) in L-band (1215–1400 MHz) installed in the 1990s for the perimeter security of the United States is called *AN/FPS-117* in its fixed version (which, according to a contract of 2011, will be modernized to extend the operational life until 2025), and *AN/TPS-117* in its transportable, tactical version.

   The Italian Navy utilizes a similar method, i.e. **MM/(1)(2)(3)-xy** where MM stands for MMI—[*Marina Militare Italiana*] and

   1. first letter: A = Airborne, B = Submarine, S = Surface Unit
   2. second letter: P = Radar, L = Countermeasures, Q = Sonar
   3. third letter: D = Radiogoniometer, G = Radar for fire control or missile guidance, N = Navigation Radar, Q = Multifunction/special set, R = Passive detection system, S = Search Radar (surface and/or air), T = Transmitter, Y = Multifunction Phased-array Radar.

      The situation of Italian Navy radars, from the 1950s till 2014, is the following.

      MM/SPQ-2 (Multifunction Radar-Surface and Low elevation Search and Navigation); MM/SPQ-3; *MM/SPQ-4B* (*Experimental radar “BST-1”*); *MM/SPQ-5A* (*experimental radar “Sarchiapone”*); MM/SPG-70 and MM/SPG-73 (Orion RTN-10X Fire Control Radar), MM/SPG-74 (RTN-20X Fire Control Radar), MM/SPG-75 and MM/SPG-76 (RTN-30X Fire Control Radar); MM/SPS-701; *MM/SPS-702 CORA* (*Condotto Radar*); MM/SPN-703 (Navigation Radar 3RM28B); MM/BPS-704 (Radar for submarines 3RM20B); MM/APS-705; MM/APQ-706; MM/APS-707; MM/SPQ-711; MM/SPQ-712 (RAN12 L/X); MM/APS-717; MM/SPN-720 (Precision Approach Radar); MM/SPS-728; MM/SPN-730; MM/SPS-744; MM/SPN-748; MM/SPN-749; MM/SPN-750; MM/SPN-751; MM/SPN-753; MM/SPS-768 (RAN-3L); MM/SPS-774 (RAN-10S); MM/SPG-775 (RTN-30X); MM/APS-784 (Eliradar); MM/SPY-790 (EMPAR Multi-Function Radar); MM/SPS-791 (RASS); MM/SPS-794 (2D Search Radar RAN-21S); MM/SPS-798 (3D Early Warning Radar- RAN-40L); MM/BPS-804.

      There is some historical interest (see the *italic items* in the above list) in the strictly secret trials made in the 1970s and 1980s by the MMI to exploit the “duct effect” propagation over the—often very humid—air just above the Mediterranean sea. In fact, this natural phenomenon generates a few meters narrow layer above the sea surface with a moisture content of the order of 80–95 % in which the radar waves are "trapped", with an attenuation proportional to the second power of the distance (not the fourth power of free-space conditions). The highly secret experimental radar SPQ-5A "*Sarchiapone*" installed from 1973 to 1987 on board the frigate *Alpino*, was able to locate aircraft during their take-off from the aircraft carrier *Kennedy* at a distance of 350 nautical miles. A further evolution of SPQ-5A "*Sarchiapone*" was the *SPS-702ACo.Ra* (*Condotto Radar,* Radar Duct) installed on board the "Lupo" class frigates toward the end of 1980s and then removed, prior to the sale of the four units to Peru. The task of the *Co.Ra* was the remote control over the horizon of the *Teseo* missiles toward their targets, without having to resort to the use of the helicopter. Three more radar sets of this type were based on the coast in La Spezia, Taranto and Venice; the latter was able to intercept, at the distance of about 280 miles, the air traffic of the large Italian air force base *Luigi Rovelli*, in Amendola near Foggia; they considered the chance to create a network of such "Radar Duct" systems for coastal monitoring throughout the Mediterranean, but the project had no follow-up because of the inconstancy of the phenomenon and the need to install the antennas at the suited, not known a priori, altitude above sea, sometimes as low as a very few metres.

[4] CRESO means *Complesso Radar Eliportato Sorveglianza Obiettivi*, i.e. Heliborne Battlefield Surveillance Radar Complex. A prototype was developed in frame of the SORAO *(SOttosistema di Ricerca ed Acquisizione Obiettividel campo di battaglia*, or *battlefield surveillance and target acquisition subsystem*) element of the Italian armed forces' CATRIN (*Campale di Transmissioni ed Informazioni*, i.e. *field communications and information system*), 1990s, with first flight trials and display to the Italian Armed Forces on September 18th, 1996. This experimental helicopter AB-412, mark E.I. 453 with the CRESO system installed can be still seen, abandoned in the Viterbo "CALE" airfield: http://heliweb.forumcommunity.net/?t=53037591. Unfortunately the programme could not be completed and the planned four "Nato 1" CRESO systems were never built.

[5] The technical data of the TPS-1D are:

- Frequency: 1220 to 1350 MHz
- Range: 160 nautical miles
- Peak Power Output: 500 kW (average: 500 W)
- Display: one 7-in. PPI and one 5-in. A-scope
- Display Ranges: 20, 40, 80, and 160 mi
- RF Power Source: Type 5J26 magnetron
- Pulse Repetition Rate: 380 pps normal (adjustable 360 to 400 pps)
- Pulse Width: 2 μs
- Horizontal Coverage: 360°
- Antenna Rotation Speed: 0 to 15 rpm
- Resolution: Range, 0.33 mi; azimuth, 4°

- Horizontal Beam Width: 4°
- Vertical Beam Width: 12°.

[6] The torpedoes factory called *Reale Silurificio Italiano* was located in the small towns of *S. Martino* and *Baia*, in the *Flegrea* area, west of Naples. During the war, the production had to be increased and the management of the *Silurificio* decided to realize a new plant in the plain of *Fusaro* 3 km away from S. Martino. The transfer of production machinery to *Fusaro* ended in the mid of 1943; the new plant was linked to the one in Baia (mainly devoted to assembly and tests of torpedoes) by means of a 1300 m long tunnel and to S. Martino with a wharf and another gallery: in this way, the three plants operated as a single plant. In late 1940 the *Silurificio* employed almost 4000 workers. After the armistice in September 8th, 1943 these plants were heavily bombed by the Germans, who destroyed them in a systematic way. The Allied troops, back in the plant on October 18th, took away every machinery and equipment and the area was occupied by the Royal Navy. These plants returned to Italy on September, 1945, and immediately the problem was posed to start new industrial activities to continue to engage the workforce. The plants were taken by *Finmeccanica*, a state owned financial company formed to manage the previous war industries which were not able to retrain quickly. The *Silurificio* was reconverted into a motorcycle factory, which from 1950 built on license the Mosquito 38 cc. engine to be installed on a bicycle. In 1958, this mechanical production was interrupted and the establishments hosted the *Microlambda* company.

[7] In addition, confirming the accuracy of ing. Musto's memories of Selenia air traffic controls radar, here is an excerpt of the interview (on February 22nd, 2000 in Washington, D.C.) of the celebrated radar expert Merrill I. Skolnik, by Michael Geselowitz for IEEE Global History Network:

"Another interesting radar company is Alenia, formerly Selenia, in Italy. **At one time they probably made the best air-traffic control radars in the world**, as well as other end military radars; but they have also experienced management changes" (bold by the author). However, since mid-2000s, unfortunately the international appeal of Selenia's Air Traffic Control Radars (ATCR's) is not as good, with a very few sales outside Italy and a partial, too slow technological and architectural updating, leaving more and more room to the European and USA competitors. Likely, the excellence of early Air Traffic Control and surveillance radar design and development team from Selenia (from the TPS-1 onwards) is being gradually lost in the ensuing generations.

[8] The air traffic radars are indicated in the USA with the acronym *ARSR* (Air Route Surveillance Radar) for the *en route* control (i.e. control of the airways network) and with *ASR* (Airport Surveillance Radar, where the term *Airport* actually denotes the surrounding airspace, not only the airport) for the control in the *terminal maneuvering area* (TMA), i.e. the airspace around one or more airports. Selenia preferred the name ATCR for both types of radar, followed by one (initially) or two digits, to which other letters were added, e.g. K for Klystron, DPC fof Digital Pulse Compression and so on.

[9] The main parameters of the *PS-810* were: Frequencies in L band (1260–1350 MHz); Magnetron Transmitter (tunable), Peak Power 1.8 MW, Pulse duration 1.7 or 2.0 μs, Pulse repetition frequency 793/680 Hz, Horizontal beamwidth 1.3°, Noise figure <4.8 dB, Rotation speed 6/12 revolutions per minute.

[10] The "magic code" solution was useful in the particular case of *Argos 5000*, where the matched filter for zero speed was not inserted, thus providing a simple, effective speed threshold; unfortunately it was also used in two other Selenia radars (but, significantly, never by other Companies) in the 1970s, namely the *RAN 10 S* and the *RAT 31 S*/"3D Medium Range", trying to implement at the same time: clutter suppression by Doppler filtering, CFAR and frequency agility for ECCM purposes. Each pulse of the "magic" sequence was Barker codified; an hard limiter upstream the Barker matched filter controlled the dynamic range in an attempt to avoid false targets due to the side-lobes of the code. However, this type of waveform was not successful because it created big trouble with clutter residuals, and was substituted by other waveforms (in particular, non-linear FM or "Chirp") in the late 1970s. The problem of moving clutter was solved with the adoption of the *Adaptive MTI* whenever needed (Air Traffic Control radar of the ATCR family and RAT 31 SL/"3D Long Range". In fact, the straightforward solution based on an the simple addition of an "*Adaptive MTI* filter" was found and tested in Selenia only ten years after the Argos 5000 design (and published only fifteen years later, see [Gal 78]).

[11] The most demanding part of the radar, anyway, was probably the transmitter. The needed power was huge, 5000 kW peak. From Raytheon two special, high power tubes, were available, i.e. the "Stabilotron" and the "Amplitron". Once connected in series, they allowed Selenia to implement a light and efficient L band, high power transmitter. The *Stabilotron* was basically an *Amplitron* (Amplitron and Stabilotron are power tubes of the crossed-field amplifier (CFA) type) with the input connected to a resonant cavity, implementing a tuneable, lightweight, and very stable (as required for the MTI operation) radiofrequency generator. The Amplitron amplifier was capable of 5 MW peak output, when fed by a 500 W input from the Stabilotron. The pulse repetition frequency was 330 Hz, corresponding to an instrumented range of 250 nautical miles (450 km). The antenna rotated at 6 revolutions per minute, and its beam width in azimuth was 1.5°, resulting in a "time on target" of 42 ms and 14 pulses per beam. The duration for all the pulses transmitted in a sweep was 6 µs, with a "duty cycle" of 0.2 %, i.e. an average transmitted power (with 5 MW peak) of 10 KW. The transmitted pulses were suitably "staggered" to avoid the blind speed of the MTI. The radio frequency (1250–1350 MHz) could easily be varied, in particular when a jammer on the frequency in use was detected, by acting on the cavity of the Stabilotron.

[12] Only after twenty years (perhaps too many) Selenia designers adopted the parallel and modular architectures studied in the early 1970s. These were not applied—and indeed, initially criticized—with an understandable—but not justifiable—internal resistance, maybe due to an exceedingly high respect of the company's tradition, or to the always present "Not Invented Here"

syndrome, or to some internal dispute between different design groups, or a mix thereof. So, the programmable devices (microprocessors, DSP, and subsequently FPGA) arrived with some delay with respect to competitors.

[13] In the same year Selenia enrolled the author in his Research Directorate headed by prof. Aldo Gilardini.

[14] Each of these "business units", called "Divisions", had a Managing Director responsible for the choice of new products to be developed. The Production, the Administration, and the Directorate of human resources reported to the Chief Executive Officer. The Technical Director headed the Research and Development Laboratory and—as a member of the top business team (formed by CEO, General Director, and Technical Director)—provided assistance to the Engineering of each Division.

The following Units were thus formed:

– The Radar Division with technologically advanced products such as the Argos 2000 and the Argos 5000. The responsible for these developments as well as for those of Air Traffic Control Radar, i.e. ing. Francesco Musto, was put at the head of this Division.
– The Missile Division, which had operated on licensed products and was entrusted to ing. Paolo Piqué.
– The of Air traffic control Division, with very valuable products and a fast-growing market, entrusted to ing Gianfranco Galotti.
– The Naval Division that inherited the technology of command and control and was entrusted to ing. Cesare Iorio.
– The Space Division was entrusted to ing. Antonio Teofilatto, which, besides having a strong technical background, was able to maintain relations with the international space organizations. Ing Antonio Rodotà was the program manager of the project Sirio, which firstly Italy and Selenia on the international scene of space systems.
– The Computers Division was entrusted to ing. Saverio Rotella, responsible for the development of the GP16, a new and very advanced minicomputer.
– The Telecommunications Division was entrusted to ing. Osvaldo Abbondanza.

The CEO had monthly meeting with each Responsible of Division and some of its employees, dealing on the results of the activities of the last month: orders, turnover, progress of new developments and economic results. Decisions relating to new products were taken—for each division—in a monthly meeting.

[15] Aldo Gilardini, born on August 16th, 1926 in Turin, graduated in electrical engineering at the Technical University of Milan [*Politecnico di Milano*] in 1948. He was lecturer in applied electronics, and carried out research at the CNR and at the Massachusetts Institute of Technology. He worked in Selenia from 1957 to 1990, and, there, was Managing Director for Research from 1974 to 1986. He published various books, including the well-known "Low Energy Electron Collisions in Gases", J. Wiley, 1972. Sadly, prof. Aldo Gilardini passed away in Roma on August 23rd, 2000 during the

organization and the development of the final version of a book on Remote Sensing co-edited with the author of this book.

[16] Benito Palumbo (1936–2011), born in in Castelluccio Valmaggiore (Foggia- Italy) on August 1st, 1936, after a period (1962–1970) of work in the engineering at Selenia SpA, was therein responsible of antennas design (1970–1985) and, then, heading the Engineering Directorate ([*Direzione Sviluppo*], 1985–1994), in charge of the whole design activities for: *antennas, microwave, intermediate-frequency and video circuits*, as well as *digital and programmable circuits and processors*. At the end of the 1970s he took numerous courses and seminars at the Universities of Ancona, Naples, Pavia, Pisa, Rome Tor Vergata, Rome La Sapienza, and at the Technical University of Turin and the Reiss Romoli School (STET). Within the IEEE he was Chairman of the *Joint Chapter AP&MTT* (Antennas and Microwave Society) in 1986–1990, and of the *Central & South Italy Section* in 1992–1995; moreover, he leaded the union of the former *Italy Sections* (North Section—C & S Section), which occurred on June 29th, 2005, into a single *IEEE Italy Section*, which he chaired in 2006–2007. Finally he was Chairman of the *IEEE Region 8 Industry Relations sub-committee* (2007–2010). He was also an Honorary Member of the Italian Society of Electromagnetism (SIEM) and member of the Technical Committee of several international conferences in the areas of antennas, microwave and radar. On October 1st, 2011 suddenly and unexpectedly Benito Palumbo passed away in his home in Rome. On February 13th, 2012 at the headquarters of the CNR (Italian National Council of Research) a Study Day was held to remember this noticeable representative of the Italian technical-scientific knowledge and know-how both in the industrial and in the institutional context .

[17] The antenna was an offset-fed reflect array with the following characteristics:

- Diameter: 730 mm.
- Array elements: 820 organized in 32 rows and 32 columns.
- Operating frequency: anyone in the 8.5 to 9.5 MHz band (after calibration).
- Beamwidth: about 3°.
- Scan angle: up to 54°.

[18] Edoardo Mosca (Ph.D.), after obtaining the Dr. Eng. degree in Electronic Engineering from the University of Rome “La Sapienza”, spent four years, from 1964 to 1968, in *Selenia* where he worked on advanced radar systems design. Thereafter, from 1968 to 1972 he held academic positions at the *University of Michigan*, Ann Arbor, Michigan, and at the *McMaster University*, Ontario, Canada. Since 1972, he has been with the Engineering Faculty, *University of Florence*, Italy: from 1972 to 1975 as an Associate Professor, and since 1975 as a full Professor of Control Engineering, now Emeritus. With T. Bucciarelli, G. Galati and G. Picardi, he is one of four persons who, after a working period in *Selenia* as design engineers, concluded their career as full professors at the University.

[19] The *EMPAR* program started in 1986, with the conclusion of the Contract n. 14581 dated 11.28.1985 for the development of a prototype shipborne "phased array" radar, called *MFR-1C* for a frigate of *Maestrale* class and for the control of a new missile system with active seeker.

[20] *EMPAR* is a passive phased array with a single face, a maximum range over 100 km and a revolution speed of 60 r.p.m., capable of simultaneous air surveillance at medium-range and three-dimensional localization, multiple target tracking and guidance of missiles, to which it can send in *uplink* the kinematic data of the targets. The antenna is able to generate an electronically scanned beam within ±45° (horizontal plane) and ±60° (vertical plane, both with respect to the perpendicular to the antenna surface), with a tracking capability of several hundreds of tracks simultaneously. The mass of the above-deck part is 2500 kg for the antenna (size in meters: $2.1 \times 2.3 \times 1$) plus 350 kg for then near-spherical *Radome*, whose diameter is about 5 m. The below-deck part has a mass of about 6000 kg.

[21] Since 1994 the frigate *Carabiniere* has been used by the Italian Navy—till November, 2008—as a platform for the development of new weapon systems. Among the tested systems there has been the multifunctional radar *EMPAR SPY-790*.

[22] The entire test phase lasted 36 months. In particular:

- 6 Months for the installation and integration on board.
- 18 Months, with execution of all tests in a real environment, for the functional set-up and performance analysis.
- 12 Months for formal qualification and acceptance.

[23] The *Future Surface-to-Air* (FSAF) is a surface-to-air missile system developed by a European consortium, with France and Italy user countries. The *Principal Anti Air Missile System* (PAAMS) is a British/French/Italian development program for naval defense, i.e. is intended to protect the equipped units—as well as those they accompany—from missile and airplane threats. When operating at short distance from the coast, PAAMS is also intended to protect ground forces such as landing troops. The versions are: PAAMS (S): British version with the multi-function radar *SAMPSON*; PAAMS (E): Italian/French version with the multi-function radar *EMPAR*.

[24] Somebody said that the choice of the name, whose structure does not include comparable parts to the two names of origin: *Aeritalia* and *Selenia*, was due to the fact that the possible names *SelAer* or *AerSel* chimed in the English language as *Air Sale,* thereby recalling those who "sell air".

[25] It is worthwhile to reproduce here the related remarks by ing. Francesco Musto (2001), from the Web Site: http://www.carlopelanda.com/theunedited/magusto/pugliaradareguerrafredda.htm

> …in my opinion, it is a good thing that the most critical and valuable core of Selenia is today practically managed by the English Marconi: *we need the stranger*. Marconi is certainly a serious and competent company, capable of developing all the existing potential, ….

[26] Some of the staff wondered why not to use, in such a favourable opportunity, the celebrated, hystorical name *Selenia*. One reason by the supporters of the new name *Selex* was that in the meantime *Selenia* became the name of a lubricant used in the automotive industry, but in reality, in different commodity sectors there is no prohibition to use similar or identical names and marks. Perhaps the name *Selex* seemed more modern and "aggressive" indicating—if read as "**Sel**enia **ex**cellence"—a sort of desirable continuity with the remarkable history of Selenia. Moreover, probably they did not pay too much attention to the fact that, since 1964, a large Italian wholesaler uses the brand name Selex, see: http://www.selexgc.it/.

Chapter 8

[1] The Italian Space Agency *ASI* [Agenzia Spaziale Italiana] is an agency of the Italian government with the task to decide and to manage the national policy for space activities. ASI uses Government funds (with an annual budget of the order of 600 M€) to finance the project, the development and the operational management of space missions, either alone or in collaboration with the major international space Agencies, first of all European Space Agency (where Italy is the third largest contributor after France and Germany), then NASA and other foreign space agencies. For the implementation of satellites and scientific instruments, ASI contracts with Italian companies active in the space sector. ASI has its headquarters in Rome and operational centres in Matera (*Giuseppe Colombo* Space Geodesy Center) and in Malindi, Kenya (*Luigi Broglio* Space Center). The first general director of the Italian Space Agency has been Carlo Buongiorno, a pupil of Luigi Broglio, and its first president, from 1988 to 1993, was Luciano Guerriero.

The Italian Space Agency has paid particular attention to the *Earth Observation* programs by participating in numerous programs of the European Space Agency (i.e. *ERS-1*, *ERS-2* and *Envisat*), and cooperating with other international space agencies. Among these programs there are the noticeable *SAR-X* and *SRTM*, for Earth observation with X-band radar, with the German space agency DLR and the NASA. Recently, ASI has developed the *COSMO-SkyMed*, a satellite constellation in low orbit, equipped with radar sensors, able to collect environmental data. In this frame, ASI has signed an agreement with the *CONAE* (Argentine space agency) for the integration of *COSMO-SkyMed* with the Argentine *SAOCOM*, in order to cover 80 % of requests by the international community. ASI has about two hundred fifty employees; from 2013, ASI headquarters are in new site in the outskirts of Roma, via del Politecnico S/N, completed at the beginning of 2012 in the area (and in the land) of *Tor Vergata University*, Roma. This huge, black-painted compound can easily host seven or eight hundred people and his final cost has been 84 million Euro (more precisely, 84 434 755 Euro and 65 cents) i.e. *seven times* the original plans in 1999. Its construction plans were *classified* by ASI, claiming *security reasons*, so avoiding a regular European competition with bidding, and the execution of the work has been entrusted—by means of a private treaty—to a Roman company selected between six companies of ASI confidence.

[2] Wiley summed up the operating principle of SAR as follows: "*I had the luck to conceive of the basic idea, which I called Doppler Beam Sharpening (DBS), rather than Synthetic Aperture Radar (SAR). Like to signal processing, there is a dual theory. One is a frequency domain explanation. This is Doppler Beam Sharpening. If one prefers, one can analyse the system in the time domain. This is SAR. The equipment remains the same—just the explanation changes*". This sentence, after sixty years, maintains all of its educational value; in the meantime, the term SAR has prevailed over the term DBS except in some operation modes of airborne radars.

[3] In 1974, the U.S. *National Oceanic and Atmospheric Administration* (NOAA), together with the *Jet Propulsion Laboratory* (within the *California Institute of Technology*), was exploring the potential of oceanic observations by means of a remote sensing satellite with a SAR sensor, whose centimetre waves makes it sensitive to changes in sea surface roughness, with the possibility to monitor the motion of the waves and the currents. In June 1978, the launch followed of the first civil satellite with a SAR payload, i.e. *SEASAT*. Unfortunately the SEASAT operation, at least as far as known to the general public, only lasted a little more than three months (instead of some years) during which, however, images of good quality were obtained of some portions of the surface of the Earth. It is not excluded, however, that in reality this system had been used for a longer time, but only for classified applications.

[4] A well-managed SAR produces images similar to optical images wherein many ground features, such as buildings and roads, as well as vehicles, such as trucks, cars, trains and so forth, can be recognized. Target motion causes moving targets to appear in the SAR image at locations different from their true ones on the ground. This is due to the coupling of the cross-range position to the target radial velocity and to the fact that the moving target and the ground have different radial velocities with respect to the platform. The result is the well-known "train-off-the-track" phenomenon where the moving train appears off the image of the track, or the "boat-off-the-wake" where the moving boat is seen off the tip of the boat's wake. However, by comparing phases of SAR images from two channels of a multichannel SAR, moving targets can be detected via *phase interferometry* when they are much stronger than the ground clutter. Moreover, a direct channel-to-channel clutter cancellation technique may suppress ground clutter by a significant amount, enhancing the detectability of the moving targets. As an example, the *Lincoln Laboratory's Multi-mission ISR Test Bed* (LiMIT) is an airborne, multi-channel, wideband phased array SAR with 8 receiving sub-apertures, and operates at 9.2 GHz with a bandwidth of 180 MHz. The basic parameters of LiMIT are: 800 m aperture (9072 pulses), 2° azimuth beam-width, 30 km standoff range, 24° grazing angle, 1 m resolution, 4 km × 2 km coverage area. A similar system is the General Dynamics DCS 8-Channel, with a 160 MHz bandwidth.

Chapter 9

[1] This nocturnal bird has inspired the poetic work by Giovanni Pascoli "L'assiuolo", from *Myricae—In campagna* (The Scops Owl, in the collection of poems *"Myricae"—In the country*):*Dov'era la luna? ché il cielo/notava in un'alba di perla,/ed ergersi il mandorlo e il melo/parevano a meglio vederla./Venivano soffi di lampi/da un nero di nubi laggiù;/veniva una voce dai campi:/chiù…*
(Where was the moon? because the sky/was swimming in a dawn of pearl, / and the almond and the apple tree/seemed to rise to better see it. /Blasts of lightning were coming/from a black cloud over there; /a voice came from the fields:/chiu …)

[2] The search for preys (small nocturnal insects such as mosquitoes and moths) occurs in phases; in a first step the bat emits 10 to 20 signals per second (a repetition frequency corresponding to a maximum non-ambiguous distance between 8 and 17 m). Once detected a prey, the emission becomes more frequent, up to 200 times per second; in essence, the bat implements a continuous trade-off between the maximum search distance and the updating rate. During the approach to the prey, the duration of the signals is also decreased (in the search for insects a duration from 0.2 to 100 ms is used, with intensity very much variable, from 60 to 140 decibels). The bat knows how to avoid the blind area due to the emission itself (a one millisecond long emission signal causes a blind range of about 17 cm), and also knows how to decrease, for obvious reasons of economy and in agreement with "the radar equation", the energy of the signals when the prey is close. Finally, some bats, called "whispering bats", utilize the techniques of low-power echo-location to avoid being "intercepted" by some types of moths that are able to hear the signals emitted by bats and implement "evasive manoeuvres" to avoid the attack. The set of bat's signals is rather complex, including pulses at a constant frequency (i.e. signals with a relatively narrow band), frequency-modulated pulses and harmonic signals, with multiple frequencies of a fundamental, of which one is a greater intensity said "dominant". The frequency-modulated signal or "Chirp" allows a very fine discrimination of the distance: with a series of elegant experiments J.A. Simmons has shown that, thanks to this type of signals, the bats can distinguish two small targets separated by the very limited distance of half a millimetre! But one should keep in mind the different speed of electromagnetic waves with respect to the ultrasounds: half a millimetre would correspond to about half a kilometre in radar, i.e. the same order of magnitude as the resolution of the E.C.3 ter—Gufo.

[3] It has to be noticed that the *stealth feature* of an aircraft covers all the domains where it can be detected and localized (i.e. not only a by radar but also—passively—in the visible, infrared, acoustic and radio frequency spectrum). Against active detection, the *stealth* techniques reduce the *radar cross section* (RCS) by shaping and coating the surfaces, achieving in some cases RCS reductions of three orders of magnitude (at microwave) with respect to

not “stealth” aircraft of comparable size. For aircraft such as the VLO (*Very Low Observable*) *F-22 Raptor* or the *Low Observable F-35 JSF*, microwave RCS values are obtained of the order of one thousandth of a square meter or even less. The methods for reducing the RCS generally are optimized in the frequency range from the S-band to the X-band and become ineffective- or less effective—at wavelengths greater than about half a metre, for which too thick coatings would be required. In addition, some parts of the aircraft have comparable in size with the VHF and HF waves, creating resonance and relatively high values of RCS at metric wavelengths.

[4] The *F-117* “Night Hawk” subsonic ground attack aircraft first flew in 1981, became operational in 1983 and its existence has been officially made public only in 1988. It was put out of service in April 2008, to be replaced by the F-22. A F-117 was shot down with SA-3 missiles on March 27th, 1999 during the NATO bombing (March 24th, 1999–June 10th, 1999) against the People’s Republic of Yugoslavia on the occasion of the Kosovo war. The F-117 has fallen at the village of Budjanovci at low speed, with the frame mainly intact. This has enabled the Russians—and subsequently, the Chinese—to discover the secret stealth techniques developed by the Americans since the 1970s with the *Have Blue* project. The wreckage of the shot down F-117 is now displayed in the Belgrade Aviation Museum near the Nikola Tesla airport. With improved computers and models, available after the development of the F-117, it has been possible to define of the curved surfaces for the project of stealth aircraft, while at the time of *Have Blue*, design techniques were limited to flat surfaces, hence the characteristic “faceted” aspect of the F-117, very different from that of the F-22, F-35 and also of the Sukhoi T-50, a recent (2012) prototype of the Russian Fifth Generation Fighter Aircraft (FGFA) Sukhoi PAK FA, whose operation is planned in 2015. The T-50 PAK FA is equipped with a new AESA (Active Electronically Scanned Array) radar developed by *Tikhomirov Scientific Research Institute of Instrument Design* with active elements in X-band on the front, the sides and on the rear of the aircraft, and two L-band active elements in the wings.

[5] One of the latest Russian radars in the VHF range (according to some observers, the traditional frequencies of these radars are from 150 to 220 MHz) is a part of the Russian point defense system named *55Zh6M Nebo M 3-D*, which has three radars, the *RLM-M* in the VHF band, the *RLM-D* in the L-band and the *RLM-S* in the C-X band. This system is known since 2011; in the period 2011/12, about a hundred units were ordered for the Russian Air Defense against attacks by bombers or ballistic missiles. The system is developed by NNIIRT, *Nizhny Novgorod Science Research Institute of Radio Engineering*, based in Nizhny Novgorod in Russia, now a division of *Almaz-Antey Joint Stock Company* in Moscow. This, perhaps unique, multi-band search and acquisition system is made up by the three

radars and one data fusion/command and control centre. The whole system is mobile, on large wheeled vehicles. The three radars are of the solid state, active phased array type. With this architecture they intend to solve the problems of the previous air defence systems regarding the acquisition of *stealth* targets. In fact, the VHF radar (which, according to a statement of Igor Krylov from the NNIIRT, is able to see targets F-117 type as well as ordinary aircraft) provides a first localization of the enemy target, from which the two microwave radar produce high precision tracks. The VHF solid state radar antenna has 84 transceiver elements and as many analog-to-digital converters with digital beam forming in the vertical plane for the detection and measurement of the height of ballistic missiles. The detection of a target with RCS of one square meter occurs: at 0.5 km height, up to 65 km; at 10 km height, up to 270 km and finally at 20 km height, up to 380 km. The surveillance is updated every 5 (or 10) s. The estimated angular errors are 0.5° in azimuth and 1.5° in elevation.

[6] The research on OTH radar systems in the USA started at the Naval Research Laboratory where, in 1955, a first experimental set, the *MUSIC* (*Multiple Storage, Integration and Correlation*) demonstrated the detection of missile launches up to thousand km. In 1961 a second, more advanced system, followed, named *MaDRE* (*Magnetic-Drum Radar Equipment*). To record the signals to be treated according to the matched-filter concept, both MUSIC and MaDRE used magnetic drums, the only fast enough memories at that time. The first OTH radar operating in the western world was the Anglo-American *Cobra Mist* (built in the late 1960s and equipped with a huge 10 MW transmitter) which in 1972 from Suffolk (Great Britain) could detect flights over the western Russia. However, due to noise sources of unknown origin, it could not operate correctly and was finally dismantled in 1973. The two OTH-B radars of the USA west coast and east coast—respectively facing east and west—worked in the Cold War period (about 1970–1990) and were finally dismantled in 2007. The *OTH-B* (military designation: *AN/FPS-118*) is a bistatic FM radar operating from 5 to 28 MHz in 6 bands, with 12 transmitters per band and an *Effective Radiated Power* of 100 MW; the frequency-modulated signal (from 5 to 40 KHz) is repeated at a rate of 10–60 Hz and processed with a coherent integration time of 0.7–20.5 s.

[7] *Project Jindalee* was started by the *Australian Defence Science and Technology Organisation* (DSTO) in 1974. The *Jindalee Operational Radar Network* (JORN) uses two operational over-the-horizon radars, plus the experimental one at the DSTO station near *Alice Springs*, Northern Territory, to monitor air and sea movements mainly in the North and West directions, with an official range of 3000 km, but probably, larger. It is used in the defence of Australia, and can also monitor maritime operations and ocean status (wave heights and direction). Project Jindalee was started by DSTO in 1974. A general description (2015) is in: http://www.airforce.gov.au/docs/JORN_Fact_Sheet.pdf.

[8] Top-secrete reconnaissance flights above the Soviet territory started in 1956, with twenty four missions in four years. In the midst of the Cold War, the USA wanted to know the extent of Soviet forces, trying to photograph from the top the bases of their intercontinental missiles and strategic bombers. The Francis Gary Powers mission, called *Grand Slam*, planned that his "Dragon Lady" U-2 would cross for 6100 km the whole Soviet Union flying at altitudes up to over 70000 ft. (about 21.5 km), beyond the expected capability of ground radars, missiles and fighter interceptors. The starting point was *Peshawar* in Pakistan, with landing expected, after nine hours of flight, in *Bodø*, at that time, a base of spy planes and strategic bombers, today the site of a civil airport in northern Norway (IATA code: BOO), hub of regional flights for the Helgeland coast, Lofoten and Vesterålen. They planned the overflights of missile sites at *Sverdlovsk* and *Plesetsk* and of the treatment site of plutonium in the industrial zone of *Mayak*. Two and a half hours after takeoff the U-2 was shot down by surface-air missiles (SAM) launched from a base in southern Russia, and, as is well known, after parachuting Powers was kept by the Soviets. From the need to reduce the radar cross-section of the U-2 (which in reality, early in 1956, was detected and tracked at the height of 20 km in the sky above *Smolensk* by a Soviet radar) the first stealth techniques (project *Rainbow*) born. Quickly, the Americans understood that low orbit satellites were preferable, first with optical and then with radar sensors, in order to cover vast territories such as the Soviet one. In a single orbit a satellite of the *Kennan* "Keyhole-class" (KH) reconnaissance satellites type could monitor an area equivalent to forty U-2 missions taking photos at decimetre resolution. In spite of that, the very successful U-2, in various subsequent versions, has served for over fifty years (till 2012).

[9] Merrill I. Skolnik, the author of the well-known book "Introduction to Radar Systems" [Sko 01], said that the digital processing was a "silent revolution" in technology: the engineers were too committed to developing and applying it to have any time for advertisements, and the passage from the analogue to digital, which took place in radar systems well before telecommunication systems, came "without fanfare", which is a noticeable and, unfortunately, rare situation nowadays.

[10] The manual of the radar, dated January 1943, can be found at http://www.researcheratlarge.com/Ships/Misc/FCR-Mk8/. The radar got noticeable performance, with an instrumented range (with accurate distance measurement) of 45000 yards (about 41 km), and a range resolution of 45 m. The azimuth scan of a 30° sector up to 10 times per second was obtained by phase shifters acted by an electric motor. The azimuth resolution was 2°, with 0.1° accuracy. The antenna was made up by three rows of radiating elements, each with 14 "polyrod" radiators, for an overall size of 4.20 m × 1.20 m; the mechanical scanning in elevation could be adjusted from $-20°$ to $+55°$.

[11] After the war, the Soviets found themselves ahead the Americans concerning the missiles and astronautics (it is well known that the first artificial satellite was the *Sputnik*, launched on October 4th, 1957 from the *Baikonur*

cosmodrome, in the today's Kazakhstan), and concerning the technology of launchers and of long-range missiles, dating back to the work by of Wernher von Braun group on *Projekt Amerika* (the prototype of a long range version of the V2 missile, capable of reaching, from Germany, New York and other American cities). Before developing their own intercontinental ballistic missiles (late 1950s), the American military strategy was based on a new bomber capable of carrying nuclear bombs on the Soviet territory, i.e. the well-known B-52 *Stratofortress*, studied by Boeing since 1946. With the B-52, the US Administration gave the world a further manifestation of the *Americanpacifism*, given the purely offensive nature of the aircraft. The first prototype of this gigantic aircraft (equipped with eight engines with a thrust of 17,000 pounds each) flew in 1952. As many as 744 B 52's were produced in successive versions: in 2010 the B 52 H was still operating.

[12] In reality, the system was an intermediate structure between a passive phased array and an active one, as, instead of one transmitter for each radiating element, it had a set of transmitters, each one feeding a group of radiating elements. Specifically, there were 96 TWT-based transmitters, each supplying 160 elements of the array. Therefore, the active elements summed up to 15360 to which more 19408 dummy elements were added. The latter were placed with a higher density at the edges of the array and with a much lower density near its centre, according to the concept of "thinned array". The *Cobra Dane* had a considerable transmitted power i.e. 15.4 MW peak, 0.92 MW average: the TWT worked with a duty cycle of 6 %, and the radar used pulse compression with a very high compression ratio, more than 10000:1, with radar ranges of over 2000 nautical miles (3700 km). Although somewhat ancient, a so cumbersome and challenging system is not easily dismounted: in 2010 a modernization program of both the hardware (receiver, signal processing, data processor, displays) and the software was in progress.

[13] One of the noticeable pioneers of this field was Sid Applebaum, perhaps the first scientist who understood (and verified via computer simulations) that if each element of a phased array is controlled in amplitude and in phase, then, in principle, the entire radiation diagram can be adapted in order to suppress interference coming from the side lobes, even with many simultaneous jammers. Of course, the implementation is not easy since one must comply with other radar requirements, and to deal with several factors such as the finite bandwidth, the mismatch in amplitude and phase of the channels and the mutual coupling between the elements of the array. The results of Applebaum's and other's works were published in a special issue of *IEEE Transactions on Antennas and Propagation* dedicated to Adaptive Arrays (September 1976, Vol. AP-24, N. 5).

[14] In the acronym STAP: (1) "Space" denotes that coefficients, computed in real time, define an antenna pattern that, ideally, has nulls in the direction of the jammer; (2) "Time" indicates that the coefficients, or weights, which are applied to subsequent samples of each element of the array define, in the

coherent processing time interval, an impulse response (and thus a response in the Doppler frequency domain) capable of minimizing the contribution of the clutter, whose spectrum is made complicated (with respect to the case of non-moving radar) by the motion of the platform and the specific pointing and diagram of the antenna; (3) “Adaptive Processing” refers to the calculation of the coefficients in real time on the basis of the real nearby clutter and jammer situation. In essence, the coefficients are derived from an estimate of the space-time covariance matrix obtained from independent samples (typically, related to different range cells) of the disturbance (i.e. clutter plus jammer plus noise). Each of these samples is a vector whose size is the product of the number of elements in the array by the number of samples (pulses) in the coherent processing time. The steps of the STAP processing, in synthesis, are: (a) Estimation of the parameters of the disturbance (covariance matrix) and of the expected targets (amplitude and phase), (b) Computation of the coefficients vector on the basis of the covariance matrix of the interference, (c) Computation of the inner product between the coefficients vector and the vector representing the received signal for the pertaining resolution cell (cell under test) and finally (d) Detection by comparison of the modulus of the inner product with an appropriate decision threshold, dependent on the acceptable rate of false alarms.

[15] The following platforms are (all or partly) equipped with AESA radars (from the production line or by update/upgrading): Boeing *F-15C*, Lockheed Martin *F-22*, Mitsubishi *F-2*, Boeing *F/A-18E/F*, Lockheed Martin *F-16E/F* (Block 60), as well as (planned or running programs): Saab *JAS-39 Gripen*, Dassault *Rafale*, Eurofighter *Typhoon*, Lockheed Martin *F-35*. AESA Radar are also produced in Russia, where the most recent is the *Sukhoi T-50* with about 1500 transceiver modules, and follows the *Phazotron Zhuk-AE* of the MiG-35, and in China, with the radar of the *J-10 B* aircraft developed by the *Nanjing Research Institute of Engineering Technology* (NRIET). The Japanese started—in 2012—the development of the missile AAM-4B for the *F2* fighter, equipped with AESA radar. Compared to the previous version AAM-4, the new missile can be launched from a distance greater than 20 % thanks to the increase of 40 % of the guidance range. In turn, the increase in range of the missile has been made possible by its new *seeker* using AESA technology (see: Aviation Week & S.T., February 27, 2012, pp. 27–28).

[16] As a follow-on of *EMPAR*, Italy has developed his own surface-based AESA radar. In early November, 2011 it was announced that Selex ES (at that time, *Selex Sistemi Integrati*), a Finmeccanica company, has been awarded contracts to supply a *KRONOS* radar system to both the Royal Thai Navy and the Royal Thai Air Force. The system to be supplied to the Royal Thai Air Force will be installed in the eastern region of Thailand for the Royal Thai Air defence system. The system to be supplied to the Royal Thai Navy will equip the Royal Navy Air and Coastal Defence Command. In 2000 Selex ES began the development of transceiver modules (TRM’s) in C-band. The development was completed in 2003 with a first partial array prototype

tested, validated and accepted by the customer, as a basis for the next active phased array antennas. The industrialization phase took place from 2004 to 2005. In 2010, the first KRONOS Naval was installed aboard the Abu Dhabi ASW Corvette for the United Arab Emirates. At 2013, 8 KRONOS Land, 7 KRONOS Naval and 3 KRONOS MFRA were globally installed.

[17] In the framework of meteorological radars, for ancient tradition, the International System (S.I.) is not strictly used, starting from the trivial fact that the rain rate (or *rainfall rate*) R is always expressed in millimetres per hour instead of meters per second. In the field of validity of certain reasonable approximations, the radar reflectivity of rain per unit of volume is proportional to the sum of the sixth powers of the diameters of the hydrometeors contained in a unit volume. This quantity, indicated by the letter Z, is expressed in millimetres to the sixth power per cubic meter (mm^6/m^3) rather than in the S.I. unit of cubic meters; if the International System would be used, the numeric values for Z would be very large, precisely 10^{18} times larger.

[18] The first studies of the so-called *Drop Size Distribution* (DSD) date back to much earlier and are due to Lenard (1904), Humphrey (1929), and, finally, Laws and Parsons (1943), which used sheets of napkin paper, a type of "recording" then very used at those times! Exposed to the rain for the required time, the sheets kept track of the diameter of the drops; from the measured diameters, histograms were done. With both scales being logarithmic, the histograms approximated quite well straight lines. Since both the reflectivity Z that the rain rate R depend on the distribution of the diameters of the drops, it is evident a Z-R "law" that must exist for a given type of precipitation. The most well-known law of this type is the celebrated one by Marshall and Palmer (1948), still used today (although there are many others). In spite of the deliberate lack of formulas in this volume (*it is said that each formula in a book will half the number of copies sold, but hopefully this prediction is not true for the end-notes*), we cannot waive to report this law here: $\boldsymbol{Z = 200 \cdot R^{1.6,}}$ with Z in mm^6/m^3 and R in mm/h.

Although less celebrated than the researchers mentioned above, a pioneer of radar meteorology was John Walter Ryde (1898–1961), a scientist many years ahead his contemporaries and little, or not at all, recognized by them. In his works in the period 1941–1966 (he carried some of them with his wife Dorothy) he developed the theory of radar waves attenuation and scattering by meteorological phenomena at centimetre wavelengths, arriving to calculate by hand the *back-scattering cross-section* on the basis of the theories formulated by Rayleigh (1871), Mie (1908), and Gans (1912).

[19] The *klystron* is a free electrons, linear beam and resonant cavity type vacuum tube. It was invented shortly before W.W.II by the *VarianBrothers* (Russel and Sigurd Varian from the *Stanford University* were the founders of the well-known Company) and can be used as an oscillator or as a microwave amplifier. In the latter case, which is of interest here, one must know that the resonant structure limits to a very few percent, or even less,

the bandwidth of the device. This feature, which may be a problem for military radars (as they must be able to vary their frequency as a function of the external interferences), is not a problem for a weather radar. The klystron, used as a power amplifier, has the remarkable ability to maintain the coherence of the amplified signal: therefore the output signal can be controlled in frequency and in phase with a very high degree of stability and spectral purity, as needed for the Doppler analysis.

[20] In 1957 professors Langleben and Gaherty from the *McGill University* in Montréal (Canada), starting from the widely used PPI display, developed a scheme of antenna scan permitting to vary the elevation angle and to store the data related to a predetermined height above the ground at different distances. They thus succeeded to organize data in series of *circular rings* at increasing distances from the radar and at a chosen height. This organization, and the display said CAPPI (*Constant Altitude* PPI), in many cases best satisfies the needs of radar meteorologists. Currently, the remarkable developments in the information technology allow for the visualization of a large amount of "products" of weather radars (*CAPPI*, PPI of the *maximum intensity above a fixed altitude*, *Range-Height Indicator*, and so on).

[21] The magnetrons for marine radars are from two manufacturers only (namely, the *English Electric Valve*, E2V- which began in the early 1940s as a part of the Marconi group, manufacturing magnetrons for defence radars—and the *Japan Radio Company*, JRC). The widely used 4, 6 and 10 kW magnetrons cost a few hundred dollars only, with slightly higher prices for the high power (25 or 30 kW) ones. Like most high-power electronic tubes, magnetrons are intrinsically low-life, with a MTBF (Mean Time Between Failures) of the order of a few thousand hours, 3000 h typical, calling for a yearly (or more frequent) replacement. Hence, their large production rates and low costs. Most of commercial magnetrons work on the nominal 9410 MHz (in practice, 9380–9440 MHz) band, while others work on the "historical" 9375 MHz. In fact, international regulations limit the operating frequencies of marine radars to the 9.3–9.5 GHz portion of the X-band, and to the 2.9–3.1 GHz portion of the S-band, (mostly used in the 3020–3080 MHz band) in large vessels when the performance in the X-band is too much limited by rain clutter and attenuation. Nearly all producers of marine radars are selling, or going to sell, new versions of their products with a solid-state transmitter, claiming technical and operational advantages over the magnetron, first of all, the fact that solid state transmitters have a much longer (order of 50,000 h) MTBF. However these transmitters have also a 200–500 times larger duty cycle, i.e. occupy a correspondingly longer time, [Har 08], [Gal 14p]. Therefore, important interference must to be expected when solid state marine radar will be in widespread use.

[22] An example of low-cost marine radar is Radar 3000 by Japan Radio Co. Ltd.; designed for small vessels and pleasure boats, operates on distances between 1/8 nautical mile and 24 nautical miles, i.e. 230 m to 44 km. The operation control uses a joystick and the display is on a monochrome liquid

crystal monitor. Working at X-band, has a pulse duration of 0.08 μs, a peak power of 4 kW and an antenna main lobe wide 6° in azimuth and 25° in elevation; the full scale is selectable between ¾ of a mile, 6 miles and 24 nautical miles. The antenna has a revolution speed between 24 and 27 rpm.

[23] An example is the system by *Bosch* called “Predictive Safety System” (PSS), which has grown in three stages. *PSS1* (introduced in 2005) is a *preparation of the brakes*, which apply their maximum braking capacity without delay when the pilot puts them in action after the long-range radar has identified a possible threat. *PSS2* (2006) provides, in addition, an alarm (acoustic and optical) for the pilot and a contemporary, short, intense braking, while the ensuing *PSS3* (2010) provides for the automatic braking when the system evaluates that the collision is not avoidable otherwise. It is easily understood that such systems have created considerable problems in terms of certification, validation, and legal liability.

[24] These actions include the traction of safety belts or a braking alarm. In enhanced versions, still under study, the radar system also works for the safety of those who are not on board of the car: it recognizes the pedestrians and cyclists as “soft targets”, and if time is critical for the avoidance action by the driver, the system automatically brakes.

[25] The traditional 76–77 GHz band for the LRR was allocated to the automotive uses in the 1990s in Europe with the *ETSI EN 301 091*; it is currently allocated for the Intelligent Transport Services (ITS) in Europe, North America, and Japan. For the automotive short-range radar (SRR) in Europe, a *permanent* frequency band (centred on 79 GHz, more precisely, 77–81 GHz, according to the decision 2004/545/EC of the European Commission) is allocated, as well as a *transient* one (i.e. limited to the period from mid-2005 to mid-2013, and centred on 24 GHz—more precisely 21.65–26.65 GHz—where there are other systems capable of interference). In the United States, the Federal Communications Commission (FCC) has established, since 2002, the use of the 22–29 GHz band for the UWB SRR in North America, with the radiated power limit of −41.3 dBm/MHz. It is expected that, in the medium term, the US and Japanese manufacturers will pass from the range of 24 GHz to that of the 79 GHz like the European ones.

[26] The means to mitigate these adverse effects are the aim of a study funded by the European Union (2011–2012), i.e. the MOSARIM (which stands for MOre Safety for All by Radar Interference Mitigation). However, presentations of the MOSARIM results in public meetings and radar conferences included only general principles for interference rejection in radars, nothing specialized nor directly useful to the co-existence of numerous automotive radars in a few hundred meters. Like the suppliers of solid-state marine radars, it seems that those of automotive radars, while being happy to receive the European funding for the related studies, in reality prefer to “forget” the problem and to increase their sales first of all. A description of automotive radars produced by Bosch, Continental, TRW, Delphi and Hella is in [WHW 09].

Credits for Images

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29	Fig. 2.24	The destroyer Fuciliere, equipped with the radar E.C.3-ter "Gufo" from January 1943	Private collection by Erminio Bagnasco
30	Fig. 2.25	A detail of the tower of the Battleship Littorio, end of 1941. The large antennas of the RDT prototype E.C.3-bis embarked for experimental purposes are visible, with the "horns" for transmission and reception	Erminio Bagnasco – Le armi delle Navi Italiane – Ermanno Albertelli editore - 1978
31	Fig. 2.26	Operating console for the control of radar Gufo and G.III, built by Galileo-Firenze (the polar oscilloscope: by SAFAR- Milan)	Museo nazionale della Scienza e della Tecnologia Leonardo da Vinci (Milano)
32	Fig. 2.27	General scheme of the first RDT conceived by Ugo Tiberio, April 27th, 1936	Paolo Tiberio
33	Fig. 2.28	Circuit scheme of the receiver of the E.C. 3-bis/ter, June 17th, 1941	Paolo Tiberio
34	Fig. 2.29	Circuit scheme of the transmitter of the E. C.3-bis/ter	Paolo Tiberio
35	Fig. 2.30	Prof. Ugo Tiberio (left) and Dr. Bianucci during the meeting on November 8th, 1976 at the firm Contraves Italiana (now Rheinmetall-Italy), Rome	Paolo Tiberio
36	Fig. 2.31	The Battleship *Littorio* with the radar Gufo (1941)	Erminio Bagnasco – In guerra sul mare – Ermanno Albertelli editore - 2005
37	Fig. 2.32	The upper part of the tower of the battleship *Italia*, previously *Littorio*, on September 11th, 1943	Erminio Bagnasco/Augusto De Toro - Le navi da battaglia classe "Littorio" 1937–1948 – Ermanno Albertelli editore - 2008
38	Fig. 2.33	The battleship *Littorio* with the *Gufo* radar (September 1943)	Erminio Bagnasco – In guerra sul mare – Ermanno Albertelli editore - 2005
39	Fig. 2.34	Siting of the antennas of the radiotelemetri E.C.3-ter "Gufo" and of the first experimental apparatus on board the battleships of "Littorio" class (Drawing by M. Brescia)	Erminio Bagnasco/Augusto De Toro - Le navi da battaglia classe "Littorio" 1937–1948 – Ermanno Albertelli editore - 2008
40	Fig. 2.35	The destroyer *Legionario*, first Italian unit equipped with an operational radar, photographed on May 18th, 1942	Erminio Bagnasco – In guerra sul mare – Ermanno Albertelli editore - 2005
41	Fig. 2.36	The Cruiser *Scipione Africano* with the radar *Gufo* (October 1943)	Erminio Bagnasco – In guerra sul mare – Ermanno Albertelli editore - 2005

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43	Fig. 2.38	The Cruiser *Luigi di Savoia Duca degli Abruzzi*, in 1944, with on board the German radar FuMO 21 G	Erminio Bagnasco – In guerra sul mare – Ermanno Albertelli editore - 2005
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48	Fig. 3.4	(a) The search naval radar CXAM-1 installed on the battleship Pennsylvania (BB 38) in the arsenal of Sea Island (S. Francisco), February 3rd, 1942; (b) drawing of its antenna	Storia Militare n. 139 – Albertelli Edizioni Speciali AES - 2005
49	Fig. 3.5	A Cavity Magneton: (a) general view, (b) photo of a magnetron operating at 10 cm wavelength, and (c) the inner block with eight cavities	Fabio Zeppieri "I radar della 2^ Guerra Mondiale", N. 2/2008 "La Scala Parlante" – A.I.R.E. - ITALY
50	Fig. 3.6	The M-16 n. 8 magnetron—this valve gave 10 W at $\lambda = 16$ cm, with a 15 % efficiency (from [Gut 38]), [BGvG 13])	2013 IEEE
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59	Fig. 3.15	The radar altimeter SCR 518 mounted in a B 17	Gaspare Galati/Sergio Pandiscia

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63	Fig. 4.4	Sir Robert Alexander Watson-Watt	© Imperial War Museums (CH 13862) - IWM London
64	Fig. 4.5	The Chain Home coverage at the height of 5 km at the beginning of the Second World War	Fabio Zeppieri "I radar della 2^ Guerra Mondiale", N. 2/2008 "La Scala Parlante" – A.I.R.E. - ITALY
65	Fig. 4.6	One of the early radar experiments in Brawdsey. The screen shows a flying group of 24 Blenheim bombers coming from the North Sea on November 22, 1938	Fabio Zeppieri "I radar della 2^ Guerra Mondiale", N. 2/2008 "La Scala Parlante" – A.I.R.E. - ITALY
66	Fig. 4.7	Chain Home Low: the interior of a transmitter room at a CHL station	© Imperial War Museums (CH 15196) - IWM London
67	Fig. 4.8	AMES Type 1 CH East Coast, 360 ft transmitter aerial towers at Bawdsey CH station, Suffolk	© Imperial War Museums (CH 15337) - IWM London
68	Fig. 4.9	AMES Type 1 CH East Coast radar installation at Poling, Sussex. On the left are three (originally four) in-line 360 ft steel transmitter towers, between which the transmitter aerials were slung, with the heavily protected transmitter building in front. On the right are four 240 ft wooden receiver towers placed in rhombic formation, with the receiver building in the middle	© Imperial War Museums (CH 15173) - IWM London
69	Fig. 4.10	Radar receiver towers and bunkers at Woody Bay near St Lawrence, Isle of Wight, England. This installation was a 'Remote Reserve' station to Ventnor CH	© Imperial War Museums (CH 15174) - IWM London
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74	Fig. 5.2	Some "Flak Towers", with Anti-Aircraft Artillery and tracking radar	© German Federal Archives (Bundesarchiv) Bild 183-G1230-0502-004 Bild 183-1992-0513-502 Bild 183-1987-0508-502 photografer Pilz
75	Fig. 5.3	The German FuMG 62D "Würzburg" radar, the first radar with sufficient precision to allow batteries to hit an air a target in the absence of optical visibility	© German Federal Archives (Bundesarchiv) Bild 101I-662-6660-27A photografer: Ketelhohn [Kettelhohn]
76	Fig. 5.4	The radar FuMG 65 "Würzburg-Riese" (Giant Würzburg) with its parabolic reflector of 7.5 m in diameter	© German Federal Archives (Bundesarchiv) Bild 101I-615-2460-31 photografer: Zwirner
77	Fig. 5.5	"Würzburg Riese" and "Freya"	© German Federal Archives (Bundesarchiv) Bild 141-2732
78	Fig. 5.6	Aerial photographs taken by a Spitfire of the RAF on 1941 at Auderville and Bruneval, with the demonstration of the existence of German radar: Würzburg (a) and Freya (b) (a) Low level oblique photo of the "Würzburg" radar near Bruneval, taken by Sqn Ldr A E Hill on 5 December 1941. Professor Jones described these photos as classics of their kind, which enabled a raiding force to locate, and make off with, the radar's vital components in February 1942 for analysis in Britain (b) Low-level aerial reconnaissance photograph of the 'Freya' radar installations at Auderville, taken using an F.24 side-facing oblique aerial camera	© Imperial War Museums (C 5477) (D12870) - IWM London
79	Fig. 5.7	Reel of aluminium foil	© Imperial War Museums (AIR 265) - IWM London
80	Fig. 5.8	A factory worker producing code-named "Window "(Chaff), foil which was dropped by allied aircraft to jam enemy radar	© Imperial War Museums (E(MOS) 1451) - IWM London

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82	Fig. 5.10	The German passive radar Klein-Heidelberg Parasit—The operating scheme and the receiving antenna.	© Imperial War Museums (IWM) London
83	Fig. 5.11	Sir John Turton Randall and Dr. Henry Albert H. Boot (left) in laboratory after W.W.II. Boot has in his hands the anode block of a six-cavities magnetron	2013 IEEE/ Y.Blanchard,G.Galati,P.vanGenderen
84	Fig. 5.12	The first laboratory magnetron by Randall and Boot, with six cavities. It was water-cooled, needed for a vacuum pump and has to be kept between the poles of an electromagnet	2013 IEEE/ Y.Blanchard,G.Galati,P.vanGenderen
85	Fig. 5.13	Sir Henry Tizard. From 1933 Tizard chairman of the Aeronautical Research Committee, was one of the pioneers in the development of the operational radar	© Imperial War Museums (HU 42365) - IWM London
86	Fig. 5.14	The first S-band power magnetron (type E1189) produced by GEC. On the bottom, a picture of the E1189 brought to North America by the Tizard mission in 1940	2013 IEEE/ Y.Blanchard,G.Galati,P.vanGenderen
87	Fig. 5.15	British Magnetron CV1481 (improved version of CV 76C). Nominal 2993 MHz, peak output 450 kW, at PRF = 500 Hz, pulse from 0.7 to 2 μs	© Imperial War Museums (COM 707) -IWM London
88	Fig. 5.16	The AN/CPS-1 Microwave Early Warning (MEW) radar, deployed in time for D-Day on the south coast of England. On the left: the British AMES Type 13 Mk III height seeking radar	National Archives USA—Holly Reed—Photograph Furnished by the USA National Archives—Still Picture Branch
89	Fig. 5.17	Comparison of effective power levels (*Leistung*) between the British and German microwave radars during the W.W.II.	Gaspare Galati/Sergio Pandiscia
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99	Fig. 5.27	(a) Patent by E. Hüttman, (b) some drawings from the patent	Patent
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