Modern Acoustics and Signal Processing

Whitlow W.L. Au
Marc O. Lammers *Editors*

Listening in the Ocean

New Discoveries and Insights on Marine Life from Autonomous Passive Acoustic Recorders

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Series Preface for Modern Acoustics and Signal Processing

In the popular mind, the term “acoustics” refers to the properties of a room or other environment – the acoustics of a room are good or the acoustics are bad. But as understood in the professional acoustical societies of the world, such as the highly influential Acoustical Society of America, the concept of acoustics is much broader. Of course, it is concerned with the acoustical properties of concert halls, classrooms, offices, and factories - a topic generally known as architectural acoustics, but it also is concerned with vibrations and waves too high or too low to be audible. Acousticians employ ultrasound in probing the properties of materials, or in medicine for imaging, diagnosis, therapy, and surgery. Acoustics includes infrasound - the wind driven motions of skyscrapers, the vibrations of the earth, and the macroscopic dynamics of the sun.

Acoustics studies the interaction of waves with structures, from the detection of submarines in the sea to the buffeting of spacecraft. The scope of acoustics ranges from the electronic recording of rock and roll and the control of noise in our environments to the inhomogeneous distribution of matter in the cosmos.

Acoustics extends to the production and reception of speech and to the songs of humans and animals. It is in music, from the generation of sounds by musical instruments to the emotional response of listeners. Along this path, acoustics encounters the complex processing in the auditory nervous system, its anatomy, genetics, and physiology – perception and behavior of living things.

Acoustics is a practical science, and modern acoustics is so tightly coupled to digital signal processing that the two fields have become inseparable. Signal processing is not only an indispensable tool for synthesis and analysis, it informs many of our most fundamental models for how acoustical communication systems work.

Given the importance of acoustics to modern science, industry, and human welfare Springer presents this series of scientific literature, entitled Modern Acoustics and Signal Processing. This series of monographs and reference books is intended to cover all areas of today’s acoustics as an interdisciplinary field. We expect that scientists, engineers, and graduate students will find the books in this series useful in their research, teaching and studies.

William M. Hartmann
Series Editor-in-Chief

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Preface

Listening in the ocean is not as novel as many scientists and the general public may believe. The US Navy began installing listening stations with limited objectives in the ocean in the early 1950s. The then highly secret Navy's Sound Surveillance System (SOSUS) consisting of arrays of bottom-mounted hydrophones was created to detect, localize, and track Soviet submarines during the cold war. In 1993 the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) was created and a plan was developed to have 11 hydroacoustic stations with bottom-mounted sensors to detect seismic and acoustic waves from nuclear detonation any place in the world. These hydrophones cabled to shore stations have been located in remote locations around the world since 1997. Many current passive acoustic monitoring tools evolved from the work of geophysicists who used long-term monitoring system of bottom-mounted low-frequency seismic sensors. They were able to detect blue and fin whales that emitted very low-frequency sounds between 10 and 20 Hz. The work of these geophysicists led directly to the creation of a variety of passive acoustic monitoring systems that can detect underwater acoustic signals from the infrasonic to ultrasonic range.

Today we know that the ocean is far from a silent world. Thanks to the ever-increasing technological tools available to marine scientists, we know that the ocean is filled with sounds produced by a wide array of biotic, abiotic, and anthropogenic sources. Marine mammals are of course well-known contributors to oceanic soundscapes, but so are many species of fish and invertebrates, as are wind, waves, rain, ice, eruptions, and earthquakes. It is increasingly clear that sound is fundamental to many biological processes in the sea, including communication, sensing, navigation, and orientation. So it is against this backdrop of realization that we have begun to consider the role of another source of sound: the rapidly increasing levels of human generated noise in the ocean.

We are still only at the beginning of our efforts to understand how all the contributors to marine soundscapes interact and ultimately affect life in the ocean, but we have made considerable progress worth noting and discussing. The convergence of new knowledge, new technology, and an increasing concern for marine habitats led to an unprecedented rise in interest in listening to the sea over the past decade.

As it became clear how important sounds are in the marine environment, scientists and engineers began intensive efforts to develop new tools and to record marine habitats throughout the world. In this book we have collected the experiences of several of the researchers who pioneered this recent revolution in marine acoustic investigation. We are well aware that the number of contributions and contributors to this field of research is increasing almost daily, so this book will eventually only be a reference point of where the state of the art stood during the middle part of this decade. A similar volume will undoubtedly be necessary only a few years from now. However, for the time being, we believe that the findings and experiences described here represent the cutting edge of the science as it stands today and we hope that you will ultimately agree that sometimes the best way to learn is to listen.

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Chapter 1
Introduction: Listening in the Ocean

Whitlow W.L. Au and Marc O. Lammers

Abstract The use of passive acoustic monitoring (PAM) to detect aquatic life continues to increase because PAM devices can be deployed in remote areas and can operate for months or years at a time in a programmed manner to control the recording time, the duration of each recording, and the time to "sleep" to preserve battery power. This introduction will discuss the early history of these tools, their architecture, their uses, and the organization of this book. The architecture of almost all PAM devices is similar in that a microcontroller is used to manage the analog to digital conversion process, the flow of data from either a buffer or directly into storage, and the mode in which the PAM will be used. There are basically two main modes, a continuous mode in which data are collected continuously and a programmed or duty-cycled mode. Some acoustic tags are designed just for short time applications (hours or several days) and are attached by suction cups on swimming animals. This book contains chapters from different researchers discussing some of the interesting and exciting findings they have made by listening in the ocean.

1.1 Introduction

One of the best ways of studying animals living in an inaccessible environment is to use autonomous remote devices that can sense the presence of animals, their movements, activities, and daily patterns. If information is desired on a 24-h basis then the best type of sensor would be an acoustic recorder that can be programmed to turn on at specified intervals for a specified duration and not be on continuously in order to conserve battery power and storage space. The process of turning a device on at a specified interval is commonly referred to as duty cycle. Various types of autonomous passive acoustic recorders (PARs) have been developed to

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study both marine and terrestrial animals. Another more popular terminology for such devices is the acronym PAM (passive acoustic monitor) although in truth these devices are really recorders. These two terminologies will be used interchangeably in this volume.

Starting around 1994, PARs have been used to study marine mammals in the deep ocean and have unveiled a cornucopia of information and understanding of marine life that had not been known or suspected. The purpose of this book is to share some of the amazing and interesting discoveries of life history and life cycles of dolphins, whales, fish, crustaceans, and other organisms that produce detectable sounds in a single volume. We have assembled the leading experts in this field to elucidate their research and finding. Hopefully, as the use of PARs continues and newer types of PARs are developed with increased capability, this volume will be but the first of future volumes on not only the use of PARs to study marine life but also terrestrial life on our planet.

1.2 Early History

There has been a continual evolution in the development of PARs over the years, but many do not realize that we have our geophysicist colleagues to be thankful in developing the precursor to the modern PAR and pushing the remote recording technology further. Among the various interests of geophysicists is the detection and localization of low-frequency seismic signals that propagate on the ocean floor. In any long-term study, researchers would just as soon deposit a package that can collect data over as long a time period as possible and retrieve the package at a later date to access the data. Byrne et al. (1987) at the Hawaii Institute of Geophysics developed a recording package that would eventually detect the signals of some baleen whales. They developed a special automatic gain control circuitry that provided 132 dB of dynamic range to extend the 40 dB dynamic range of an analog magnetic tape cassette tape recorder (a standard procedure in the HIG Ocean-Bottom Seismometers). The tape recorder motor was slowed down so that 14 days of operation could be achieved with a single C-90 cassette tape. Then a time-delayed circuit was used to sequentially turn on a series of five cassette recorders after a 13-day delay between the turn on of the previous recorder to the next recorder, thus providing 1 day of overlapping data from the previous recorder. The recording system provided 66 days of continuous recordings with an analog bandwidth of approximately 44 Hz.

Duennebier et al. (1987) reported on the low-frequency noise levels, signal-to-noise ratios, and noise sources detected by the geophone system discussed by Byrne et al. (1987). They reported the detection of a “large biological source.” At the time, they were not aware of the characteristics of different baleen whale calls but later Duennebier described the sounds as coming from fin whales (personal communications). Other geophysicists began to report on the presence of baleen whales on various types of bottom-mounted Seismometers between 1994 and

1995 (McDonald et al. 1995; Matsumoto and Fox 1996). The geophysicists' community also continued to devise different methods to gather their data which eventually paved the way to the first generation of modern autonomous remote passive acoustic recorders developed mainly to record the sounds of whales and dolphins.

1.3 The Anatomy of Modern Autonomous Remote Underwater Acoustic Recorders

There are a host of different models and type of autonomous remote underwater acoustic recorders developed by research institutes, universities, and commercial endeavors. Some of the vintage models that arrived on the scene during the 1994–1997 period include the Haruphone (designed by Haruyoshi Matsumoto at the Hatfield Marine Science Center in Oregon), the Lcheapo (developed at Scripps Institute of Oceanography), the Cornell University Pop-up, and the Greenridge bowhead whale recorder (Greene 1997). These were some of the first PARs that moved from a tape technology to microcontroller technology. The anatomy of a typical PAR is shown in Fig. 1.1. Some of the first microcontrollers used were the Tattletale 7 and 8 manufactured by Onset Computers and the CF1 and CF2 from Persistors Instruments, Inc. The hard drive consumes the most power. In some models, the compact flash serves as an intermediate low-power storage device and data are transferred to the hard drive only when the compact flash reaches a

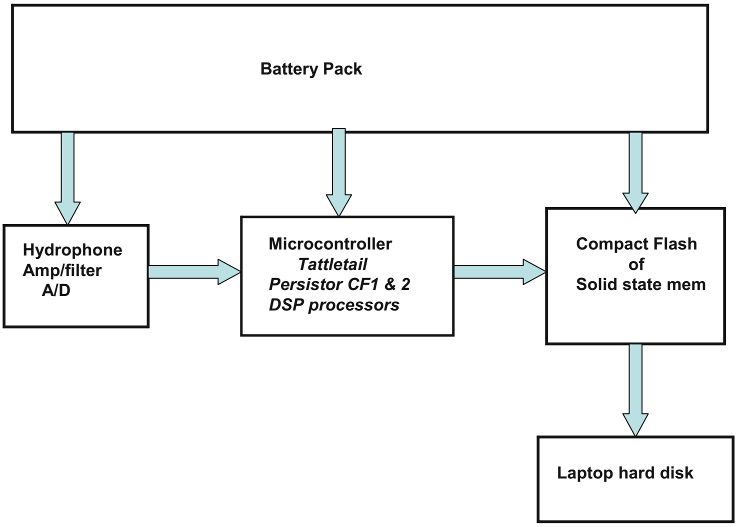

Fig. 1.1 Anatomy of an autonomous remote acoustic recorder

predesigned storage level. This process is important in minimizing the use of the hard drive and conserving power while not losing any data. The Cornell University Pop-up, using a Tattletale 8, was the probably the first system designed specially to capture whale sounds. Today there are a number of different types of PAR that are commercial available or available through different types of agreements between research institutes and university laboratories.

The major differences in the capabilities of the various types of PARs include differences in the sampling rate of the analog-to-digital (A/D) converters, the frequency range of the hydrophones, the amount and type of data storage, power requirements, and size. Some are specialized mainly for certain types of animals while others are more general in scope. Some are packaged in ways that have certain depth limitations; however, the internal electronics can be repackage in more robust housings for deeper depth with hydrophones suited for the desired depth. There is one PAR, the C-POD that does marine mammal monitoring in a totally different manner. The C-POD is designed to detect cetacean click signals and logs the time, center frequency, sound pressure level, duration, and bandwidth of each click and stores the results instead of the acoustic signal. This technique minimizes the amount of storage space needed and can monitor the environment continuously. A small memory size of 4 GB will last for approximately 4 months.

1.4 Examples of Three Early PARs

1.4.1 Cornel Pop-Ups

The Cornell Bioacoustics Laboratory developed an autonomous remote acoustic recorder that can be deployed to a depth of 6000 m and later retrieved by sending a special acoustic signal from the surface to detach it from its mooring, allowing it to pop up to the surface, and hence was given the name "pop-up". The electronics consist of a Tattletale 8 microcontroller from Onset Computer Corp. that has an onboard 8-channel analog-to-digital converter with a throughput of 100 kHz to acquire acoustic data from the hydrophone that is connected to it, with the data being stored on 128 GB of compact flash memory and eventually to hard disks. A schematic of the pop-up subsystems is shown in Fig. 1.2 with the electronics housed in a 17-in diameter glass sphere. The microcontroller can control the turn-on and record phase and the turn-off and sleep phase under software control. Therefore, the battery power can be minimized and the unit deployed for an extended period until either the capacity of the hard drive is reached or the batteries are drained.

A deployed pop-up is connected to an anchor with a stainless steel wire which can be "burned" to release the pop-up form the anchor. Acoustic communications from the surface to the pop-up occur with the use of a surface controller unit and a hydrophone. When the pop-up receives the appropriate signal from the surface, it

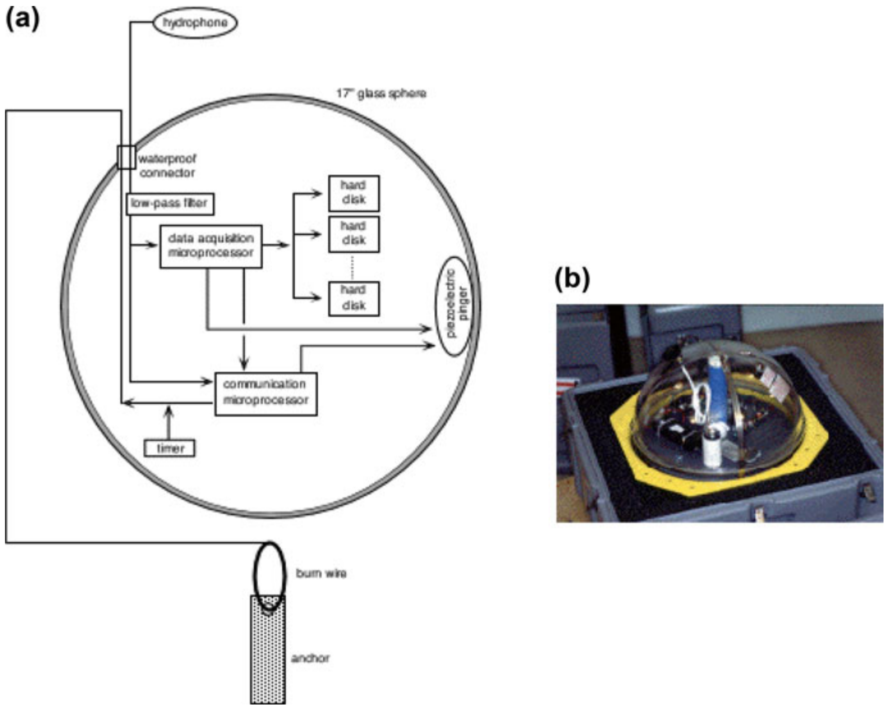

Fig. 1.2 (**a**) Schematic of the "pop-up" and (**b**) a pop-up in a shipping container

acknowledges by emitting its own acoustic response signal. Depending on what signal is sent from the surface vessel, the pop-up responds either with its acoustic response alone, or by triggering the burn wire to release the anchor. A VHF radio beacon is housed with the pop-up unit which will begin transmitting as soon as the unit reaches the surface and the antenna is out of the water. A high-intensity strobe light is also automatically turned on when the device reaches the surface so that the unit can be easily spotted and retrieved. Once the pop-up is retrieved, the unit can be refurbished by removing the hard disk, and downloading the acoustic data to a computer. The information on the disk reformatted or is then erased, the disk reformatted or replaced, new batteries are installed, and the unit is ready for redeployment.

1.4.2 Scripps HARP

Scripps Oceanographic Institute has long been involved with developing remote autonomous seafloor data loggers, mainly for geophysical research, and eventually developed the LCheapo (Tattletale-8 system) around 1998. This trend eventually led

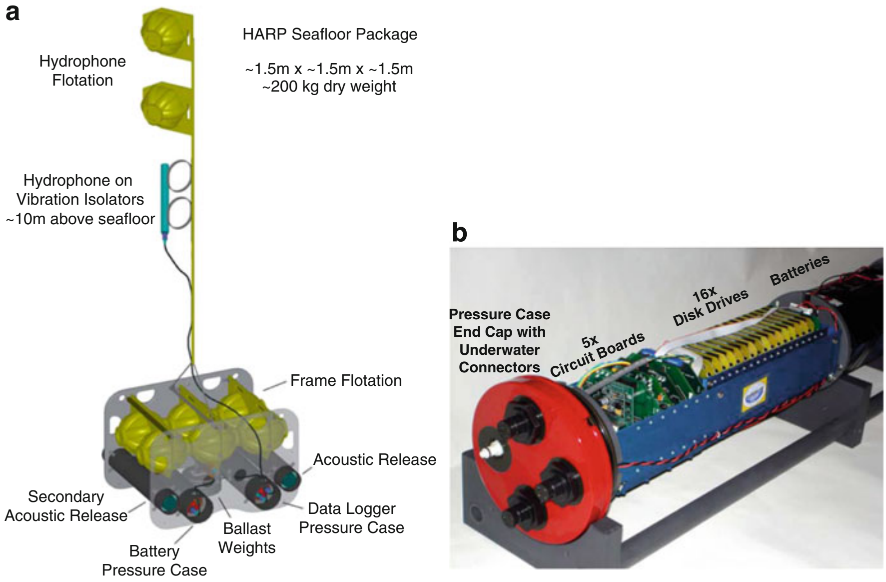

Fig. 1.3 (**a**) A schematic of the HARP system deployed on the ocean bottom, (**b**) the internal configuration of the HARP recording package

to the development of a seafloor data logger for recording baleen whale calls and songs, the ARP (Acoustic Recording Package) in 2003. The ARP sampled at a low frequency of 500 Hz. However, it served as the precursor for the highest sampling rate seafloor acoustic recording system today, the HARP (high-frequency acoustic recording package), to perform continuous long-term monitoring in remote locations under various weather conditions and independent of daylight (Wiggins and Hildebrand 2007). Development of the HARP was motivated by the need for a broader-band, higher-data capacity system capable of autonomously recording toothed whales and other marine mammals for long periods. A picture of the HARP system deployed on the bottom is shown in the left panel of Fig. 1.3 and the HARP module acoustic package is shown in the right panel of Fig. 1.3. The acoustic recorder is controlled by a 32-bit 20 MHz Motorola microcontroller with an Analog Devices 16-bit A/D converter used to digitize acoustic signals detected by the hydrophones. The sampled data are stored temporarily into a data buffer consisting of 16 2 MB SRAM chips until about 30 MB of data are collected and then the data are sent to one of 16 laptop type hard drives for permanent storage via an Ethernet 10BaseT link. A total of 1.92 TB of data storage capacity is available so that 55 days of continuous sampling at a sample rate of 200 kHz can be achieved. Lower sampling rates will allow for longer total recording time and so would scheduled sampling where the recorder is turned on for a period of time between off or sleep periods.

The HARP comes with two hydrophones, one for low frequencies from 10 Hz to 2 kHz and a high-frequency one from 1 to 100 kHz. An International Transducer ITC-1042, spherical omni-directional transducer is used for the high-frequency hydrophone. The low-frequency hydrophone consists of six cylindrical Benthos AQ-1 transducers connected in series for increased sensitivity. A 40-dB gain preamp is used for the low-frequency recordings and an 80-dB gain preamp is used for the high-frequency recordings. Both signals are prewhitened for the frequency variation of typical ocean ambient noise.

1.4.3 HIMB/PIFSC Ecological Acoustic Recorder (EAR)

The ecological acoustic recorder (EAR) was developed jointly between the Hawaii Institute of Marine Biology (HIMB) and the Pacific Islands Fisheries Science Center (PIFSC) and has been used in the field since 2006. It was designed to be a bottom-moored passive acoustic logger with a capability for long-term monitoring of the underwater ambient sound field (Fig. 1.4). The EAR is a digital recorder based on a Persistor™ CF2 microprocessor. It is a low-power system that records continuously or on a programmable duty cycle and is also capable of responding to sounds detected within a pre-adjustable bandpass filter. It offers a maximum sampling rate of 125 kHz.

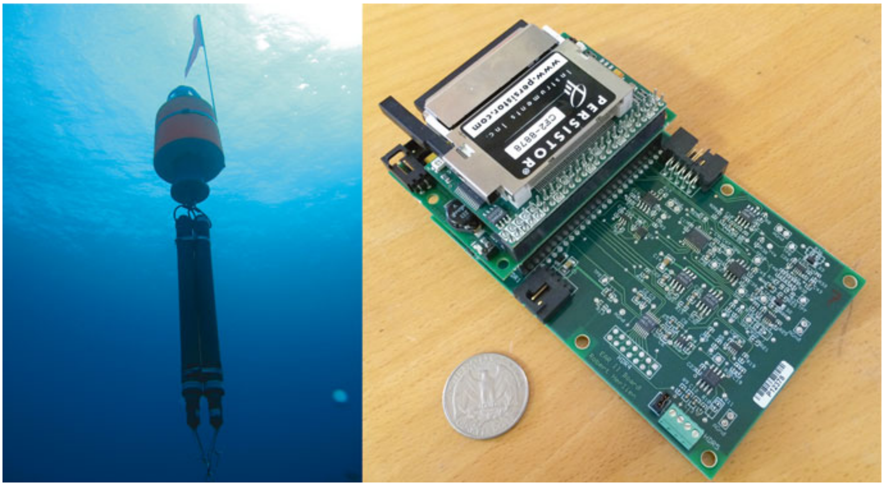

Fig. 1.4 *Left*—EAR packaged for mounting on the bottom of the ocean, *right*—Internal electronics showing a mixed signal preprocessing board with analog amplification-filtering and analog-to-digital conversion controlled by a Persistor CF2 microcontroller

1.5 Acoustic Recording Tags

There is another class of autonomous acoustic recording devices that are small and light enough to attach to animals in the field using support structures that are connected to suction cups. The architecture of such tags is essentially the same as shown in Fig. 1.1 with different microcontrollers and solid state memory.

1.5.1 The Bioacoustic Probe/Accusonde

Many marine animals rely on acoustics to capture prey, avoid predators, reproduce, and navigate, yet we know very little of the type of acoustic signals marine mammals encounter in the open ocean. The ocean is a very noisy environment, especially at low frequencies. In order to measure and record the noise field that marine mammal swims in, Burgess et al. (1998) developed the compact acoustic probe (CAP) which was a data logger controlled by a TattleTale 7 with a 340 Mb hard disk enclosed in a 36 cm long, 10 cm diameter cylindrical hydrodynamic housing capable of withstanding 2000 m depth. It was first used with northern elephant seals to monitor the low-frequency sounds from the ATOC (acoustic thermography of ocean climate) source as tagged elephant seals would swim in the vicinity of the source (Fletcher et al. 1996). These seals regularly haul out on land, allowing easy access for attachment and recovery of instrumentation packages. These animals migrate annually, swimming thousands of kilometers north and west from California and during this migration they experience a wide variety of acoustic environments (Le Boeuf et al. 1993).

Eventually, the CAP gave way to the biological acoustic probe (Bprobe) shown in Fig. 1.5. It combines a hydrophone, pressure (depth), temperature, and acceleration sensors, a data acquisition unit, data storage, and a field replaceable battery in a single, self-contained package. The heart of the Bprobe is a programmable microcontroller chip. A 16-bit A/D converter that can sample the hydrophone output at rates up to 20 kHz and stores the results in a 1 GB flash memory is used. The user can select a hydrophone amplifier gain of 0, 10, and 20 dB. The Bprobe can be programmed to

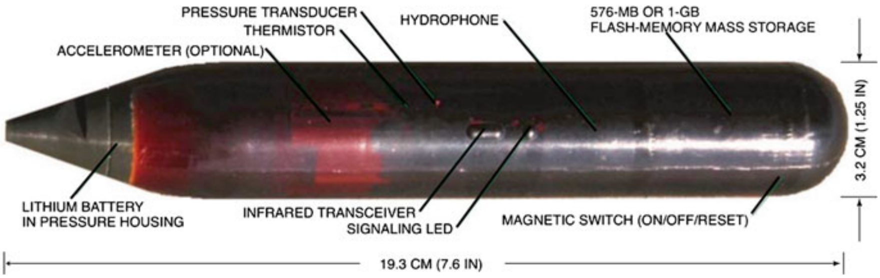

Fig. 1.5 Picture of the Bprobe (courtesy of W. Burgess)

Fig. 1.6 An elephant seal carrying an instrumentation package preparing for its winter migration (courtesy Burney LeBeouf)

sample at specified intervals for a specified duration and between sampling intervals the probe can be put to sleep to conserve battery power. A total of approximately 41 h of operation time can be achieved. The probe is small, light weight, and is encapsulated in polyurethane epoxy. Communication with the probe for setting of the A/D sampling rate and the hydrophone gain are done via an infrared serial link that operates at a speed of 5.3 kB/s.

With this instrumentation package, researchers can determine if diving marine mammals make active sounds, measure the frequencies and levels of sounds diving seals encounter in their environment, and have the acoustic data related to diving behavior of elephant seals (Burgess et al. 1998). A picture of an elephant seal carrying a Bprobe on its back is shown in Fig. 1.6. An example of the acoustic signal received by a seal is shown in Fig. 1.6, with the depth of dive shown above the color sonogram. Most of the received signals had frequencies in the range of 20–200 Hz. Snapping shrimp, cetacean sounds, boat noise, seal swim strokes, and heart beats are clearly audible in some of the data. Flow noise, correlated with swim speed, suggests that optimal time for acoustic sampling would be when the seals are swimming slowly. Results of several deployments have indicated that it is also feasible to obtain long-term, reliable, quantitative, and noninvasive cardiac monitoring of elephant seals and other marine mammals. This capability has been an important bonus to the project.

In 1997, three early versions of the Bprobe were mounted on northern elephant seals just prior to their annual migration from California to Alaska. Two of the packages were recovered after over 4 months at sea (Burgess et al. 1997). The hard disks contained measurement of pressure, temperature, ambient noise as well as acoustic signatures of swim speed, swim stroke rate, respiration, and cardiac function. One subject swam across the northeastern Pacific averaging 58 dives per day with a maximum dive depth of 780 m during the 26 days that the logger batteries supported data acquisition. The other subject swam along the West Coast, diving 81 times per day with a maximum dive depth of 770 m. The results suggest that electroacoustic packages

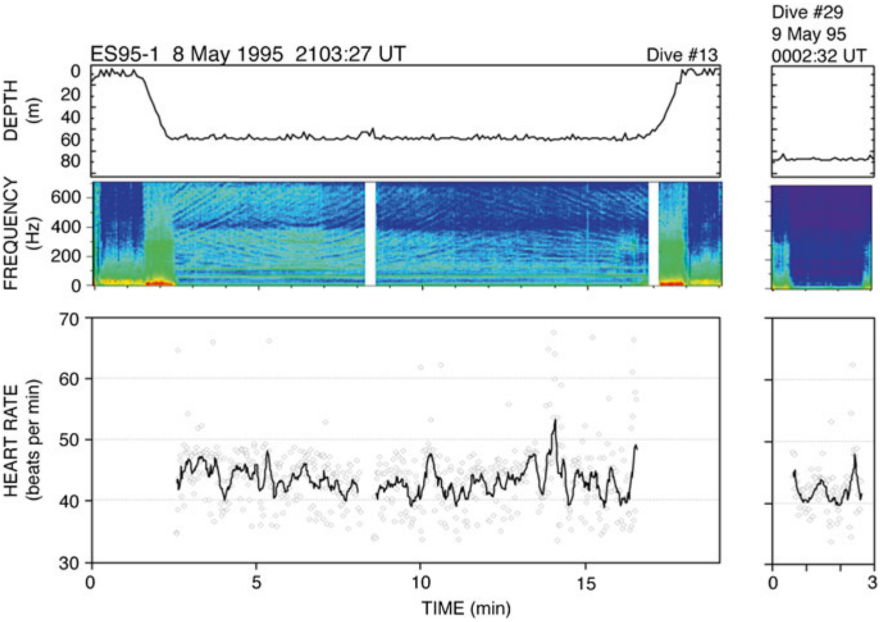

Fig. 1.7 Example of the acoustic signal received by the instrumentation package on a diving elephant seal (courtesy of W. Burgess)

offer a comprehensive and reliable means of sampling acoustic stimuli and associated behavior for free-ranging marine animals over long periods at sea (Fig. 1.7).

A unique application of the Bprobe was devised by Thode et al. (2004) in which a number of them were used as the element of a vertical line array to measure the songs emitted by humpback whales in Australian waters. The use of Bprobes in an array configuration allows for a tremendous amount of flexibility since the sensor spacing can be readily changed and the requirement of a multiconductor power and signal carrying cable is eliminated. In order to utilize this "insta-array," Thode et al. (2004) had to develop a procedure to time-synchronize the recorded data to within a ms or less. The raw acoustic data may be offset in time by several seconds because they cannot be precisely activated at the same time. Thode et al. (2004) first made use of an external broadband signal that would allow synchronization of the probes spaced 3 m apart to with 10 ms, by calculating the cross-correlation function of the signals measured by a pair of probes. They next utilized a global inversion algorithm to maximize the fit between measured acoustic data and the output of a propagation model, a process referred to as "geoacoustic inversion" or "focalization" (Collins et al. 1992). Finally, they were able to exploit the spatial coherence of ocean ambient noise. Providing that the Bprobes are not spaced too far apart, there should be a high correlation of the ambient noise recorded by each probe. The relative difference in timing of each probe can be determined by cross-correlating the signals from each probe with the other probes in the array. The tilt in the line array caused by current was also monitored so that correction for tilt could be made.

1.5.2 Digital Acoustic Recording Tag: D-tag

Another successful acoustic tag or probe that was developed by Mark Johnson at Woods Hole Oceanographic Institute (Johnson and Tyack 2003) is called the D-tag. It has a complementary function to the tag developed by Burgess. It too uses a DSP module to control acoustic data acquisition and storage as well as the measurement of various parameters such as acceleration, depth, temperature, orientation, and magnetic field strength. The principle differences between the Bprobe and the D-tag are imbedded in the design objectives of both tags. The Bprobe was designed to be deployed over a long period of time in the order of months and be used with animals that emit low-frequency sounds and encounter low-frequency noise. The D-tag was designed to measure high-frequency sound emissions on a continuous basis for a short period of time in the order of several hours. Sampling rates as high as 196 kHz for a 12-bit A/D have been achieved with the D-tag and still higher sampling rates are being considered (Tyack, personal communications). The D-tag was designed to be flexible in terms of modifications and therefore not necessarily "user" friendly except to a small cadre of well trained users. The Bprobe sacrificed flexibility for user friendliness and simplicity in operation. The D-tag is packaged in a bag of oil so that modifications can be done as needed. A picture of the D-tag electronics is shown in Fig. 1.8. A complete tag with suction cup mounts is shown in Fig. 1.9. A burn-wire attachment between the housing and the suction cup is used to release the vacuum seal so that the tag can be released off the animal.

The Dtag has been used with northern right whales, sperm whales (Johnson and Tyack 2003), Blainville's beaked whales, *Mesoplodon densirostris*, and Culvier beaked whales, *Ziphius cavirostris* (Johnson et al. 2004; Madsen et al. 2005). The deployment of the Dtags on the beaked whale resulted in some very interesting data, providing extremely important insights into the echolocation process of beaked whale. One Culvier beaked whale performed one foraging dive of 50 min to 824 m. One of the Blainville's peaked whale made six foraging dives to between

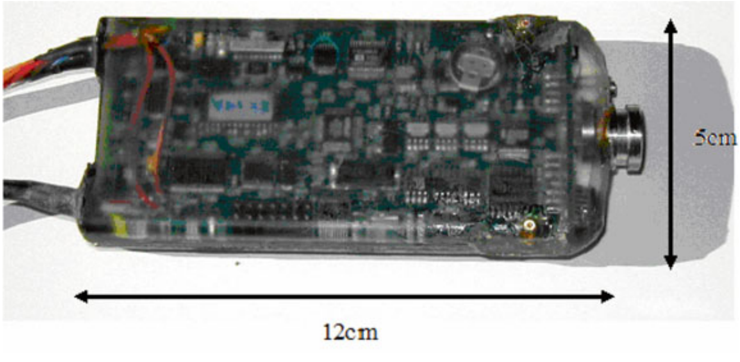

Fig. 1.8 An encapsulated electronic package of the D-tag (from Johnson and Tyack 2003)

Fig. 1.9 Complete tag including plastic fairing floatation and two suction cups (from Johnson and Tyack 2003)

655 and 975 m in 15.4 h while the tag was on the animal. The second Blainville's beaked whale made two deep dives to 730 and 815 m in the 3 h that the tag was attached to the animal. Echolocation signals were not detected until the whales were at least 200 m deep after which they clicked continuously. The *Ziphius* started clicking at an average depth of 475 and stopped clicking when they started their ascent at an average depth of 400 m. The *Mesoplodon* began clicking at an average depth of 400 m and stopped clicking when they started their ascent at an average depth of 720 m. Click intervals during much of a dive varied between 0.2 and 0.4 s. As the whales apparently closed in on their prey, the click rate increased to about 250 clicks/s.

Johnson et al. were also able to record signals that may have been emitted by conspecifics. Two of these signals are shown in Fig. 1.10. The spectra of the two clicks shown in Fig. 1.10 suggest that these beaked whales emit echolocation clicks with peak frequencies between 30 and 40 kHz, and that the spectra of the clicks can extend beyond 45 kHz (the Nyquist frequency of the data acquisition system). These two clicks are the widest band clicks recorded for beaked whales. Besides measuring click from conspecifics, the D-tag has also been able to detect the echoes from prey and other organisms (Madsen et al. 2005). The outgoing signal (measured in the back of the sound source) and the echo from a prey are shown in Fig. 1.11.

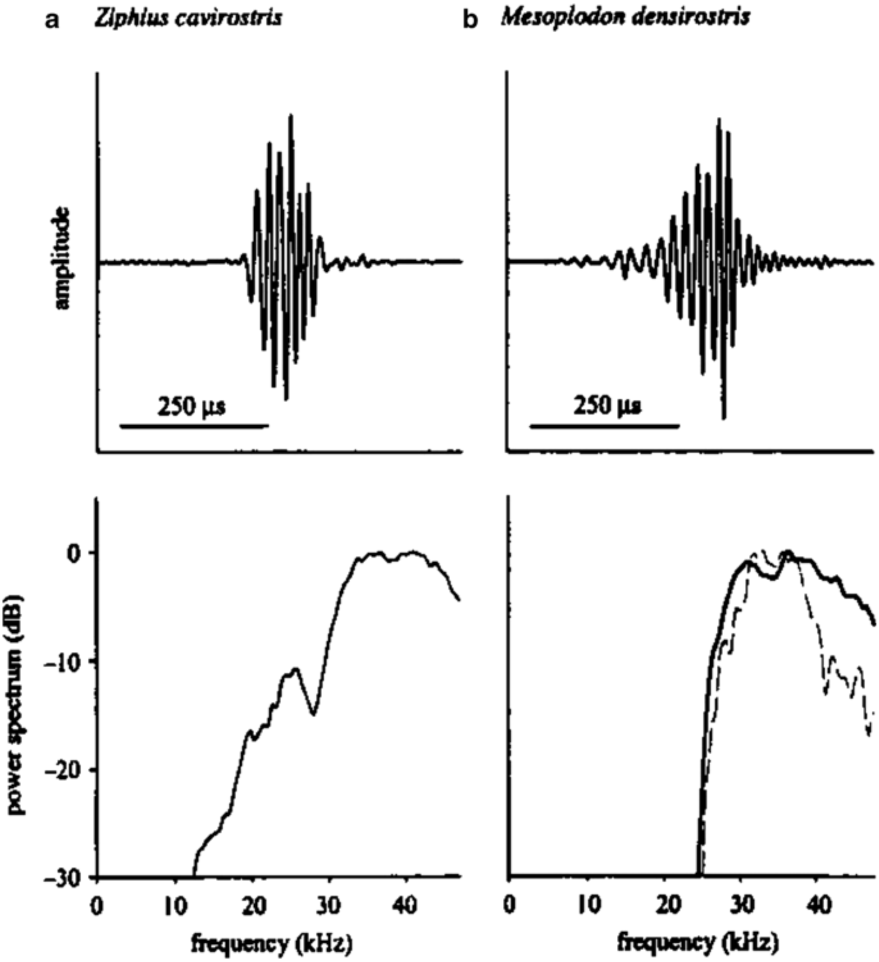

Fig. 1.10 Waveforms and spectra of echolocation clicks seemingly emitted by conspecifics (**a**) *Ziphius cavirostris* and (**b**) *Mesoplodon densirostris* (from Johnson and Tyack 2004)

1.5.3 A-Tag

Akamatsu et al. (2000) used a simple tag to study the echolocation behavior of the finless porpoise (*Neophocaena phocaenoides*) and the Chinese river dolphin, baiji (*Lipotes vexilolifer*). A peak-hold circuit is used to capture the peak output of the echolocation signal and the peak is recorded by a Sony ICD-80 integrated circuit recorder. With this simple device, the time of occurrence and peak amplitude of echolocation signals could be recorded. During nonecholocation periods greater than 1 s, the recorder was turned off to conserve battery power. The data logger was

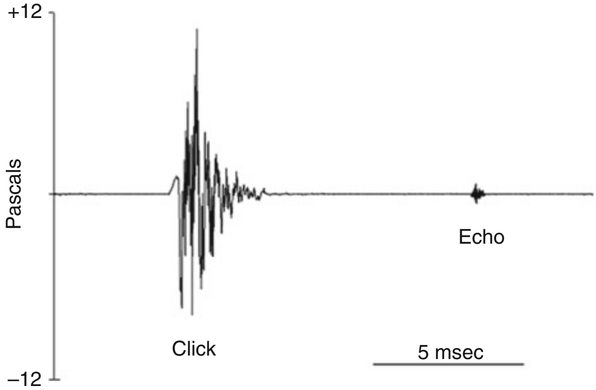

Fig. 1.11 An echolocation signal measured by the D-tag located behind the blow hole of a Blainville's beaked whales (*Mesoplodon densirostris*) and the corresponding echo from a prey (from Madsen et al. 2005)

used by capturing the subject, attaching the tag with a suction cup, and then releasing the animal. A second tag or data logger that measured behavioral information such as depth, swim speed, and the tilt angle of the subjects was also attached to subjects (Akamatsu et al. 2000).

The *A-tag* was originally developed to observe biosonar behavior by tagging on dolphins and porpoises in the wild. In recent years, the *A-tag* has been applied for acoustic transects to count the number of dolphins and porpoises, and for long-term stationed observations. The *A-tag* can be attached on a rope towed from a boat, on a pipe fixed beside a water break, or on an animal using a suction cup. The *A-tag* is enable to record sound pressure at each hydrophone as well as the sound source direction calculated by the sound arrival time difference between two hydrophones (Akamatsu et al., 2005). Identification of each sound source can be used to discriminate each phonating animal individually. The *A-tag* is a small and stand-alone system. The water resistant body of the *A-tag* sizes 21 mm in diameter and 108 mm in length + external stereo hydrophones (see Fig. 1.11). All of the data are stored in the flash memory of the *A-tag* and are downloaded after retrieval. The *A-tag* works up to 40 h by CR2 lithium battery (standard type) and 1 month by two D cells for long-life stationed deployments (optional).The *A-tag* does *not* record the sound waveform. It is an event recorder of each pulse having a sound pressure level over the preset detection threshold level, although the 70 kHz high-pass filter on the *A-tag* rejects undesired low-frequency noise. Chapter 10 by Dr. Tomonari Akamatsu, the driving force in the development of the *A-tag*, will discuss the design and application of the tag with considerably more details (Fig. 1.12).

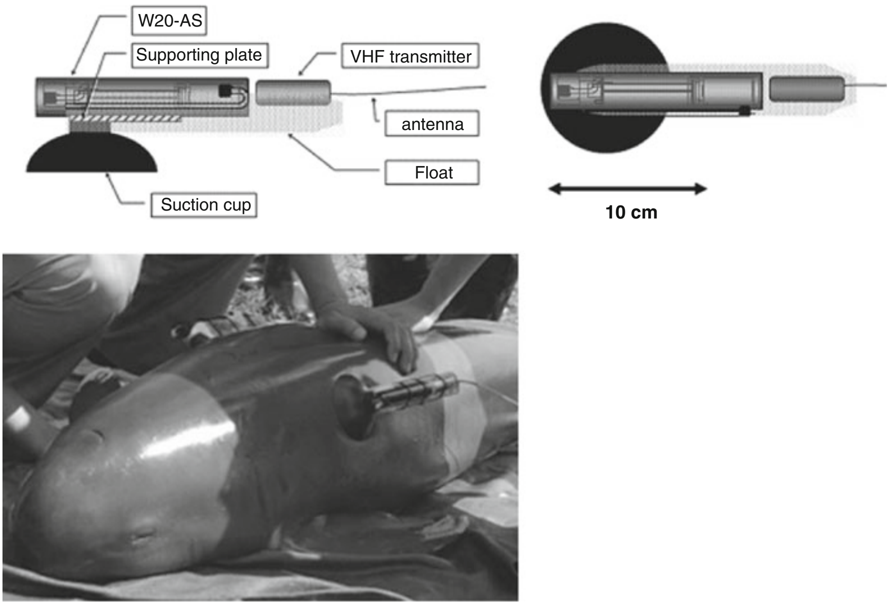

Fig. 1.12 Drawing of one version of the A-tag and its placement on a finless porpoise

1.6 Discussion

1.6.1 Current State of Development

The field of electronics and computer technology continues to expand rapidly, especially in the area of cell phones and mobile devices, and PAM developers have taken good advantage of the new microcontrollers with higher speed, lower power requirements, and more versatility. Coupling this growth with the growth in electronic memory and the development of loss-less data compression algorithms has fueled the development of second and third generation PAM devices. The first generation of PAM devices used laptop hard drives which require almost all the battery power in a PAM device. Today, these laptop drives have been replaced by electronic memory which require considerably less battery power. New microcontrollers have more programmable capabilities so that the microcontroller can perform more functions, including supervision of multichannel data acquisition and data management and data flow. Since about 2010, a host of new PAM devices, too many to list without the danger of excluding some, have become commercially available. These all use more advanced and powerful microcontrollers than the first generation of devices. They all use solid state memory such as SD memory cards which can be stacked to increase storage space. Solid state memories not only use considerably lower power than laptop hard drive but are much faster so that faster data acquisition can be achieved with less of a need for large buffer memory.

The use of single-channel PAM has provided much important data and information and has allowed researchers to gain a comprehensive understanding of how marine mammals utilize their environment. The next step in the development is to have multiple PAM devices that are synchronized so that whales and dolphins can be localized and tracked in three-dimensional space. Drift in the crystals that control the clocks within individual PAM is the major culprit in this area so that multiple PAM devices who's clocks have been synchronized before deployment will no longer be synchronized as the time of deployment increases. One way to handle the synchronization problem is to have a surface buoy extending from PAM devices deployed on the bottom that will receive GPS timing information. However, in many if not most application, having a surface buoy is not desirable because of the danger of damage or theft. Having a cable extending from the ocean bottom to the surface will also present a potential hazard to the marine mammals that are being studied. If a surface buoy is integrated with a PAM device, there is the possibility of near real-time data acquisition using a satellite link or radio transmission back to a land base. In order to utilize radio links, it would be best if the microcontroller could process received data in real time and develop a summary report, such as the number of detections of particular species over a specific time interval while the preprocessed data are stored on-board in electronic memory. In such a system, the amount of data that will be sent via a radio link would be minimized. Such an approach has been taken by use of the Sea-Glider (Klinck et al. 2012). An Iridium satellite transmission was made every time the glider surfaced and directed its tail containing the antenna toward the sky.

1.6.2 Organization of This Book

This book will focus mainly on results of observations of different species of marine animals, with a heavy emphasis on cetaceans recorded in different areas of the world by different devices as in Chaps. 2–14. The second chapter discusses the use of the HARUphone in research on blue whales. The HARUphone was probably the first autonomous portable passive recording buoy used to study animal sounds in the ocean. It was developed for seismic research by scientists at the Pacific Marine Environmental Laboratory of the US National Oceanic and Atmospheric Administration at the Oregon State University Hatfield Marine Science Center. They were first deployed in the Gulf of Alaska as early as spring of 1996 (Matsumoto and Fox 1996; Fox et al. 2001) and it soon became apparent that baleen whale signals, especially blue whales signals, were being recorded.

Another early PAM device developed and deployed in 2000 was the Acoustic Recording Package (ARP) (Wiggins 2003) which was used mainly to study baleen. Like the HARUphone, the development of the ARP had a seismic research origin as seismologists from Scripps Institute of Oceanography realized that baleen whales calls were being recorded on their seafloor array of seismometers (McDonald et al. 1995). The development of the ARP was soon followed by the most sophisticated autonomous recorder, the HARP (high-frequency acoustic recording package) by the Scripps group (Wiggins and Hildebrand 2007). Two noteworthy features of the HARP are its high sampling rate of 200 kHz and its high data storage capacity of 2 TB which included data compression. Some of the results from research using the ARP and HARP are discussed in Chap. 3.

Chapters 4–7 will discuss results obtained with the three different types of PAM devices. Chapters 4 and 5 will discuss signals from marine animals in different ecosystem in the western Pacific. Sounds from snapping shrimp, fish, and odontocetes in a coral reef environment recorded using an EAR will be the subject of Chap. 4, while Chap. 5 will focus on echolocation or biosonar signals used by deep diving odontocetes while foraging. Results from recordings with the Environmental Acoustic Recording System (EARS) buoy mainly used in the Gulf of Mexico will be the subject of Chap. 6. The CPOD and TPOD are PAM devices that operate on a different principle than the devices discussed in Chaps. 2–6. They are designed to detect echolocation clicks within an adjustable band-passed frequency range and the results of their use will be discussed in Chap. 7.

Cabled acoustic observatories have been in existence since the early 1960s for military applications in the form of the SOund SUrveillance System (SOSUS). However, the data collected by SOSUS arrays have not been available except under exceptional circumstances to a civilian scientist. In recent years there have been a number of beaked whale strandings that have been linked to Navy mid-frequency sonar activities (D'Amico et al. 2009) and so the Navy has installed a hydrophone array system entitled Marine Mammal Monitoring on Navy Ranges (M3R) in several Navy underwater ranges in U.S. waters. Chapter 8 discusses some results of detecting and tracking beaked whales with the M3R system.

A unique observatory in Antarctica titled “The Perennial Acoustic Observatory in the Antarctic Ocean” with an emphasis of on pinniped sounds that is a cabled system with a radio link to a base station at which batches of data are transmitted to a home station in Germany via a satellite link will be covered in Chap. 9. This will be followed by a chapter on the seasonal presence of five species of baleen whales in Hawai’ian waters obtained by the Station Aloha Cabled Acoustic Observatory that is moored close to the bottom at 4700 m depth at a distance of about 100 km north of the island of Oahu, Hawaii.

Pinniped sounds recorded in the polar ocean in the artic is the topic of Chap. 11. A Passive Aquatic Recorder (PAL) was used to collect some of the pinniped sounds. The PAL is a unique PAM in that it collected four series of sounds of 1024 points at a sampling rate of 100 kHz (Nystuen et al. 2010). Each sample is separated by 5 s, and the FFT of each series is calculated and compressed to 64 frequency bins and stored on disk. The whole sequence of event required 15 s. The PAL was originally developed to collected ocean environmental acoustic signals.

The sounds produced by deep dwelling fishes are covered in Chap. 12 followed by sounds recorded from benthic shrimp in Chap. 13. Chapter 14 will be devoted to the information obtained with an acoustic tag on different species of dolphins.

The last chapter on signal processing will wrap up this book. The last chapter is especially important since the recorded sounds are only valuable if scientific results can be extracted from them. Therefore, signal processing techniques are the lynch pin that determine the value of passive recording. Most recordings will contain noise and the challenge is to detect and classify sounds in the presence of noise. Noise is a factor in all recordings because sound from animals that are far away will be affected by noise. There is no escape from this and the amount of noise on the recordings will determine how far away specific animals can be detected and identified.

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Chapter 2
A Review of Blue Whale Studies from HARUphones in the Pacific

Kathleen M. Stafford

Abstract The earliest long-term monitoring of low-frequency signals of large whales was via cabled military arrays. These arrays provided valuable new data but were restricted in the locations that were monitored and there was no open access to the data collected. In order to monitor the low-frequency signals of large whales in different areas and over shorter time scales, Haruphones, single hydrophone, autonomous recording packages, were developed by the Pacific Marine Environmental Laboratory of the US National Oceanic and Atmospheric Administration and deployed in the Gulf of Alaska and the eastern tropical Pacific. By integrating the acoustic data from these broadly spaced deployments with other data streams, new discoveries about blue whales in the eastern Pacific Ocean were made. These included establishing the geographic range and migratory patterns of eastern north Pacific blue whales; establishing that the eastern tropical Pacific appears to be a blue whale "hot spot" where as many as four, but primarily three, acoustic populations of blue whales occur; determining that the Gulf of Alaska is a region where eastern and western North Pacific blue whales overlap in space and time; and showing that blue whale calling behavior has a diel pattern whereby animals produce more sounds at night than during the day. In aggregate, these data show that passive acoustic monitoring is a valuable tool for establishing blue whale population identity, determining habitat range, and studying behavioral ecology over long time periods and in remote regions of the ocean.

2.1 Introduction

Many of the first long-term recordings of baleen whale sounds came from military arrays placed in different oceans to listen for the acoustic signatures of submarines (Nishimura and Conlon 1994). Those recordings contained thousands of low-frequency signals of unknown origin. Based on the seasonal occurrence and repetition rates of these signals, they were believed to be produced by "unknown biological

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sources.” As recordings were made in the presence of large whales, these sources were identified as different species of baleen whale. Probably the most written about were the “20-Hz pulses” recorded around the world and later attributed to fin whales (*Balaenoptera physalus*). Second to these were the “long 20-Hz pulses” that have since been identified as blue whale (*B. musculus spp.*) vocalizations. In general, most signals produced by the great whales are relatively long (1–20 s) and of low frequency (<1000 Hz). Although these signals share the characteristics of being low frequency (often overlapping in bandwidth), and therefore capable of long-distance propagation, the best studied stereotyped signals are readily distinguishable to species. The development of “dual use” of the Integrated Undersea Surveillance System (IUSS) allowed scientists access to these acoustic time series (Nishimura and Conlon 1994). This allowed multiple species of baleen whales to be acoustically monitored remotely over great temporal and spatial scales at fixed locations on these ocean bottom arrays (cf. Thompson and Friedl 1982; Clark 1995; Clark and Fristrup 1997; Clark and Gagnon 2002; Stafford et al. 2001; Mellinger et al. 2000; Watkins et al. 2000, 2004; Charif et al. 2001; Mellinger and Clark 2003).

2.2 Haruphone Deployments

In order to monitor seismic signals in other oceans of the world and over shorter time scales, single hydrophone, autonomous recording packages (sometimes called Haruphones) were developed by the Pacific Marine Environmental Laboratory of the US National Oceanic and Atmospheric Administration (Fox et al. 2001). These instruments can be deployed in any ocean of the world, usually in the sound channel. Each instrument is an autonomous recording package that writes acoustic data to an on-board hard drive and is moored in or near the sound channel axis. Unlike long-term cabled arrays, the instrument and mooring hardware have to be recovered in order to access the data. Further, the recording package acquires data from a single, omni-directional hydrophone. By deploying multiple instruments in an array, sound sources can be localized in postprocessing, depending on the spacing of the instruments and the frequency of the signal of interest. Haruphones were designed to be deployed for 1–2 years. Since their development, the sample rate of these instruments has varied from 100 Hz to 2 kHz (0.1–40 Hz and 0.1–970 Hz), and 1–2 byte resolution. The long-term deployments of these instruments have provided surprising new data on large whales from remote areas of the globe, including the Pacific, and illustrate the power of passive acoustic monitoring over broad temporal and spatial scales. In this review, results from the deployment of Haruphones in the eastern tropical Pacific (ETP) and the Gulf of Alaska (Fig. 2.1) are presented with a particular focus on blue whales.

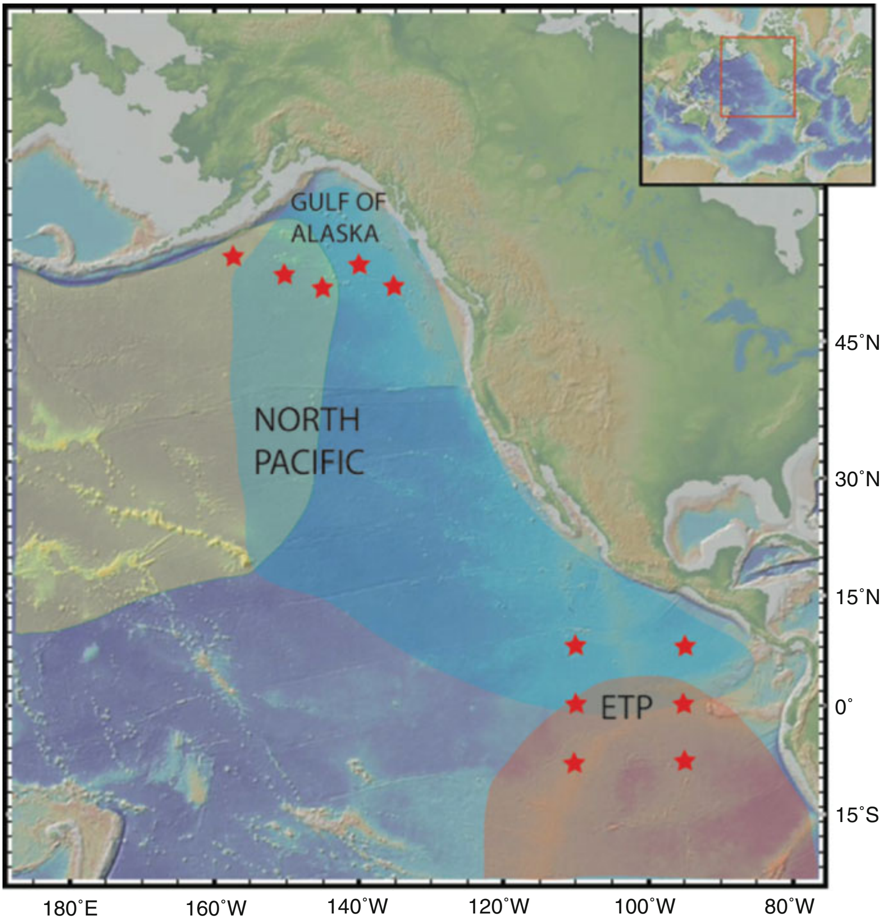

Fig. 2.1 Locations (*red stars*) of Haruphones moored in the eastern Pacific Ocean. *Blue shading* shows approximate distribution of eastern North Pacific blue whales. *Red* and *yellow shadings* show approximate distribution of eastern South Pacific and western North Pacific blue whales respectively. Note the overlap between the acoustic populations of blue whales

2.3 Studying Blue Whales with Passive Acoustic Monitoring

Blue whales are a wide-ranging species found in all of the world's oceans. Their apparent preference for pelagic habitats has made it difficult to assess whether or not over 50 years of international protection has led to increases in populations that were greatly reduced by commercial whaling. The question of the recovery of an endangered species such as the blue whale is important not just because United States law currently mandates recovery, but also because these animals play a role in larger ecological systems (Katona and Whitehead 1988). Monitoring signs of recovery of different populations have been the focus of many research efforts and most of these have involved traditional methodologies such as shipboard and aerial line-transect surveys that are expensive, time-consuming, and restricted by weather and light conditions and, most importantly, the behavior of individual animals. These studies tend to be focused in small areas for short periods of time. For over the past two decades or so, the use of passive acoustic monitoring has become increasingly important in understanding the seasonal and geographic occurrence of large whales.

The use of acoustic detections of whale calls has been useful in providing a very broad view of whale occurrence and seasonality in the Northeast Pacific over relatively long time spans. The advantages of this passive acoustic monitoring include being able to remotely monitor widespread areas at all times of day and year for vocalizations of multiple species and acoustic populations of whales. Additionally, animals are monitored while underwater, where they spend most of their time. Finally, while blue whale calls throughout the world share the characteristics of having long (>10 s), low-frequency (<20 Hz) notes, the sounds they make are geographically distinct such that different "acoustic populations" have been suggested as a means to distinguish among blue whales (Thompson et al. 1996; Stafford et al. 1999a, b, 2001; Mellinger and Clark 2003). Stereotyped call types recorded in the eastern North Pacific (ENP) consist of a two-part phrase, often called AB where the A call is a series of low-frequency pulses and the B call is a long, low-frequency tonal (Fig. 2.2a).

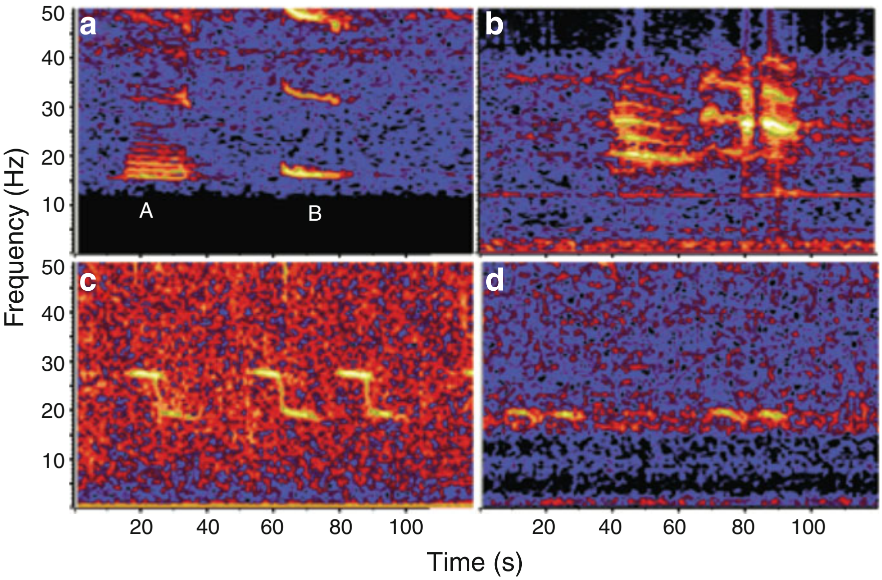

Fig. 2.2 Spectrograms of four blue whale call types recorded in the Pacific Ocean. (**a**) Eastern North Pacific AB phrase; (**b**) Eastern South Pacific phrase; (**c**) Three Antarctic 28 Hz calls; (**d**) Two western Pacific calls. Phrases from ENP and ESP blue whales are multipart, frequency and amplitude-modulated signals whale and those from the Antarctic and the western Pacific are simple, frequency-modulated signals

The eastern North Pacific blue whales are the best studied in the world.

Near shore line-transect and photographic identification studies have been undertaken numerous times off the coast of central and southern California (Calambokidis and Barlow 2004) and provided one of the first postwhaling population estimates for blue whales. It was thought that this population of blue whales ranged only from California during the summer to Baja, California, Mexico during the winter. Acoustic recordings of these animals were all of the northeastern Pacific vocalization type (Thompson et al 1996; Rivers 1997; Clark and Fristrup 1997). This same call type was also recorded off Oregon, Washington and Vancouver Island, Canada (Stafford et al. 2001). Acoustic data, in combination with photo ID and satellite telemetry, have shown that the range of this population is much greater and extends from the equator up to the far northern Pacific.

Blue whales had been seen in the ETP during different seasons and different locations during shipboard surveys in the 1970s–1980s. Initially these sightings were attributed to wintering animals from the California/Mexico stock (Berzin 1978; Wade and Friedrichsen 1979). Because they were seen in the region year-round, it was thought that these animals might be a resident population of blue whales or possible animals from a southern hemisphere population (Reilly and Thayer 1990).

In 1996, the first Haruphones were deployed in the ETP on either side of the East Pacific Rise in order to monitor seismicity in this area (Fox et al. 2001). Six instruments were first deployed in May (Fig. 2.1). Because they were “listening” for high amplitude, low-frequency earthquakes, these instruments were spaced widely apart in three lines at 8° N, 0°, and 8° S and 95° W and 110° W. This spacing was too great to detect the same signal from an individual baleen whale so each of the six locations represents a discreet sampling region. Although the instruments were deployed for a study of seismicity, when the data were recovered, there were whale calls on every instrument, including blue whales.

Northeastern blue whale calls were recorded on the very first day the instrument at 8° N 95° W sampled data and were detected on almost 80 % of the days during the first year of deployment. Detection of these calls was highest from November through May and lowest from June through October (Fig. 2.3). More calls were recorded per day and during more days per month during the northern hemisphere winter and this pattern was complementary to that of the same call type at more northerly latitudes. This correspondence, combined with decreasing detection of this call type at the more southern hydrophones, strongly suggested that at least some of the blue whales seen during visual surveys were from the “California/Mexico” stock, that this population produced AB calls year-round, and that their distribution extended south from Mexico to the tropical Pacific off central America supporting the idea that the ETP might be a possible wintering ground for these animals (Stafford et al. 1999a, b). Presently, in part due to these acoustic results, the population is no longer referred to as the California/Mexico stock and is known as the Eastern North Pacific stock (Carretta et al. 2010).

However, although ENP blue whale call types were recorded in many months of the year in the ETP, they were recorded mostly on a single hydrophone, that at 8° N 95° W in proximity to the Costa Rica Dome. Blue whales had been seen on either

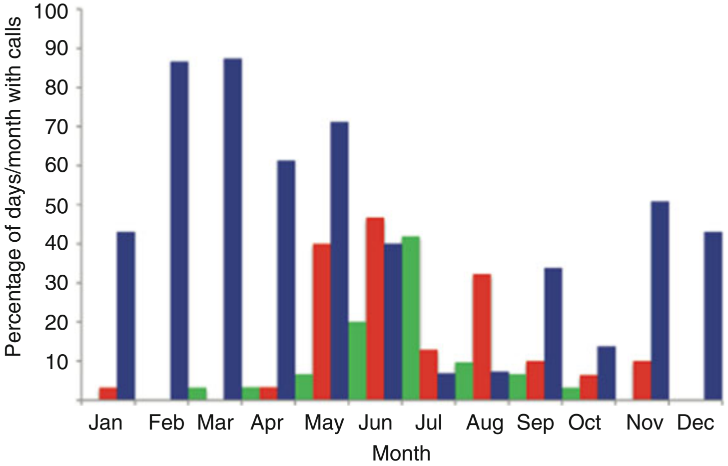

Fig. 2.3 Seasonal occurrence in percentage of days per month with calls for three different acoustic populations of blue whales in the eastern tropical Pacific: eastern North Pacific (*blue*), eastern South Pacific (*red*), and Antarctic (*green*)

side of the equator during shipboard surveys and in months when there were few or no AB calls recorded. A survey of the other five hydrophones in the array revealed the acoustic presence of an additional three call types that have since been definitively attributed to blue whales. The most commonly recorded, after the ENP AB calls, were two call types that closely resembled the signals that were the first blue whale calls ever identified. These were three to four part amplitude-modulated and frequency-modulated notes recorded off southern Chile in 1970 (Cummings and Thompson 1971; Fig. 2.2b) and the recordings from the ETP were the first time these calls had been "heard" since they were first recorded. This "eastern South Pacific" (ESP) call type was recorded most commonly on the hydrophones at the equator and at 8° S 95° W, due south of the equator from the hydrophone that recorded the greatest number of ENP calls. These signals were recorded primarily from March through August (Fig. 2.3; Stafford et al. 1999b). This seasonality is opposite of the ENP calls and, when combined with the location of the 1970 recording, strongly suggests that these are southern hemisphere blue whales that migrate northwards to the ETP during the southern hemisphere winter (Stafford et al. 1999b, Buchan et al. 2014). The different geographic and seasonal patterns of the different blue whale vocalizations identified supported a separation of northern and southern hemisphere animals and showed that each use different regions of the ETP at different times of year and migrate north or south during summer and fall.

The ETP is clearly an area that is an important habitat used regularly by two coastal populations of blue whales that, despite presently considered the same subspecies as most blue whales worldwide (*B m musculus*), are morphologically more similar to so-called 'pygmy' blue whales (*B m brevicauda*). It is also, based on acoustic detections, an area sometimes used by Antarctic blue whales (*B m intermedia*;

Stafford et al. 2004). Unlike the coastal blue whales, Antarctic blue whales repeat a simpler, single FM call that is somewhat higher in frequency than the ENP or SEP calls (Ljungblad et al. 1998; Rankin et al. 2005; Fig. 2.2c). This call type has been recorded around the Antarctic (Stafford et al. 2004; Širović et al. 2009). Antarctic blue whale populations were decimated by whaling in the early twentieth century and presently may be at less than 1 % of their original numbers (Branch et al. 2004). Because most of the whaling was concentrated at high latitudes in the Southern Ocean, nothing was known of the wintering grounds of these animals except that they were believed to migrate northwards (Mackintosh 1966).

Antarctic blue whale calls were detected every year, primarily in July (Fig. 2.3), from 1996 to 2002 at the two southernmost of the six hydrophones in the ETP (8° S 95° W and 8° S 110° W, Stafford et al. 2004). During each year, a large number of calls were recorded over only a few days at a time suggesting that perhaps only a few, vocal animals were in the area during that time. Simultaneous recording of the same call type at low latitudes in the Indian Ocean (Stafford et al. 2004), and near South Georgia in the South Atlantic (Pangerc 2010), demonstrates that there are likely multiple wintering destinations for this population of blue whales.

The ETP is an area in which blue whales have been sighted year-round (Reilly and Thayer 1990; Palacios 1999). Because it is nearly impossible to visually distinguish among subspecies, without acoustic recordings it would not be clear that rather than a resident single population of blue whales, animals from three different populations use this area at different times of year. Although the northern and southern hemisphere populations are somewhat geographically segregated, each occurs near the equator, albeit at different times of the year.

Similar to Antarctic blue whales, blue whales in the far North Pacific, particularly the Gulf of Alaska and along the Aleutian Islands, were hunted extensively such that no animals were seen during shipboard surveys in this region until the mid-2000s. Like the ETP, the population affiliation of whales taken in the North Pacific was unclear. As many as five populations were thought to occupy the whole North Pacific. These included not only the eastern North Pacific discussed above but also northwestern and central Pacific populations as well as an eastern Gulf of Alaska population (Ohsumi and Wada 1973). Acoustic data from cabled hydrophones off Hawaii, in the western North Pacific and the west coast of the United States up to Canada, showed that there were only two different call types recorded in all of the North Pacific: that attributed to the eastern North Pacific population (ENP) and a distinct call type (Fig. 2.2d) that was recorded primarily in the western North Pacific, along the Aleutians, and off Hawaii (WNP call type, Thompson and Friedl 1982; Stafford et al. 2001). From an acoustic population standpoint, it appears that rather than five populations in the North Pacific there were perhaps only two: a western North Pacific population that occurred off Kamchatka, south of the Aleutians and Hawaii (where it overlapped in space but not time with the eastern North Pacific population) and an eastern North Pacific population the ranged from the equator along the west coast of North America to Canada.

To determine if blue whales might still be found in the Gulf of Alaska, and if so, to what acoustic population they belonged, five Haruphones were deployed there from 1999 to 2002 (Fig. 2.1). This was the first deployment of these instruments to

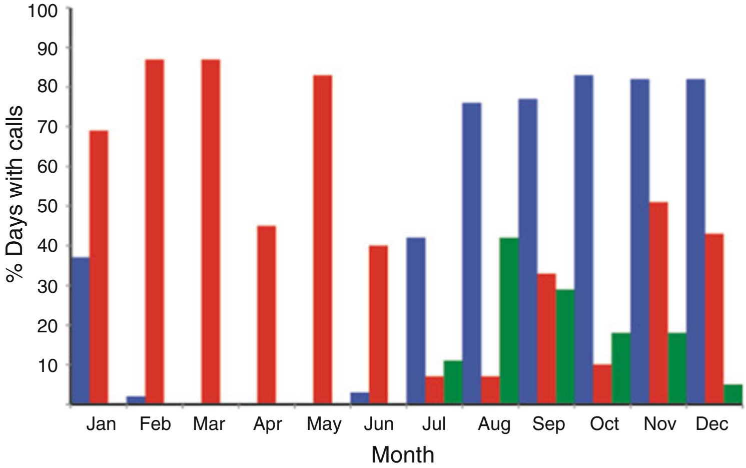

Fig. 2.4 Seasonal and geographic occurrence of ENP blue whale calls in the eastern tropical Pacific (*red*), off California/Oregon/Washington (*blue*), and in the Gulf of Alaska (*green*) in percentage of days per month with calls

specifically monitor for marine mammal vocalizations rather than for geophysical monitoring. As with the data from the ETP, blue whale calls were detected on the first days the instruments began recording. Both ENP and NWP call types were recorded from August to December annually and overlapped in space and time at all locations except on the westernmost hydrophone, closest to the Aleutian chain. Despite this overlap, there was an east–west trend in call detections where NWP calls were recorded more often on the hydrophones west of 145° W longitude and ENP calls were more frequently recorded east of this longitude (Stafford 2003).

These data provide evidence that the range of the eastern North Pacific stock extends into the Gulf of Alaska and thus covers the entire west coast of Central and North America (Fig. 2.4). It also shows that the Gulf of Alaska is a shared habitat for two acoustic populations of blue whales (eastern and western North Pacific) and that there is no “eastern Gulf of Alaska” population.

The overlap of these two acoustic populations in the fall and early winter, which is thought to be the breeding season for blue whales, suggests that acoustic call type differences may be used as population identifiers and/or as an isolating mechanism to prevent interbreeding between these congeners. Globally, for as long as it has been monitored, blue whale song has been relatively stable (but see McDonald et al. 2009 and Gavrilov et al. 2012 for changes in the fundamental frequency of notes) and this stability makes the signals robust for population differentiation. There has only been one documented instance of a hybrid song produced by a blue whale; a single animal in the Gulf of Alaska combined WNP and ENP units in a single song bout (Stafford and Moore 2005). This long-term stability in song units within an acoustic population allows the seasonal and geographic distributions and changes therein to be monitored over broader spatial and temporal scales than is possible using more traditional methods for assessing blue whale populations.

Many of the call types detected for these studies were long, repeated bouts of calling and focused exclusively on the stereotyped units known to make up parts of blue whale song. These units are only part of the repertoire of blue whale calls and are believed to possibly serve as a male display (McDonald et al. 2001; Oleson et al. 2007a). As far as we know, "songs" seem to be produced by solitary, mobile animals although single A and B units and D calls (which are higher frequency short down-swept signals, Rankin et al. 2005) are produced by whales in feeding groups (Oleson et al. 2007a). Information on gender and behavior has come from short-term tagging studies; data on specific behaviors while vocalizing cannot currently be obtained from single fixed sensors. These are the types of data needed to better understand the behavioral ecology of sound production, not just in blue whales, but also in all large whales.

However, some behavioral aspects to sound production can be hypothesized when the environment in which sounds are produced is understood. Unlike humpback whales (*Megaptera novaeangliae*), or fin whales, for instance, that sing primarily in the winter, blue whales produce songs year-round (Stafford et al. 1999a, 2011; Watkins et al 2000; Širović et al. 2009; Samaran et al. 2010). Further, because they tend to be found in areas of high productivity where food is likely available (Branch et al. 2007), sound production could serve a role in food advertisement as has been suggested for fin whales (Croll et al. 2002), or may be incompatible with active feeding.

The ETP, particularly near the Costa Rica Dome, is an area of high year-round productivity. It is also one of the regions proposed as wintering or breeding grounds for blue whales. Blue whales feed almost exclusively on krill, large zooplankton that aggregate in immense swarms that are exploited by feeding blue whales. Most species of krill, including those in the ETP, undertake diel vertical migrations where they disperse surfacewards at night after spending daylight hours often in dense patches at depth (Sameoto et al. 1987). Day–night differences in blue whale feeding behavior have been documented by whalers and by ecological studies of blue whales on known feeding grounds (Fiedler et al. 1998; Croll et al. 2001).

Counts of ENP blue whale calls by hour showed a diel pattern in call rate (calls/h) and call occurrence (Stafford et al. 2005). When the data were divided into Light, Dark, and Dusk by hour, there were significantly more calls per hour during dark and dusk than during light (Fig. 2.5). Blue whales were calling more often in the dark. A similar pattern was also found for singing ENP blue whales off southern California (Clark and Fristrup 1997; Oleson et al. 2007b).

This increase in call rate occurred at the same time in the evening that many krill species are migrating towards the surface of the ocean where they are more dispersed, and the morning decrease matched that time when krill move back down in the water column as the sun rises. These are also the times when whalers documented whales' stomachs as being more 'full' than at other times of the day. The similarity between the diel pattern of blue whale calls and their prey behavior suggests that calling in blue whales may be inversely related to foraging. When prey is concentrated at depth, blue whales spend time feeding on this prey, and not calling. When prey is more disperse, it may be more energetically conservative to spend this time displaying as has been suggested for sei whales (*B borealis*; Baumgartner and Fratantoni 2008). Data from tagged whales and vertical hydrophone arrays have shown that blue whales make calls relatively close to the surface (Thode et al. 2000;

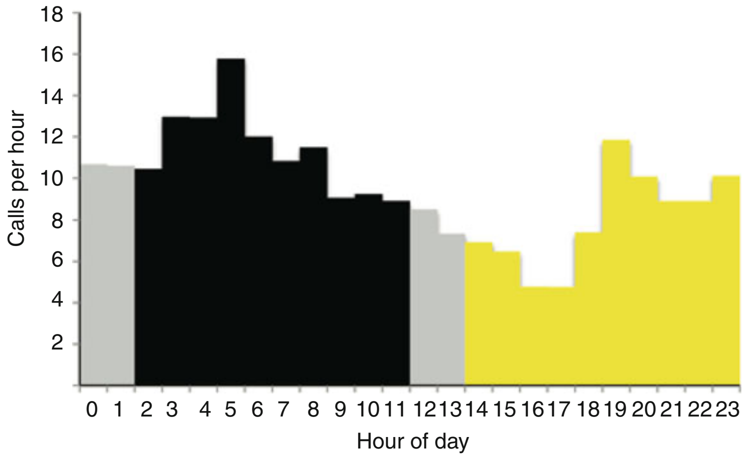

Fig. 2.5 Diel variation in call occurrence for blue whales in the eastern tropical Pacific. Overall, there were more calls per hour during dark (*black bars*) and dusk (*gray bars*) than during daylight (*yellow bars*)

Oleson et al. 2007a) and that actively feeding whales are not likely to be singing (Oleson et al. 2007a).

Although the information presented here provides a very broad overview of geographic, seasonal, and diel variations in blue whale vocal behavior, this overview can provide baseline data for new questions of interest. These questions may be as simple as where blue whales are found during any month of the year, and to which acoustic population the calling animals belong, to more complicated exploration of the role of acoustic signaling in the behavioral ecology of blue whales. New techniques are being developed that may soon allow whale populations to be counted using acoustic data from single hydrophones and "acoustic tags" have provided exceptional insight into the behavioral context of signaling in blue whales. While single hydrophone data provided the first long-term understanding of populations' differences, deep-water habitat, and seasonal occurrence of blue whales, the best chance for a complete understanding of acoustic ecology in these animals is via an interdisciplinary approach that combines new methods and technologies and integrates sighting, molecular, and telemetry data with acoustic recordings.

2.4 Key Findings

1. Blue whales seen in the ETP and the Gulf of Alaska are related to blue whales off California and western Mexico. Formerly known as the California/Mexico stock of blue whales, these animals are now considered the northeastern Pacific stock and range all along the coasts of North and Central America.
2. The ETP is a hotspot for multiple acoustic populations of blue whales.

   (a) Eastern North Pacific.
   (b) Eastern South Pacific—recordings of the same call type that was the very first to be attributed to blue whales from off Chile.
   (c) Antarctic.

3. The Gulf of Alaska is a region where eastern and western North Pacific blue whales overlap in time and space suggesting that acoustic identification might be used for animals from different populations to tell each other apart.
4. Blue whales produce more calls at night and during dusk hours than during the day suggesting a partitioning of energetic effort between calling and foraging behaviors.

This work provided new information on the population identity and migration patterns of blue whales in the eastern North Pacific, provided the long-term information on eastern South Pacific blue whales since 1971, and showed that two different acoustic populations overlap in space and time in the Gulf of Alaska.

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Chapter 3
Long-Term Monitoring of Cetaceans Using Autonomous Acoustic Recording Packages

Sean M. Wiggins and John A. Hildebrand

Abstract Autonomous acoustic recorders have advanced our understanding of cetaceans, providing information for better models of species distribution, behavior, ecology, and conservation. For over a decade, Acoustic Recording Packages (ARPs), and its broader-bandwidth successor, High-frequency Acoustic Recording Package (HARP), have been used for Passive Acoustic Monitoring (PAM) providing high-fidelity, long-term acoustic data sets for cetacean studies. Some of these studies are summarized below showing a wide range of applications and results including species signal characterization, seasonal and daily presence patterns, geographic and habitat use, population density and abundance estimations, acoustic stimuli behavioral response, and swimming behavior via array tracking. Species studied include low-frequency baleen whales and high-frequency dolphins and beaked whales.

3.1 Introduction

There are various approaches for passive acoustic monitoring (PAM) of cetacean and other oceanic sounds. One technique uses hydrophones cabled to land-based recording stations. In an early example of recording cetaceans, Thompson (1965) employed a cabled hydrophone array off San Clemente Island, California to record blue (*Balaenoptera musculus*) and fin (*Balaenoptera physalus*) whale sounds on magnetic tape for 8 days. Thompson and Friedl (1982) used hydrophones cabled north of Oahu, Hawaii to study 6 species of cetaceans for about 2 years showing seasonal and migratory patterns. Cabled hydrophones have the advantage of monitoring in real-time, but they also have high installation and operational costs. Portable hydrophone arrays towed or dangled from ships (Thomas and Evans 1982; Barlow and Taylor 2005) are a similar technique that have relatively low hardware costs, but typically only provide short duration recordings because ship and personnel operational costs are high.

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Autonomous acoustic recorders are another PAM tool used to monitor cetacean sounds and are often deployed in remote locations for long periods. They consist of a hydrophone and digital recording device, are battery-powered, and are packaged to withstand the ocean environment, but must be recovered from the ocean to retrieve the data for analysis. These recorders come in many different configurations depending on scientific goals and environmental conditions. For example, instrument design and costs are affected by whether the deployment location is shallow (<100 m) or deep (>1000 m), recording duration is short (1 week) or long (1 year), and focal species is baleen (low sample rate) or odontocete (high sample rate).

Two recording devices that were specifically designed for long-term (months to year) acoustic data acquisition are the Acoustic Recording Package (ARP) (Wiggins 2003) and the High-frequency Acoustic Recording Package (HARP) (Wiggins and Hildebrand 2007). HARPs are essentially enhanced ARPs that record at higher bandwidth and therefore detect a wider range of species. ARPs have been used worldwide since 2000 to study marine mammal sounds offshore of Alaska, California, Hawaii and Antarctica in shallow (<100 m) to deep (>3000 m) water and over long periods (years). From 2000 to 2006, there were 113 ARP deployments resulting in over 38 instrument-years of low-frequency (10–500 Hz) ocean sound recordings (Table 3.1). The maximum sample rate for ARPs was 1 kSamples s^{-1} (kHz), limiting the recorded animals to mysticetes and some pinnipeds. Beginning in 2004, the HARP data logger was developed to record both mysticetes and odontocetes while maintaining the long-term capabilities of ARPs. To record odontocetes, faster sampling (200 kSamples s^{-1}) was employed, which led to the need for increased data storage capacities and the need for lower power electronics to obtain long duration recordings. Since 2006, HARPs have been recording underwater

Table 3.1 ARP and HARP number of deployments, data duration, and data quantity from 13 years of long-duration recordings

	Deployments		Recording Duration (days)		Quantity (bytes × 10^9)	
Year	ARP	HARP	ARP	HARP	ARP	HARP
2000	23		1580		211	
2001	27		3942		441	
2002	26		3669		413	
2003	21		2454		363	
2004	11	9	835	550	119	6117
2005	3	18	863	960	75	20,918
2006	2	23	752	1167	65	26,780
2007		46		2066		61,277
2008		62		2711		86,987
2009		91		4170		125,847
2010		80		5215		167,817
2011		52		5320		184,019
2012		51		6138		230,906
Total	113	432	14,095	28,297	1686	910,668

sounds with high-fidelity from 10 Hz up to 100 kHz, initially with 2 months of continuous data storage (Table 3.1). Development of HARP capabilities continues to advance, for example, in 2010 loss-less data compression was employed with larger data storage devices, boosting recording durations by a factor of five to achieve 10 month continuous recording with 100 kHz bandwidth. As of 2012, HARPs have amassed close to one petabyte (1×10^{15} bytes) of acoustic data, with each year incurring more data than the previous year (Table 3.1).

Processing and analyzing large, long-term acoustic data sets can be challenging. Typical spectrogram evaluation for wideband (100 kHz) data can be conducted by an analyst only near real-time because of human and computational limitations, prohibiting the detailed analysis of long-term data sets. Automated detectors have been useful in finding cetacean sounds in large data sets, but require extensive training to provide good performance and typically only detect sounds with known characteristics, missing new or uncharacterized sounds. As an efficient alternative, Long-Term Spectral Averages (LTSAs) provide an overview of a large data set, along with providing a means to search for and evaluate events of interest such as cetacean calling bouts (Wiggins and Hildebrand 2007). LTSAs are essentially spectrograms with each time slice representing many (1000s) spectra averaged together, allowing multiple hours or days of wideband acoustic data to be displayed on a single page or viewing screen. *Triton* (www.cetus.ucsd.edu) is a software package developed in MATLAB (www.mathworks.com) to analyze ARP and HARP data including calculating and displaying LTSAs, but also works with standard wav audio files. In addition to providing a long-term view of acoustic data, LTSAs provide a means of quickly accessing the original acoustic data for more detailed analysis via cursor selecting events from the LTSA spectrogram. Automated detectors can also be used on LTSAs files, for example, to identify start and end times of calling bouts, which then can be used to define periods upon which to execute fine scale automated detectors for individual calls, reducing overall processing time on large data sets.

Calibrated hydrophones and recording electronics are required to determine accurate received sound pressure levels. Received levels allow estimation of source levels for calling animals when their call detection ranges are known. Understanding detection ranges also can provide insights into animal communication ranges, animal foraging and navigation capabilities, and population density estimations using distance sampling techniques (e.g., Buckland et al. 2001; Marques et al. 2009). All ARP and HARP hydrophone sensors are laboratory-calibrated before deployment and at the end of service life, and representative hydrophones are routinely calibrated at the US Navy's transducer evaluation center, TRANSDEC, in San Diego, California. Calibrated hydrophones also allow for studies on ambient noise and how anthropogenic sources such as ships or airguns may mask whale calls (McDonald et al. 2006a, 2008; McKenna et al. 2009, 2012a, b, 2013; Roth et al. 2012, 2013; Širović et al. 2013a).

What follows is a summary of cetacean-related results from long-term autonomous acoustic recordings using ARPs and HARPs, including studies on temporal and spatial distribution patterns, species call characteristics, and passive acoustic tracking. Focal species include blue and fin whales in the Southern California Bight and around Antarctica, North Pacific right whales (*Eubalaena japonica*) in the Bering Sea, Byrde's whales (*Balaenoptera edeni*) offshore of southern California and in the Gulf of Mexico, dolphins offshore of southern California, and beaked whales throughout the North and Central Pacific.

3.2 Blue and Fin Whales

Blue and fin whales have been recorded worldwide, documenting nine different blue whale regional call types (McDonald et al. 2006b). Some blue and fin whale calls have been characterized as song; these are stereotyped, low-frequency (~10–100 Hz), high-intensity (>180 dB re 1 μPa at 1 m) sounds that are produced in a repetitive pattern. These characteristics make their calls well suited for long range reception and allow for relatively straight-forward detection and classification.

From 2000 to 2004, five ARPs recorded baleen whale calls offshore of southern California at Tanner and Cortez Banks around 200 m water depth. The focal population for this study was Northeast Pacific blue whales, which migrate annually between North American summer feeding grounds and Central American breeding grounds. Offshore of southern California these whales produce three primary call types designated as: A, B, and D. Types A and B are often produced in a repetitive song sequence, are made only by males, and have been associated with reproductive behavior, whereas type D calls are made by both genders during intervals between foraging at depth (McDonald et al. 2001; Oleson et al. 2007a). By monitoring these calls types over 4 years, a temporal separation between type B and D calls was observed both seasonally and daily (Fig. 3.1) (Oleson et al. 2007b). It was found that type D calls occur earlier in a given season than type B calls, and D calls are produced primarily during daylight hours, correlated with feeding behavior on aggregated prey at depth. In contrast, type B song calling was greater during nighttime with peaks during twilight periods, just after sunset and before sunrise, which correlate with the vertical migration of the prey, when they may be less aggregated and foraging is less efficient (Fig. 3.2) (Wiggins et al. 2005).

In a more recent study using a HARP offshore of southern California near a naval test range, it was found that blue whales were less likely to produce D calls when military tactical mid-frequency active sonar was present and that the response was more pronounced when the sonar source was closer (i.e., higher sound levels) to the animals (Melcón et al. 2012). This shows that anthropogenic noise, even at frequencies well above the blue whales' sound production range (Fig. 3.3), can change their vocal behavior; however, the long-term consequences this disruption to blue whale foraging is currently not well understood.

In the Southern Ocean, three long-term ARP studies were conducted to monitor blue and fin whales: from 2001 to 2003 at seven sites off the Western Antarctic Peninsula (WAP), at four circumpolar Antarctic locations during 2003 and 2004, and at two locations off eastern Antarctica for 2005–2007 (Fig. 3.4). These recordings

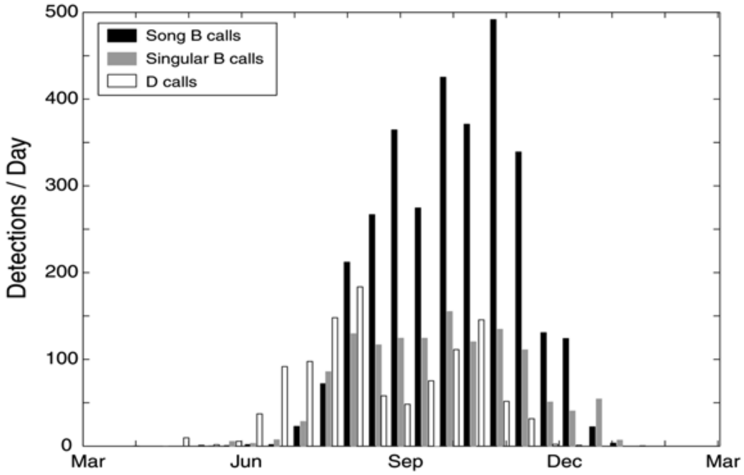

Fig. 3.1 Seasonal calling rates for blue B and D calls at Tanner and Cortez Banks, offshore of southern California. Detections are grouped into 2-week bins and averaged over 4 years. Foraging-related D calls (*white bars*) peak earlier in the season than song B calls (*black bars*) or singular B calls (*gray bars*) (from Oleson et al. (2007b); Fig. 3.4)

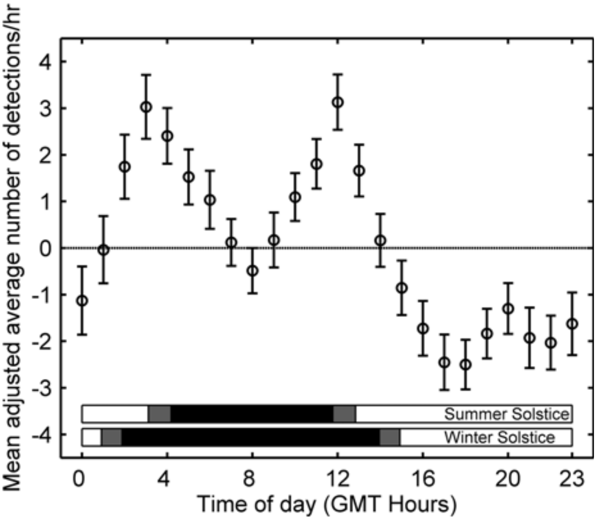

Fig. 3.2 Daily calling rates for blue B calls at Tanner and Cortez Banks, offshore of southern California. Detections are mean adjusted for each day. *Bottom horizontal bars* show day (*white*), dawn and dusk twilight (*gray*), and night (*black*) periods. Peaks occur just after sunset and before sunrise, correlated with the vertical migration times of krill, blue whale's primary food source (from Wiggins et al. (2005); Fig. 3.5)

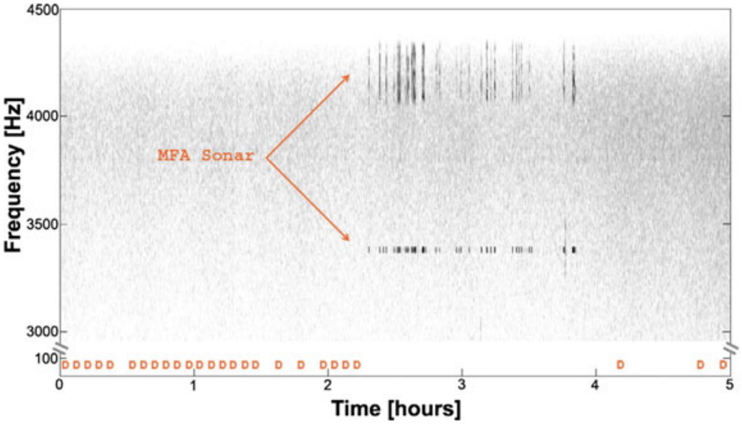

Fig. 3.3 Temporal sequence of Navy tactical mid-frequency active (MFA) sonar and blue whale D calls. Each orange "D" represents the presence of D calls in a 5-min bin. Note D calls do not occur during period of MFA sonar although they occupy different frequency bands (from Melcón et al. (2012); Fig. 3.1)

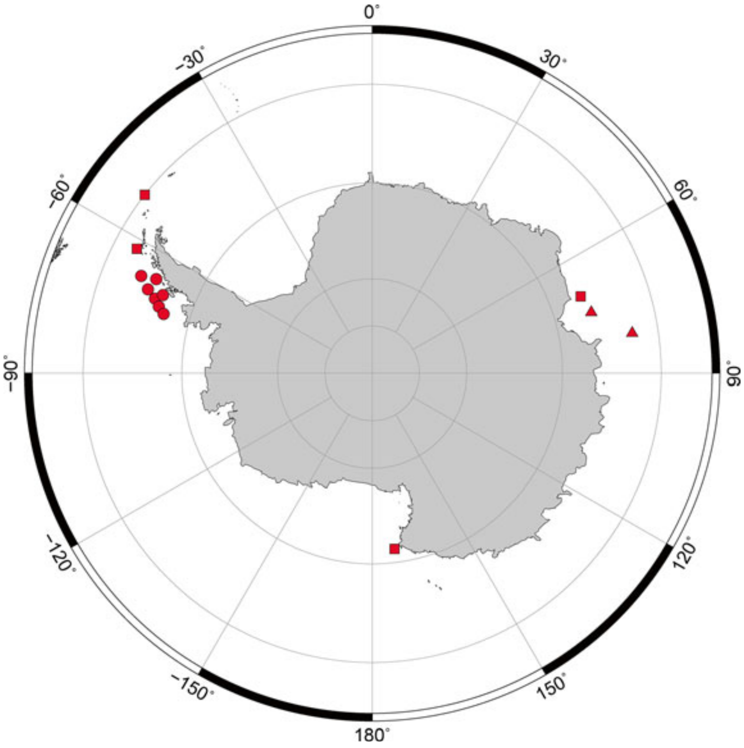

Fig. 3.4 Antarctic ARP deployment locations (*red symbols*) for blue and fin whale call studies. Red circles: ARPs deployed 2001–2003 near the West Antarctic Peninsula (WAP) with two on the shelf and six in deep water (>3000 m) (Širović et al. 2004). *Red squares*: ARPs deployed 2003–2004 around Antarctica at four sites: WAP, Scotia Sea (SS), Ross Sea (RS) and Eastern Antarctic (EA) (Širović et al. 2009). *Red triangles*: two ARPs deployed in eastern Antarctica from 2005 to 2007 (Gedamke et al. 2007)

of blue whales near Antarctica show different patterns than those observed off southern California. Blue whales were detected year round at both the WAP study area and at the four circumpolar locations with peaks in March–May and November suggesting asynchronous migrations of subgroups between feeding and breeding grounds (Širović et al. 2004, 2009). Similar results showing year around blue whale presence and a peak calling in fall were observed using from the 2005–2007 recordings off eastern Antarctica (Gedamke et al. 2007). Daily patterns in blue whale calling were not observed, presumably because light does not affect krill concentrations in the same way as at lower latitudes.

As with blue whales, fin whales have a different acoustic presence near Antarctica than offshore of southern California. ARP multiyear acoustic records offshore of southern California show fin whales call year round, whereas around Antarctica their calling is seasonal between February and June–July for the three study sites (WAP, circumpolar, eastern) from 2001 to 2007 (Širović et al. 2004, 2009; Gedamke et al. 2007). Also, as with blue whales which have different regional call types, fin whales calls from WAP are different than those from eastern Antarctica and different than those offshore of southern California. All three types have a call component that sweeps down in frequency from around 30 to 15 Hz over 1 s, but the WAP type has another component around 89 Hz, the eastern type has a component around 99 Hz, and the southern California type lacks the higher frequency component (Gedamke et al. 2007; Širović et al. 2009).

During the WAP study, ARPs were positioned approximately 100 km apart along the 3000 m depth contour and were intended to be independent monitoring sites. However, because blue and fin whales produce high-intensity calls and propagation conditions are favorable at high latitudes for low-frequency sounds, some calls were received on multiple instruments allowing them to be localized and source levels to be estimated. Blue whale calls were located up to a range of 200 km using time-difference of arrival analysis, and fin whale call ranges were estimated up to 56 km using multipath arrival techniques (Širović et al. 2007). Both average blue and fin whale source levels were 189 dB re: 1 μPa at 1 m with blue calls spanning 25–29 Hz and fin whale calls over 15–28 Hz. These source levels and detection ranges have the potential to be used to estimate population densities from distance sampling techniques and knowledge of calling rates.

In the eastern North Pacific, two, low-frequency downswept fin whale calls are present: 20 and 40 Hz calls. Using HARP recordings from over 5 years in the Bering Sea, offshore of southern California and in the Gulf of California, it was found at all three sites that fin whale 40 Hz calls peaked 3–5 months before 20 Hz calls (Fig 3.5). This temporal offset suggests both call types need to be monitored to provide a more complete description of their seasonal presence, and that the temporal separation may show that these two call types serve different purposes such as foraging (40Hz) and other social interactions (20Hz) (Širović et al. 2013b).

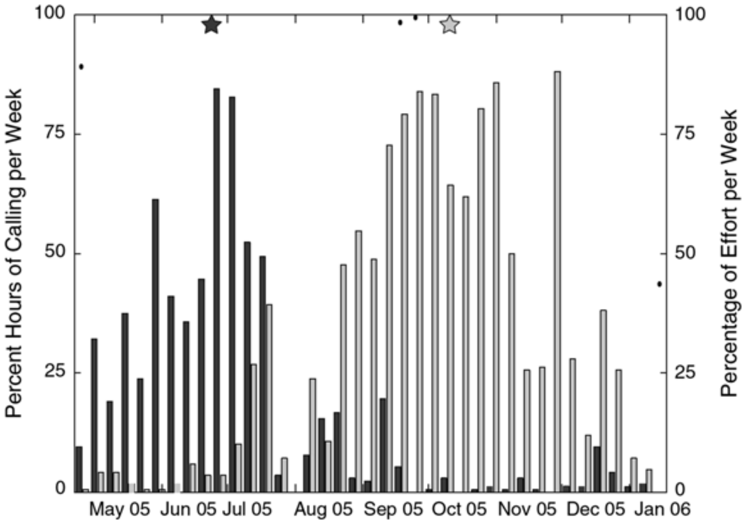

Fig. 3.5 Percent of hours per week with fin whale 20-Hz (*light gray*) and 40-Hz (*dark gray*) calls recorded in the Bering Sea. *Black dots* and *right axes* show percentage of recording effort when less than 100 %, and stars at *top* show mean day of calling presence for both call types (from Širović et al. (2013b); Fig. 3a)

3.3 North Pacific Right Whales

Eastern North Pacific right whale populations were heavily depleted during the commercial whaling era of the nineteenth and twentieth centuries; they are now the world's most endangered large whale species. Population estimates are uncertain, but totals are less than a hundred individuals (Wade et al. 2011). Based on visual sightings of right whales during the summer months in the southeastern Bering Sea (SEBS), ARPs and HARPs were deployed on the Bering Sea shelf and at the shelf break in various configurations from 2000 to 2006.

Right whale calls travel long distances on the Bering Sea shelf because of favorable propagation conditions provided by a uniform shallow water waveguide (Wiggins et al. 2004). Detections ranges of approximately 200 km have been observed, allowing autonomous acoustic recorders to monitor large regions for this sparsely populated species (Munger 2007). Even with large detection ranges, long duration records show calling bouts of a few hundred calls per day, that are often separated by days to months of no calling (Fig. 3.6). These data suggest that right whales may use the SEBS middle shelf intermittently and may be transiting through on their way to other areas (Munger et al. 2008).

Right whales have been associated with several different low-frequency sounds. In the Bering Sea, upsweeping frequency modulated calls from about 90 to 170 Hz over approximately 0.7 s are the most common type. Right whales upswept calling bouts were observed as early as May and as late as December, seasonally much earlier and later than anticipated based on visual encounters. July to October showed

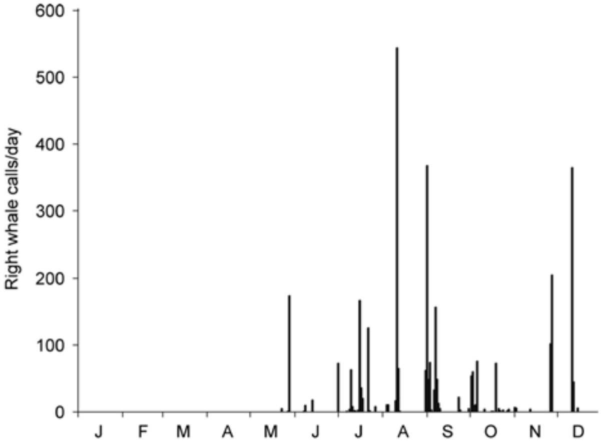

Fig. 3.6 Seasonal calling rates for Northeastern Pacific right whales from 2000 to 2005 on the Bering Sea middle-shelf (depths < 100 m). Upswept calling bouts were observed seasonally much earlier and later than previous visual encounters (from Munger et al. (2008); Fig. 4a)

more days per month of calling (≥6 days/month) than earlier or later (≤3 days/month). Hourly calling rates were significantly higher during nighttime than during day light hours, and most calls were clustered in temporal bouts with intercall intervals between approximately 10 and 500 s (Munger et al. 2008).

The SEBS ARPs were placed as independent sites, but the same calls were recorded on multiple instruments allowing them to be localized. These locations were coupled with detection range estimates from shallow water waveguide modeling to estimate call source levels. Right whale call source levels were approximately 177 dB re 1 μPa at 1 m, acoustic transmission loss was roughly $15 \times \log_{10}$ (range), and ambient noise levels were around 70–90 dB re 1 $\mu Pa^2/Hz$ over the right whale calling band 90–170 Hz (Munger et al. 2011). These parameters along with detection range estimates and calling rates were used for estimating right whale population densities from autonomous acoustic recorders in the SEBS using the distance sampling technique, acoustic cue counting (Marques et al. 2011). A point estimate of 25 animals (CV 29 %; 95 % confidence interval 13–47) agrees well with estimates by others using photographic and genetic data with mark–recapture techniques (Wade et al. 2011).

3.4 Bryde's Whales

Bryde's whales are typically found in tropic and subtropic regions and unlike other mysticetes do not appear to migrate. They produce a variety of low-frequency (65–950 Hz) moans, tones, and pulses which potentially delineate different stocks (Oleson et al. 2003). A small population of ~15 Bryde's whales, the only known group of baleen whales in the Gulf of Mexico, was recorded with a HARP during an

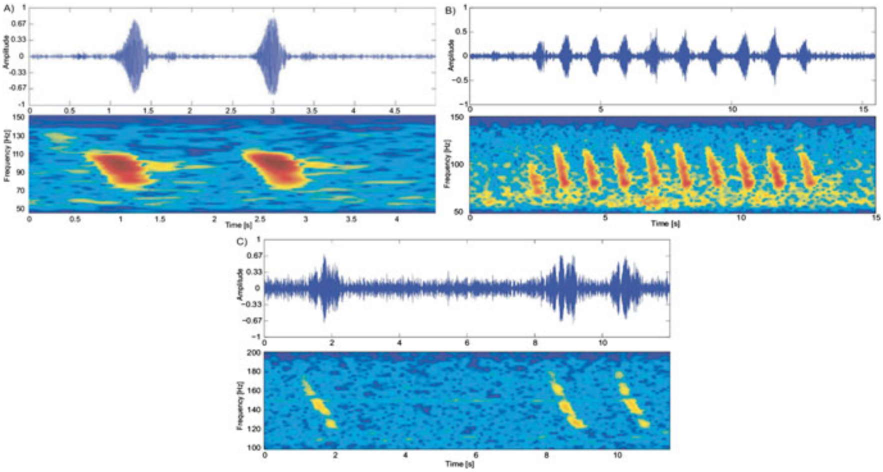

Fig. 3.7 Time series and spectrograms of Bryde's whale calls in the Gulf of Mexico. (**a**) Be9 pulses from sonobuoy recording, (**b**) Be9 pulse sequence recorded on HARP, and (**c**) possible Bryde's whale calls recorded on HARP (from Širović et al. (2013a); Fig. 2)

ongoing experiment to monitor the effects on marine mammals of the Deepwater Horizon oil spill (Širović et al. 2013a). DeSoto Canyon, in the northeast Gulf at about 260 m depth, was the only site of three evaluated to have Bryde's whale calls recorded; the other two sites were about 200 km west and 400 km south. Be9 calls (Fig. 3.7), ~140–80 Hz downswept pulses often in sequences as first described by Oleson et al. (2003) were detected from March to January with a peak in June and an absence in calling in November and December; no recordings were available from late January to mid-March. Significantly more calls were detected at dusk and night than during dawn and daylight hours.

While Bryde's whales are typically found in low latitudes, we have been recording their calls in the temperate waters offshore of southern California using ARPs and HARPs since 2000 (Kerosky et al. 2012). In this study, the calls were observed from summer to early winter and calling presence was found to significantly increase over the study period from 2000 to 2010, but calling was not found to correlate with local sea surface temperature. This seasonal pole-ward range expansion in the Pacific is likely caused by prey availability within the California Current ecosystem, which may be a result of climate change and oceanographic conditions.

3.5 Dolphins

A diverse group of odontocetes are found in the waters offshore of southern California including: sperm whales, beaked whales, porpoises, and dolphins, all of which produce echolocation clicks. The ability to differentiate between click types can provide insights into the foraging and migratory behaviors of these animals from autonomous recordings. Fortunately, some clicks are distinguishable based on their spectral and temporal characteristics allowing for click classification, such as sperm whales. On the other hand, species-level classification of echolocation clicks is still a topic of active research (Roch et al. 2011).

Commonly observed species of dolphins found in the waters offshore of southern California include: short-beaked common (*Delphinius delphis*), long-beaked common (*D. capensis*), bottlenose (*Tursiops truncates*), Pacific white-sided (*Lagenorhynchus obliquidens*), and Risso's (*Grampus griseus*) dolphin. Soldevilla et al. (2008) compared the spectral and temporal properties of echolocation clicks from ship-based single species recordings and found unique spectral peak and notch patterns for Pacific white-sided and Risso's dolphins, allowing species classification in autonomous recordings. Furthermore, two distinct subsets of click types were observed for Pacific white-sided dolphin (designated as types A and B), suggesting two geographically distinct populations of this species occur within the Southern California Bight with differing foraging strategies (Henderson et al. 2011).

As part of a long-term, broadband monitoring effort in the Southern California Bight, acoustic recordings were made at six sites with HARPs sampling at 200 kHz from 2005 to 2007. In these recordings, Risso's dolphin echolocation click bouts were identified based on their unique spectral structure (Fig. 3.8) and evaluated for diel, seasonal, and geographical patterns (Soldevilla et al. 2010a). Out of a cumulative total of 1959 recording days for all sites, Risso's click bouts were observed on 739 days with the majority of bouts occurring inshore and peak occurrence at the southern end of Santa Catalina Island (Fig. 3.9). At the inshore sites, clicks were observed year-round with high seasonal and interannual variability, but typically

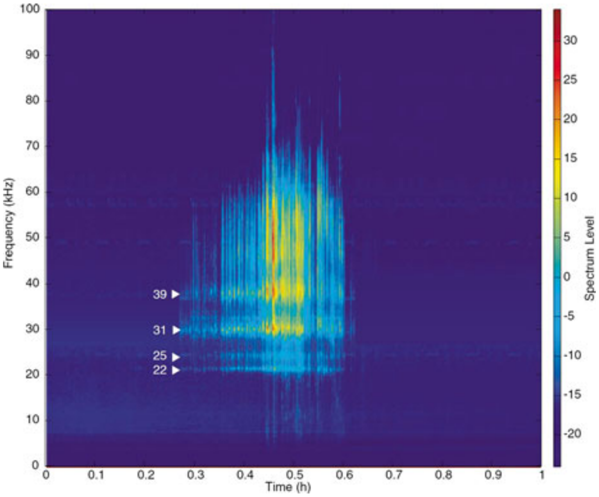

Fig. 3.8 Long-Term Spectral Average (LTSA) of Risso's dolphin echolocation clicks offshore of southern California. Spectral peaks (*horizontal bands*) are at approximately 22, 25, 31 and 39 kHz (from Soldevilla et al. (2010a); Fig. 3)

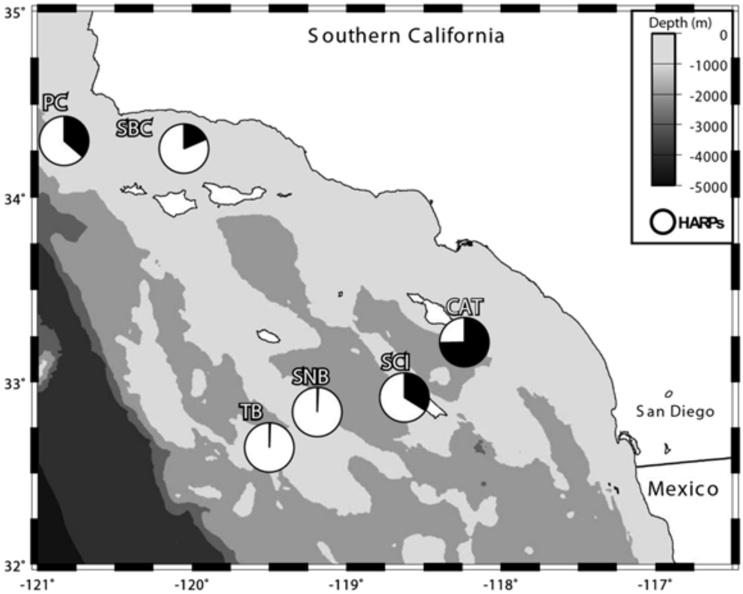

Fig. 3.9 Geographical occurrence of Risso's dolphin in the southern California Bight from 2005 to 2007. Six HARP locations are shown as pie charts with black sections representing percentage of recording days with Risso's dolphin click bouts. Island and near shore sites had Risso's dolphin clicks most often (from Soldevilla et al. (2010a); Fig. 1)

with peak occurrence in the autumn. Click rates and the hourly occurrence of click bouts were both observed to be significantly higher at night than during the day, suggesting increased foraging activity on diel-vertically migrating prey (Fig. 3.10).

Using the same HARP recordings as for the Risso's dolphin study, Pacific white-sided dolphin clicks were identified and their temporal and spatial occurrence offshore of southern California was investigated (Soldevilla et al. 2010b). Both Pacific white-sided type A and type B click bouts were identified (Fig. 3.11). Type A clicks were observed on 317 of the 1959 recording days at all six sites, whereas type B clicks were identified on 130 recording days at only the two southern inshore sites, supporting the hypothesis that there are two separate populations of Pacific white-sided dolphins and that these click types are population-specific (Fig. 3.12). Seasonal patterns show both types peak in fall-winter at the southern sites and peak in spring for type A at the northern offshore site. Inversely related diel patterns were observed for the two click types with type A click bouts and click rates higher at night, and type B with higher click activity during daylight hours, suggesting specialization on different prey by the two populations (Fig. 3.13).

Environmental variables can be combined with cetacean acoustic occurrences to create predictive models for whale and dolphin distributions. Time-lagged predictor variables and hourly occurrence of click types for Risso's and Pacific white-sided dolphins from the 2005–2007 southern California HARP recordings were investigated using generalized additive models (Soldevilla et al. 2011). Various oceanographic

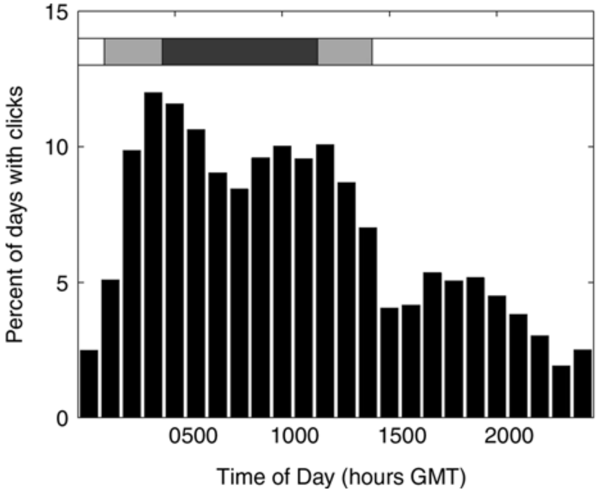

Fig. 3.10 Diel patterns of Risso's dolphin echolocation click bouts for the six sites shown in Fig. 3.9. In the *horizontal bar*, daylight, twilight, and nighttime are represented by *white*, *gray*, and *black*, respectively. Peak clicking occurs during twilight and night (from Soldevilla et al. (2010a); Fig. 4)

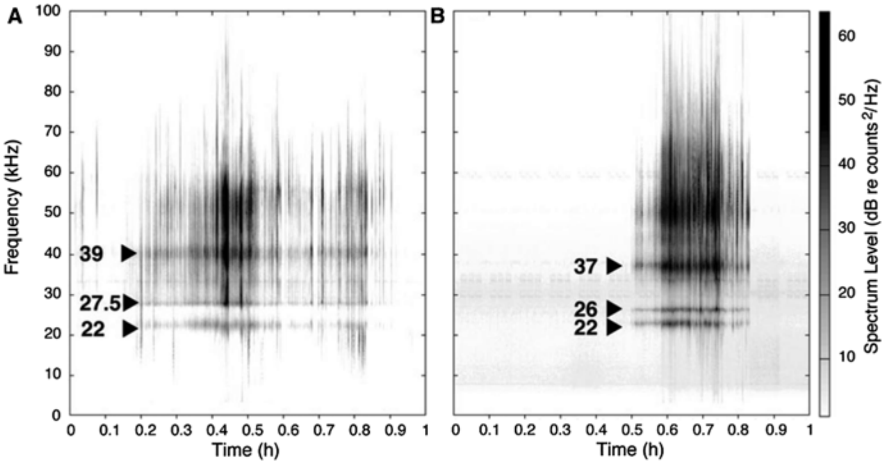

Fig. 3.11 LTSAs of Pacific white-sided dolphin echolocation clicks offshore of southern California. (**a**) Type A and (**b**) type B clicks with different spectral bands may be from different populations (from Soldevilla et al. (2010b); Fig. 3)

variables were evaluated including sea surface temperature (SST), SST coefficient of variation (CV), solar and lunar temporal indices, sea surface chlorophyll concentration (Chl), Chl CV, and upwelling indices. For all click types, SST and SST CV were consistently selected as important variables (i.e., 80–100 % of models) with the addition of solar indices selected for Pacific white-sided types A and B (100 % of models). The best model for Pacific white-sided type B clicks included concurrent environmental data, suggesting oceanographic fronts or convergence zones aggregate prey

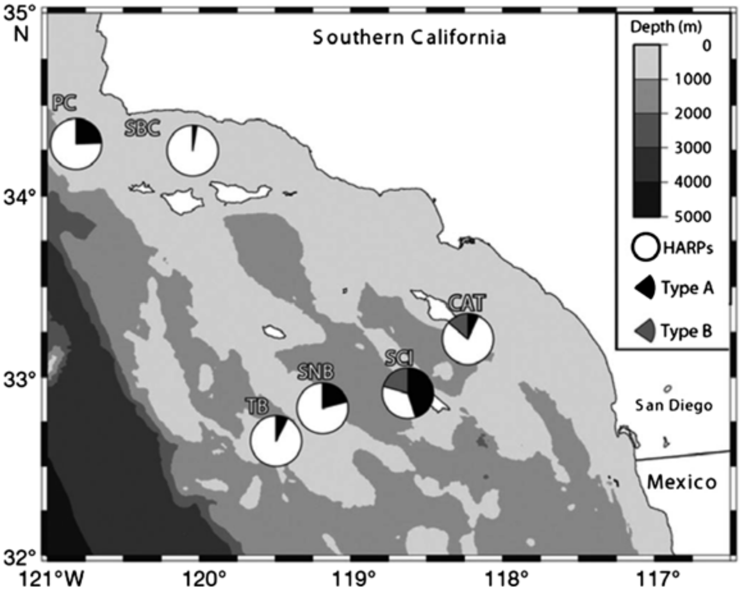

Fig. 3.12 Geographical occurrence of Pacific white-sided dolphin type A and B echolocation clicks in the southern California Bight from 2005 to 2007. Six HARP locations are shown as *pie charts* with *shaded sections* representing percentage of recording days with type A (*black*) and type B (*gray*). Type A clicks were recorded at each site, but type B occurred only at the southern sites near islands (from Soldevilla et al. (2010b); Fig. 1)

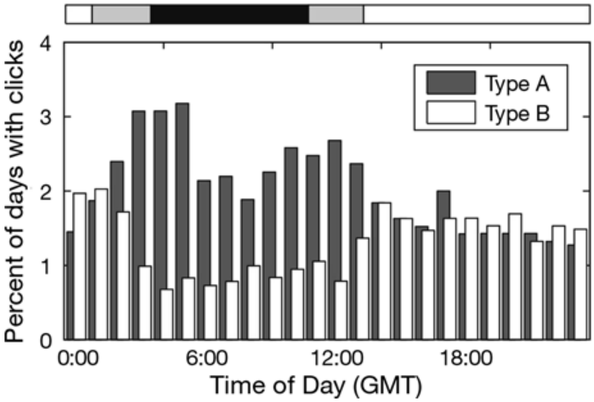

Fig. 3.13 Diel patterns of Pacific white-sided dolphin types A and B echolocation click bouts for the six sites from Fig. 3.12. The *horizontal bar* shows periods of daylight (*white*), twilight (*gray*), and night (*black*). During twilight and night, type A clicking peaks but type B clicking is at a minimum (from Soldevilla et al. (2010b); Fig. 5)

for foraging. Conversely, the best models for Risso's and Pacific white-sided type A clicks included 4-week time lagged variables, suggesting ecological succession processes following events such as upwelling may affect foraging.

Using HARP recordings near the Aleutian Islands, offshore of Washington and southern California, and near the tip of Baja California, high frequency downswept

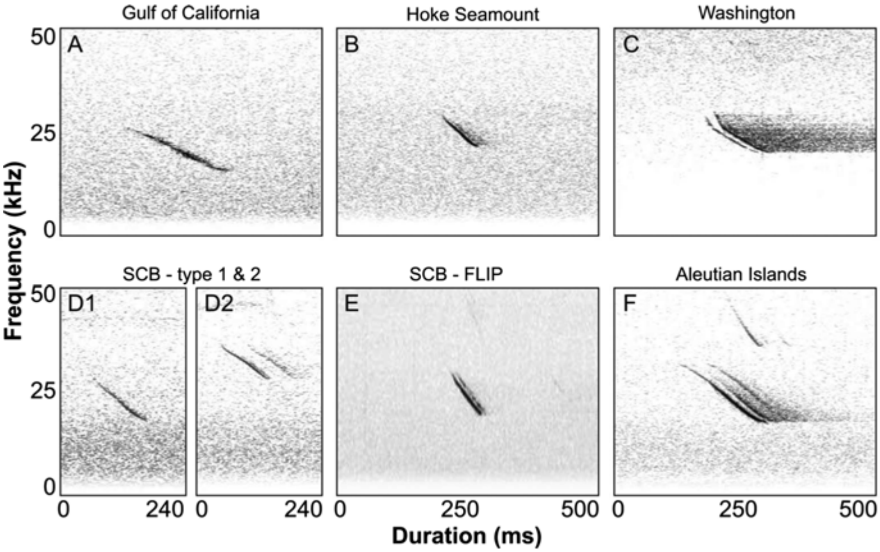

Fig. 3.14 Killer whale high frequency modulated signal spectrograms for five regions in the North Pacific (from Simonis et al. (2012); Fig. 2)

signals from killer whales (*Orcinus orca*) were identified, similar to those reported for Atlantic populations, but not previously described for the North Pacific (Fig. 3.14) (Simonis et al. 2012). Two types of high frequency modulated signals (~25 and ~35 kHz, 50–160 ms duration, source level ~190 dB_{pp} re 1 μPa at 1 m) were described as similar to bat echolocation signals and potentially could serve the same purpose with a large time-bandwidth product that increases the signal processing gain (Au 1993). As a result, these signals are more suitable than typical echolocation clicks for long range detection tasks such as identifying prey and underwater features for navigation.

3.6 Beaked Whales

More than one-fourth of all cetacean species are in the family Ziphiidae (beaked whales), although until recently not much was known about these animals because they are difficult to observe, spending relatively little time near the sea surface and foraging at great depths. Recent interest in the impact of tactical Navy sonar on beaked whales (Frantzis 1998; Cox et al. 2006) has motivated the development of tools to aid in learning about these animals. For example, the DTAG acoustic archival tag (Johnson and Tyack 2003) has provided details on the behavior of beaked whales, including swimming, diving, foraging, and echolocating behaviors. Furthermore, the wideband (100 kHz), deep water (>1000 m) capabilities of HARPs has provided long duration recordings of beaked whale echolocation foraging dives

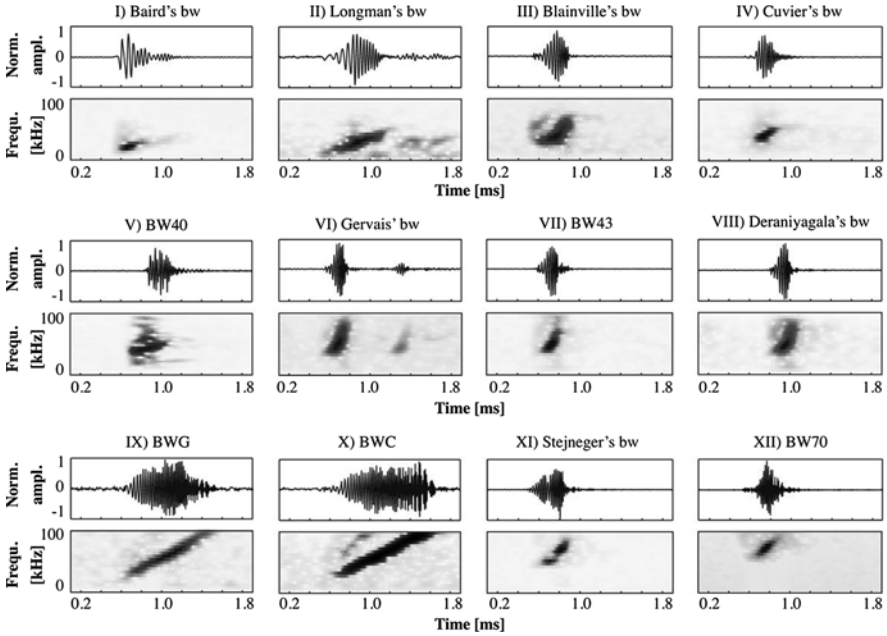

Fig. 3.15 Time series and spectrograms of 12 beaked whale species-specific frequency modulated pulses for known (*I–IV*, *VI*, *VIII*, *X*, *XI*) and unknown (*V*, *VII*, *IX*, *XII*) origin (from Baumann-Pickering et al. (2013a); Fig. 4)

throughout the North Pacific including offshore of southern and central California, off the coast of Washington, near the Aleutian Islands, in the Gulfs of Alaska, Mexico, and California, around the Main and Northwestern Hawaiian Islands, and Saipan (Baumann-Pickering et al. 2013b). These recordings include sounds previous attributed to specific species as well as ones that have been newly associated and others that are beaked whale-like echolocation sounds but from unknown origin (Fig. 3.15) (Baumann-Pickering et al. 2013a).

Wideband recordings were made from April 2005 to May 2006 by a HARP deployed on top of Cross Seamount, west of the island of Hawai'i, at approximately 400 m depth (Johnston et al. 2008). The prominent signal recorded was an approximately 1000 μs, frequency modulated (FM) upswept signal starting around 40 kHz and extending past the HARP Nyquist frequency limit of 100 kHz (Fig. 3.15X). The general high-frequency, upswept character of this signal is similar to Cuvier's (*Ziphius cavirostris*) (Fig. 3.15IV) and Blainville's (*Mesoplodon densirostris*) (Fig. 3.15III) beaked whales echolocation signals (Johnson et al. 2004; Zimmer et al. 2005) suggesting that the Cross Seamount sounds are also from beaked whales, but likely a different species based on its significantly different signal duration, inter-pulse interval and frequency range (McDonald et al. 2009). The Cross Seamount beaked whale echolocation signals were shown to be present year-round with some seasonal variability and occur almost entirely during night at Cross

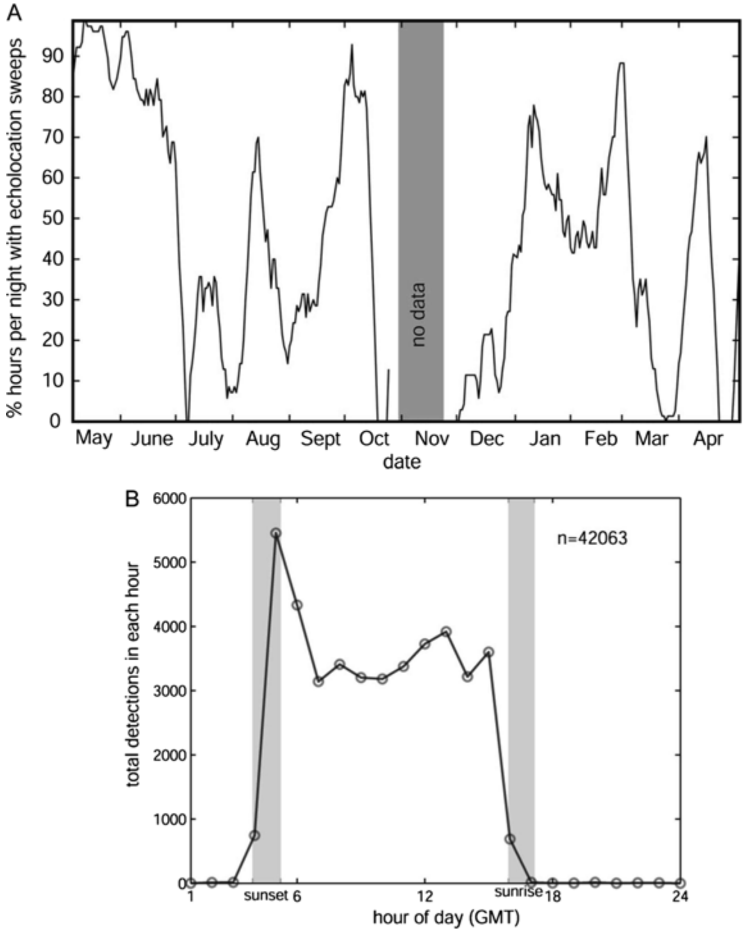

Fig. 3.16 Cross Seamount beaked whale echolocation pulse occurrence. (**a**) Daily and (**b**) hourly presence over 1 year. The diel pattern shows echolocation (foraging) only at night (from McDonald et al. (2009); Figs. 2 and 3)

Seamount and other locations suggesting they forage only at night (Fig. 3.16). These sounds are hypothesized to be from *M. ginkgodens* based on known habitat and comparisons to recordings elsewhere throughout the North Pacific (Baumann-Pickering et al. 2013b).

Similar to the Cross Seamount study, a HARP was deployed at Palmyra Atoll for approximately 1 year from October 2006 to September 2007 at about 600 m depth and recorded FM upswept pulses from another apparent beaked whale with signal characteristics differing from Cuvier's, Blainville's, and Cross Seamount beaked whales (Baumann-Pickering et al. 2010). In addition to the HARP recordings, concurrent visual observations and hydrophone array recordings were made in the presence of an unidentified beaked whale with the array recordings including upswept FM pulses similar to the HARP recordings. The Palmyra Atoll beaked whale signal sweeps from about 34 to 65 kHz, has a pulse duration of about 430 μs and inter-pulse interval of 225 ms (Fig. 3.15VIII). Additional analysis is being conducted to investigate diel and seasonal patterns of beaked whale signals from HARP recordings at Palmyra Atoll from 2006 to 2010. These signals, also recorded at nearby Kingman Reef, may be from Deraniyagala's beaked whale (*M. hotaula*) based on this small geographical distribution and past strandings in the region (Baumann-Pickering et al. 2013a, b).

In 2010, a HARP was deployed in the Aleutian Island region near Kiska, Alaska at over 1000 m deep. This area is a known habitat for three beaked whale species: Baird's (*Berardius beardii*), Cuvier's, and Stejneger's (*M. stejnegeri*). FM upswept pulses were recorded throughout the 3 month data set with no clicks matching the characteristics from Baird's beaked whale (Dawson et al. 1998; Baumann-Pickering et al. 2013d) and only one click sequence from Cuvier's beaked whale (Zimmer et al. 2005); therefore, the pulses were presumed to be associated with Stejneger's beaked whale which had not been previously described. The FM pulses ranged from 40 to 100 kHz with a peak frequency around 48 kHz, pulse duration of 115 μs, and a median inter-pulse interval of 77 ms (Baumann-Pickering et al. 2013c) (Fig. 3.15XI).

Baird's is the largest known beaked whale species and from two encounters were recorded producing whistles, burst pulses, and echolocation clicks (Dawson et al. 1998). Using HARP recordings from southern California and towed array recordings offshore of central and northern California, tens of thousands of detections were used to characterize their echolocation clicks showing two types of signals (Baumann-Pickering et al. 2013d). One of the signals was a beaked whale-like FM pulse with 230 ms inter-pulse interval (Fig. 3.15I). The other signal was a dolphin-like broadband click. Both signals' spectra were composed of multiple frequency peaks consistently around 9, 16, 25, and 40 kHz, but with varying relative amplitude.

In addition to the four species described above, and the well-known Cuvier's and Blainville's beaked whales, HARPs have recorded five additional unique beaked whale-like FM pulses (Baumann-Pickering et al. 2013a). These additional pulses include those from Gervais' beaked whale (*M. europaeus*) and four pulses of unknown origin named BW40, BW43, and BW70 after their peak frequency, and BWG from the Gulf of Mexico (Fig. 3.15). Uniquely identifying the signal characteristics for these pulses allows for intra- and inter-species analysis of spatiotemporal patterns of beaked whale sounds (Baumann-Pickering et al. 2013b), and potentially the evolutionary niche separation that may have caused differences in beaked whale signals.

3.7 Tracking Cetacean

Long-term recordings from ARPs were used to localize calling blue, fin, and right whales (above), however, these results were serendipitous as the ARPs were deployed as independent stations and it was not anticipated that the same call would be recorded on more than one instrument. On the other hand, autonomous acoustic recorders can be configured into preplanned large aperture (~1–5 km) arrays to localize cetacean sounds, providing the recorders are time-synchronized and locations of receiving sensors are well known. While source level and detection range estimates used for population density estimates can be derived from localizations, locations can be combined sequentially to produce tracks which can provide information on cetacean swimming behavior including direction, speed and response to acoustic stimuli.

In the fall of 2007, four time-synchronized HARPs sampling at 200 kHz were deployed in a 2 km × 2 km array on the seafloor about 800 m deep offshore of southern California (Wiggins et al. 2013). Typically, odontocete echolocation clicks are not well suited for localization in this type of array because of their narrow-beam directional character; however, some odontocetes also produce nearly omnidirectional whistles which were localized and tracked (Fig. 3.17). Bouts with large numbers of whistles and clicks were presumed to be from common dolphins based on previous concurrent ship-based single species visual identifications and acoustic recordings. Temporal analysis of these recordings showed dolphins tend to whistle more during day and click more at night. The one month recordings provided tracks of dolphin whistles with typical swimming speeds during daytime transiting behavior of about 2 m/s, and disjointed shorter and slower tracks during nighttime, presumably related to foraging activities. Swimming behavior from tracking could potentially be used to evaluate dolphin responses to various stimuli. Additionally, in the fall of 2008, a similar km-scale HARP array was deployed about 400 m deep in the same region and was used to track high frequency modulated signals from killer whales (Gassmann et al. 2013) showing this approach can be used for other species with nearly omnidirectional, intense signals.

In 2009, a HARP was configured with four hydrophones separated by about 0.5 m each in a small aperture array to track odontocete narrow-beam echolocation clicks (Wiggins et al. 2012). The hydrophones were each sampled at 100 kHz and arranged in a tetrahedron configuration. The small aperture allowed the same click to be received on all four sensors and standard time difference of arrival processing provided three-dimensional angles from the HARP to the sources. About 1 month of recordings provided tracks for both near-surface dolphins and near-seafloor beaked whales (Fig. 3.18). The ability to track free-ranging odontocetes provides a better understanding of habitat use and ranges from these tracks can be used to estimate population densities from distance sampling techniques.

3.8 Summary

Long duration autonomous acoustic recordings have provided insights into the diel and seasonal behaviors of cetaceans. When accumulated over long periods, calls and echolocation pulses show daily trends often related to foraging and seasonal patterns associated with behavior and migration. ARPs and HARPs were designed specifically to provide persistent recordings over long periods using large data storage solutions. They have been used to monitor a wide range of species often in

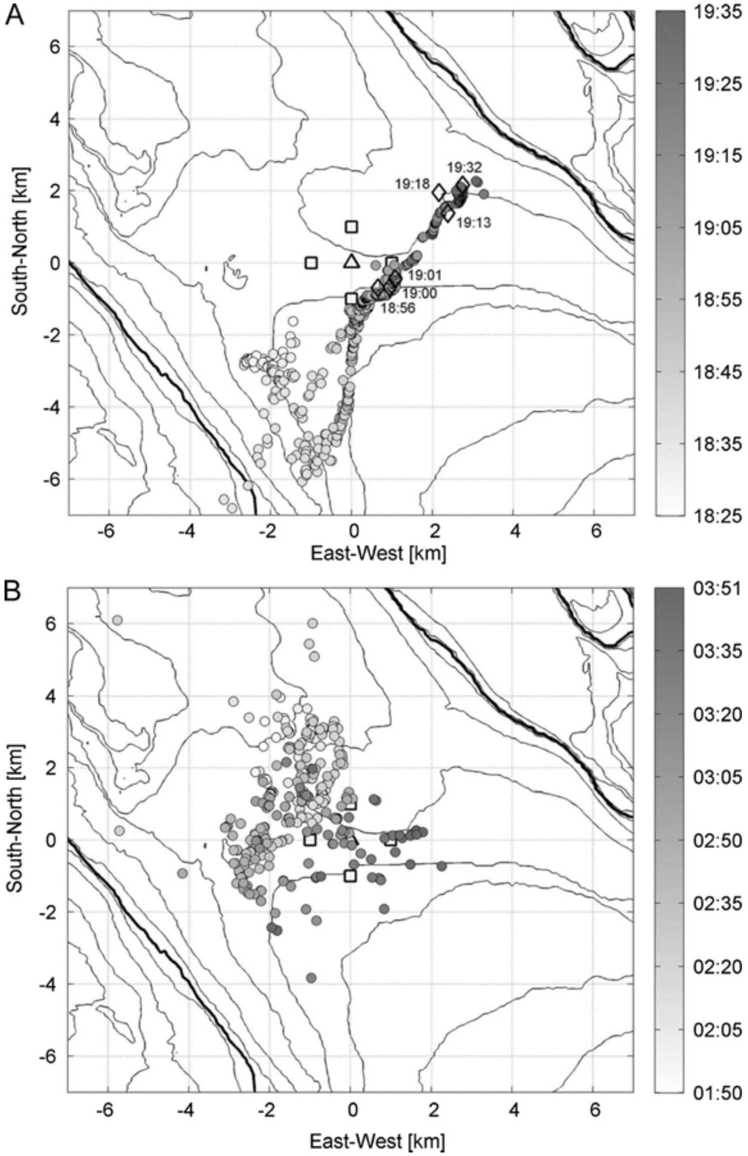

Fig. 3.17 Dolphin tracks from a km-scale HARP array offshore of southern California in 2007. *Filled circles* are dolphin locations with *shading* corresponding to the time scale on the *right*. HARP locations are *squares* on a ridge; *thick contour lines* are 1000 m deep and *thin lines* are at 50 m increments. (**a**) 575 localized whistles over 50 min during daytime hours show *tight clustering* and a directed path. *Diamonds* are visual observed dolphin locations with corresponding times. (**b**) 325 localized whistles over 2 h in the early night show many short tracks over a wide area with slow overall group movement north of the array (from Wiggins et al. (2013); Figs. 5 and 6)

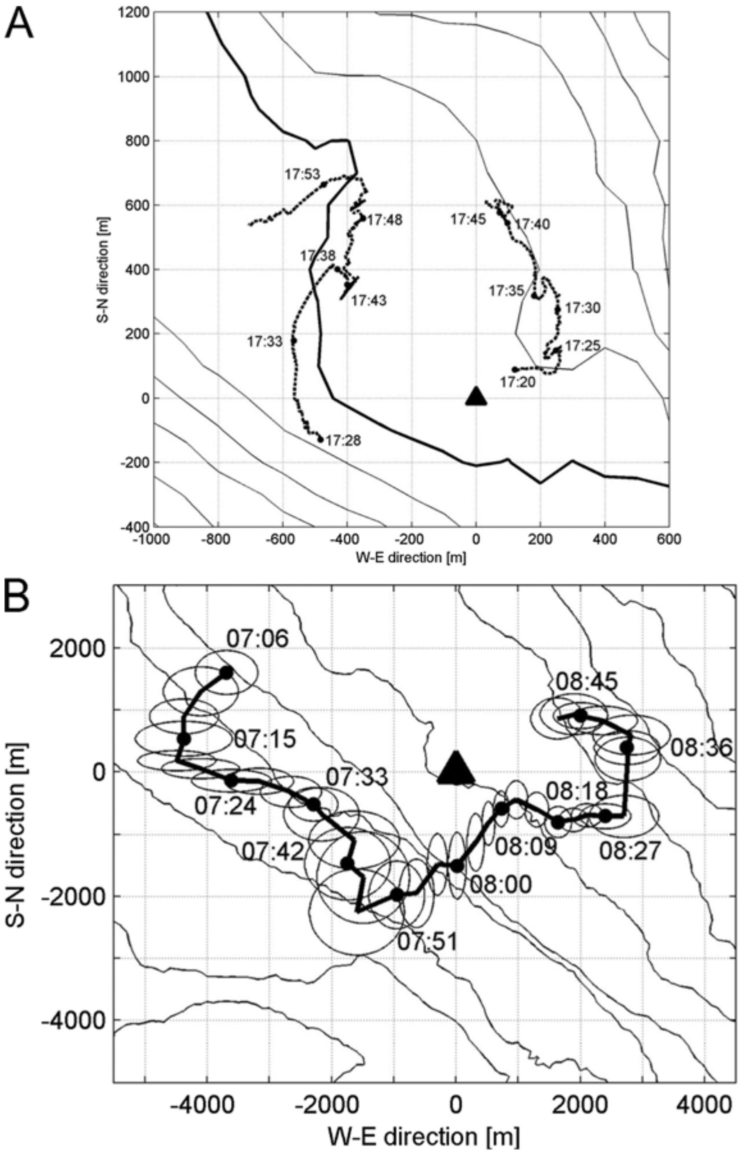

Fig. 3.18 Tracks from echolocation clicks using a HARP configured with a small aperture array offshore of southern California in 2009. (**a**) Two beaked whale tracks show slightly different behaviors, but both appear to follow the seafloor bathymetry. *Dark contour* is 1000 m and *light contours* are 10 m increment, deeper to the northeast. (**b**) Median dolphin group track with standard deviation error *ellipses* showing group spread. *Dark triangle* (HARP) is on 1000 m contour, other contours are 100 m apart with deeper to the northeast (from Wiggins et al. (2012); Figs. 5 and 7)

remote and inhospitable locations for relatively low cost. HARP wideband recordings (100 kHz) include high-fidelity sounds from endangered blue, fin, and right whales, rarely observed and unknown species of beaked whales, and free-ranging dolphins with distinct click types. Long duration temporal and spatial patterns of these sounds are being used with environmental measures to develop predictive cetacean distribution models for ecological studies and conservation and management efforts. In addition, ARP and HARP calibrated hydrophones have provided cetacean source levels and detection ranges as well as ambient noise levels which can be used with distance sampling techniques to estimate population densities.

While HARPs will continue to be used to monitor cetaceans over long periods in fixed-point independent and large aperture array configurations, additional configurations and advanced capabilities are being developed, for example, recently a HARP has been integrated into a Wave Glider and recorded dolphin whistles and clicks while transiting offshore of Kona, Hawaii (Willcox et al. 2009)

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Chapter 4
From Shrimp to Whales: Biological Applications of Passive Acoustic Monitoring on a Remote Pacific Coral Reef

Marc O. Lammers and Lisa M. Munger

Abstract Passive acoustic monitoring (PAM) can be an effective tool for studying marine fauna in coral reefs and other ecosystems. We analyzed PAM data from 2006 to 2009 at French Frigate Shoals (FFS) in the Northwestern Hawaiian Islands. We measured received sound pressure levels (SPL) over time within different frequency bands from 0 to 20 kHz, and used automated and manual techniques to detect parrotfish scrapes and cetacean vocalizations. SPLs were greatest overall in the snapping-shrimp-dominated bands above 2.5 kHz, and they increased at night and decreased during cold months. In frequency bands <1.5 kHz, containing mainly fish sounds (and seasonal whale song), SPL peaked at dawn and dusk. Humpback whale song was detected in December through April; occurrence was greater during 2008–2009 than 2006–2007, possibly reflecting an increase in whale density near FFS. Parrotfish bite sounds were detected year-round, and parrotfish foraged most actively during the afternoon. Dolphins were detected on 12–64 % of days per month, with low levels of activity during the day that increased in late afternoon and were highest at night. More frequent detections of dolphins in February/March 2007, October 2008, and February/March 2009 may correspond to pulses of food availability via the mesopelagic prey community. Minke whale "boing" sounds were detected from late October, with one or two peaks in the December–March period; during March 2009 minke whale calls were present nearly every day. The results provide the first long-term record of minke whales in the NWHI, and show the potential of PAM on remote coral reefs to monitor patterns over time of many trophic levels, from herbivores to apex predators.

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4.1 Introduction

Long-term ecological monitoring of coral reefs is crucial for assessing the effectiveness of management efforts and documenting changes over time in reef health and biodiversity. However, traditional visual survey techniques are labor intensive, expensive, and logistically challenging in remote areas, potentially disruptive to organisms, limited to daylight and good weather/sea conditions, and often provide only a "snapshot" view of an ecosystem at a particular time. Passive acoustic monitoring (PAM) can be an effective and complementary tool for coral reef research and long-term monitoring of both biotic and abiotic sound sources. Passive acoustic recorders can be relatively cost effective (e.g., compared to ship and personnel time), cause minimal disturbance, can operate during nighttime and poor weather conditions, and can autonomously collect continuous data for months to years. These data sets can provide information on the distribution, abundance, and behavior of numerous species concurrently, as well as environmental conditions, anthropogenic noise, and changes of the soundscape over time.

The use of sound for communication and perception of the environment is essential for many marine animals. In coral reef and other nearshore ecosystems, numerous animal taxa such as crustaceans, fish, and cetaceans produce repeated and identifiable sounds within a variety of behavioral contexts. The most ubiquitous sound on tropical and subtropical reefs is produced by snapping shrimp in association with feeding (Au and Banks 1998; Lammers et al. 2006a; Versluis et al. 2000), but sounds are known from other crustaceans such as the defense sounds of spiny lobsters (e.g., Bouwma and Herrnkind 2009; Patek et al. 2009; Staaterman et al. 2009) and mantis shrimp (Patek and Caldwell 2006). Numerous fish species on coral reefs are also known to produce sounds associated with a variety of behavioral functions, including feeding, courtship, spawning, territorial defense, agonistic, and other behaviors (e.g., Boyle and Cox 2009; Lobel 2002; Lobel and Kerr 1999; Lobel et al. 2010; Mann et al. 2009; Maruska et al. 2007; Myrberg et al. 1993; Myrberg 1997; Parmentier et al. 2005, 2009; Rountree et al. 2006; Tricas et al. 2006; Tricas and Boyle 2014). Marine mammal (especially cetacean) calls have been extensively characterized for many species and populations, and passive acoustic monitoring (PAM) has become a reliable technique to investigate species occurrence and their distribution, behavior, population structure, abundance, and ecology (Mellinger et al. 2007; Van Parijs et al. 2009).

Taken together, the cumulative "soundscape" of biological and environmental sounds is an important feature of the nearshore environment in and of itself, and varies distinctly between localized habitats (Radford et al. 2010). The sound signature of coral reefs has been documented to be an important attractant for the pelagic larvae of some corals, crustaceans, and reef fish to find suitable habitats for settlement (e.g., Leis and Lockett 2005; Montgomery et al. 2006; Vermeij et al. 2010), with the component produced by snapping shrimp being the primary noise to which some larval fish are attracted (Simpson et al. 2008). Snapping shrimp noise intensity (and therefore the overall soundscape) varies cyclically on diel, lunar, and seasonal time scales, as well as in response to environmental variables such as rainstorms

(Lammers et al. 2006a, 2008a) and water quality (Watanabe et al. 2002), and may also be a good indication of habitat quality measures such as substrate rugosity. As such, soundscape-level patterns in acoustic activity on coral reefs can be indicative of reef health and resilience, and ever-increasing anthropogenic noise in the ocean may have negative impacts on reef communities over time by disrupting or masking biologically relevant sounds.

As technology for underwater recording and storage/transmission of acoustic data continues to advance, so does the potential for acoustic monitoring to provide valuable information on a range of biological, spatial, and temporal scales (Van Parijs et al. 2009). Passive acoustic monitoring of coral reefs has the potential to provide a wealth of information on the biodiversity, health, and change over time of coral reef and other marine communities. In this chapter, we explore the application of long-term PAM over a three-year period at French Frigate Shoals, a remote atoll within the Papahānaumokuākea Marine National Monument (Northwestern Hawaiian Islands). We examine variation of the soundscape over time by calculating received sound pressure levels within different frequency bands, each of which broadly represents a different group of sound-producing taxa. We then present case studies of specific organisms whose known sounds were detected within the data sets: parrotfish feeding scrapes and the calls/songs produced by three marine mammal taxa: delphinids, humpback whales, and minke whales. Each of these groups represents a different trophic level and plays an important ecological role either on the coral reef itself or within the broader nearshore ecosystem. Parrotfish scrapes represent instances of fish feeding on reef algae and are therefore an indicator of a primary consumer's activity on the reef. Cetaceans use nearshore habitats for the purposes of feeding, resting, calving, nursing, and breeding. They interact with the ecosystem in a variety of ways, including as secondary consumers, prey and vectors for nutrient influx (Smith et al. 2013; Lavery et al. 2014), and microbial transport (Apprill et al. 2011).

4.2 Methods and Results

NOAA's Pacific Islands Fisheries Science Center (PIFSC), in partnership with the Hawaii Institute of Marine Biology, initiated a passive acoustic coral reef monitoring program in 2006. Long-term data were obtained using Ecological Acoustic Recorders (EARs; Lammers et al. 2008a), which record autonomously on a programmable sampling schedule for months to years (Fig. 4.1). EARs were deployed by divers between 2006 and 2010, in conjunction with vessel-based surveys at over 50 locations on reefs throughout the tropical Pacific, including several in the Northwestern Hawaiian Islands. We examined data from an EAR deployed at French Frigate Shoals (FFS), located in the northwestern Hawaiian Islands. The EAR was first deployed on 6 September 2006 at Rapture Reef on the south side of FFS (23° 38.1 N, 166° 11.1 W) at a depth of 23.5 m (Fig. 4.2). The site is adjacent to the slope of the shoals and is approximately 1.5 km from the 500-m isobath and 2.2 km from the 1000-m isobath.

Fig. 4.1 EAR deployed on a coral reef

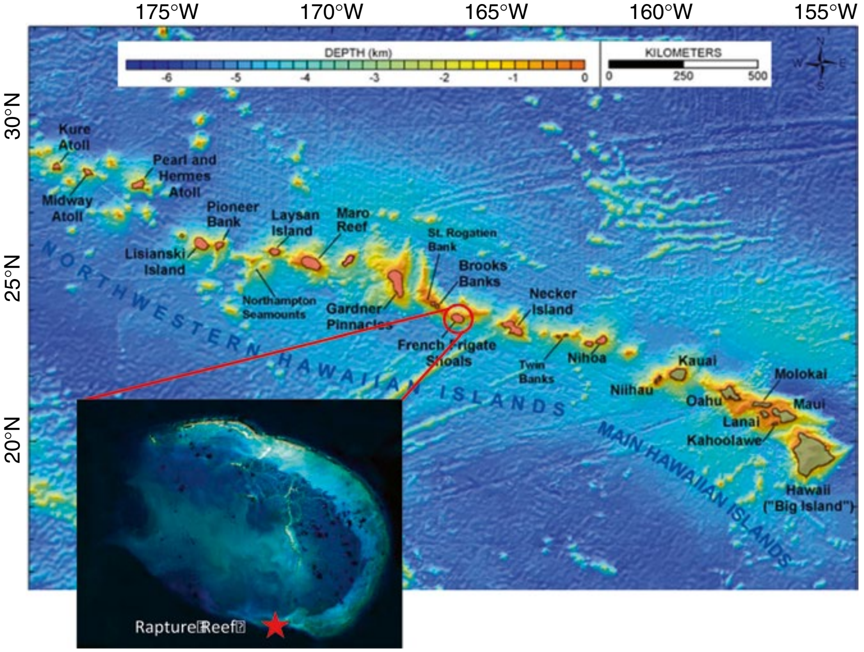

Fig. 4.2 Hawaiian Island archipelago and NOAA bathymetric map of French Frigate Shoals (*inset*). The *red star* indicates the location of Rapture Reef

The EAR was programmed to record for 30 s every 15 min at a sampling rate of 40 kHz, providing an effective recording bandwidth of 20 kHz. The first deployment recorded ambient sounds until the EAR ran out of power on 31 May 2007. That unit was replaced on 25 September 2007 with a new EAR. This second deployment obtained data between 1 October 2007 and 8 February 2008. The third and final deployment was made on 15 September 2008 and data were recorded between 21 September 2008 and 14 July 2009.

4.2.1 Frequency Band Analysis

The soundscape at Rapture Reef was analyzed by calculating ambient noise received levels within different frequency bands of recording. For each of the 30-s recordings, root-mean-square (RMS) sound pressure levels (SPL) were calculated in Matlab™ using

$$\text{RMS SPL} = 20\log\sqrt{\frac{1}{T}\int_0^T p^2(t)\,\mathrm{d}t}$$

where T is the duration of each file and $p(t)$ is pressure p re 1 μPa at time t of the acoustic waveform. This calculation was performed for the full frequency band (0–20 kHz) and also the five following 1-octave bands: 0–1.25, 1.25–2.5, 2.5–5, 5–10, and 10–20 kHz. The RMS SPL values for each recording were averaged over each day to provide a time series of ambient noise variability over the duration of the deployment, and were also averaged by the hour of the 24-h day (e.g., 8 AM, 9 AM) to investigate diel patterns over the warm (May–Oct) and cold (Nov–Apr) month periods.

Ambient sound levels were 5–10 dB greater in the two highest frequency octave bands (>5 kHz) than in the three bands below 5 kHz, with the lowest sound levels in the 1.25–2.5 kHz band (Fig. 4.3). Sound levels decreased slightly by 1–2 dB between warm and cold periods, but exhibited higher variability during cold months (Fig. 4.3). This variability was more pronounced in the two lowest octave bands (0–1.25 and 1.25–2.5 kHz), and was due primarily to the seasonal occurrence of singing humpback whales in the NWHI during winter months (Lammers et al. 2011).

Ambient noise increased at night in all frequency bands greater than 1.25 kHz (Fig. 4.4). Acoustic energy in the 0–1.25 kHz band was either unchanged or greater during daytime hours. In addition, this band exhibited consistent peaks in sound levels of 3–5 dB during crepuscular periods at dawn and dusk (~0600–0700 and ~1800–2000), concurrent with the shift from daytime to nighttime levels in the other frequency bands, The octave band between 1.25 and 2.5 kHz contained the lowest amount of acoustic energy and had either a weak or no diel trend, reflecting an intermediary pattern between the lowest octave band and the bands above 2.5 kHz (Fig. 4.5).

These differences in temporal patterns by frequency band are suggestive of an acoustic niche partitioning process by sound-producing animals on the reef similar to ones described for animals in tropical and temperate woodlands (Depraetere et al. 2012; Sueur et al. 2008). Snapping shrimp (family Alpheidae) produce the major component of reef noise at frequencies above 2 kHz. Individual shrimp produce high-amplitude (~190 dB re 1 μPa) broadband clicks (~2 to >200 kHz) while capturing zooplanktonic prey with large frontal chela (claws) and also during territorial defense (Au and Banks 1998; Versluis et al. 2000). These sounds dominate the ambient noise field in most tropical and temperate nearshore reefs and can easily be heard by human swimmers and divers as a constant crackling sound. The reduction in acoustic received level in the octave bands associated with snapping shrimp activity (≥2.5 kHz) during cold months in 2006–2007 and 2008–2009 is consistent with seasonal trends previously reported by Lammers et al. (2006a), which documented

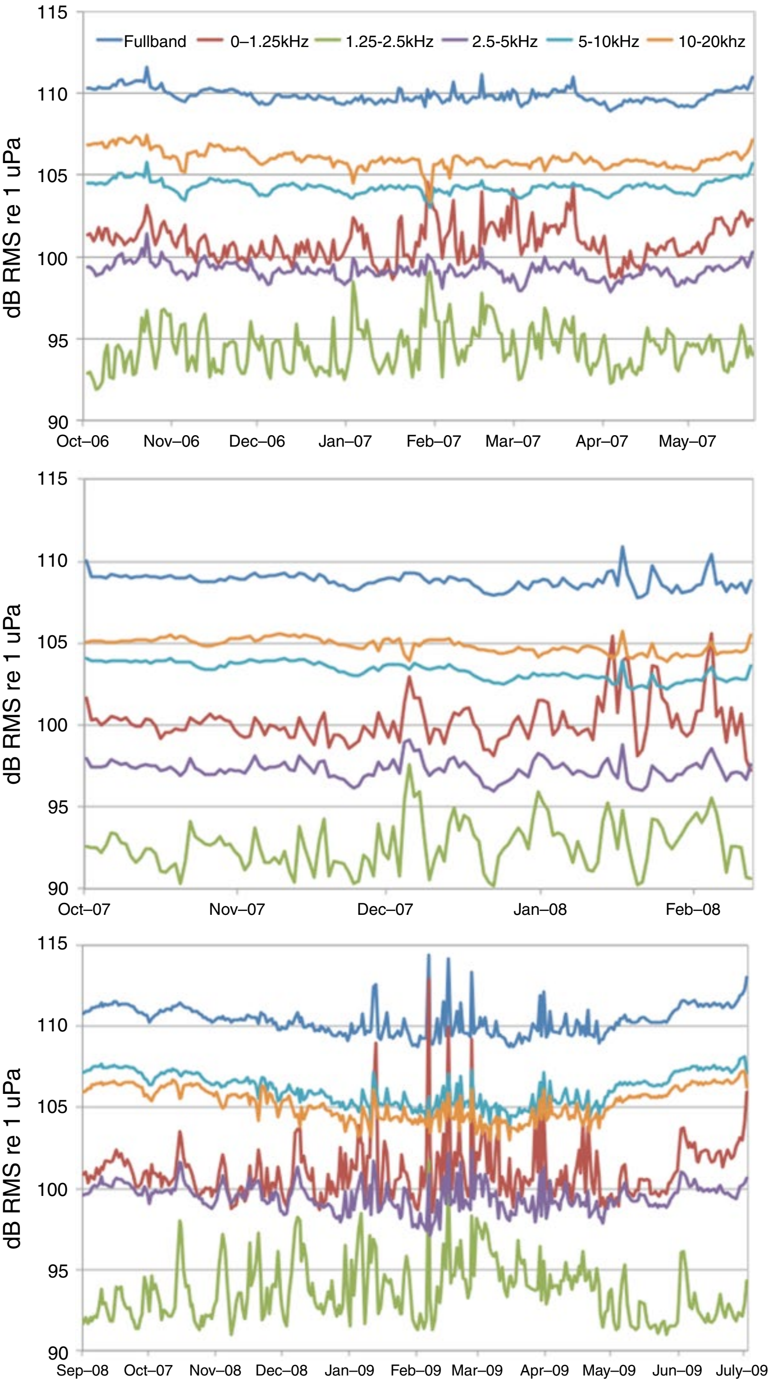

Fig. 4.3 Daily mean RMS sound pressure level within the full effective bandwidth and five octave bands measured at Rapture Reef, French Frigate Shoals between Oct 2006 and May 2007, Oct 2007 and Feb 2008, and Sep 2008 and Jul 2009

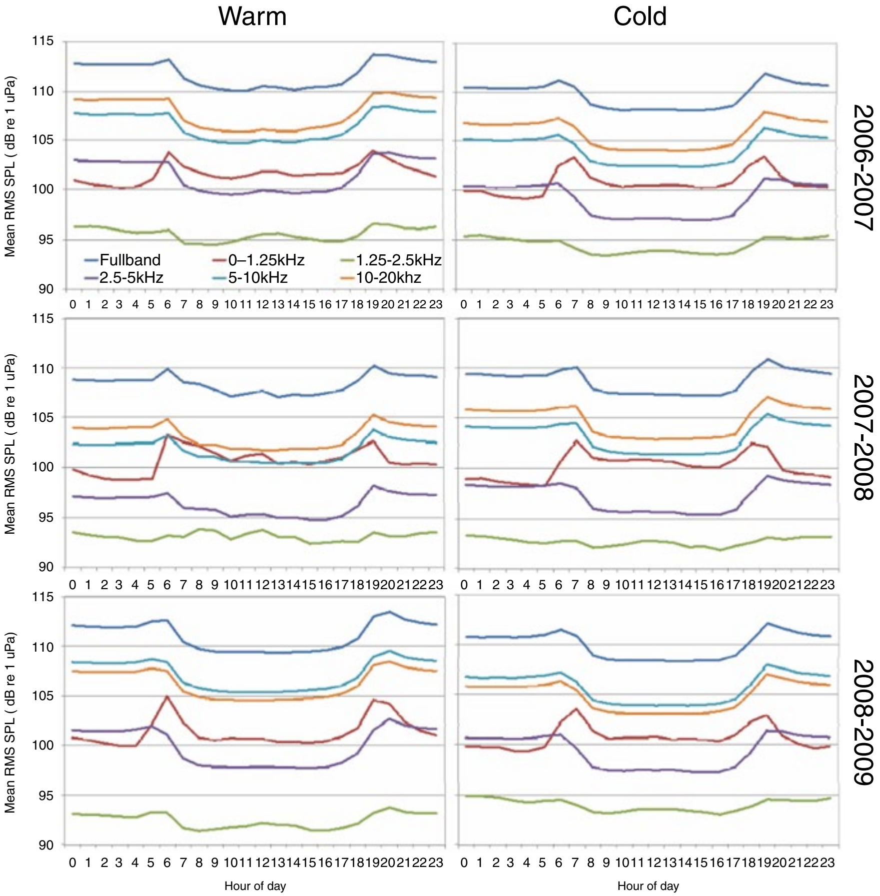

Fig. 4.4 Hourly averaged SPL during warm (May–Oct) and (Nov–Apr) cold months at French Frgate Shoals, for EAR deployments between 2006 and 2009

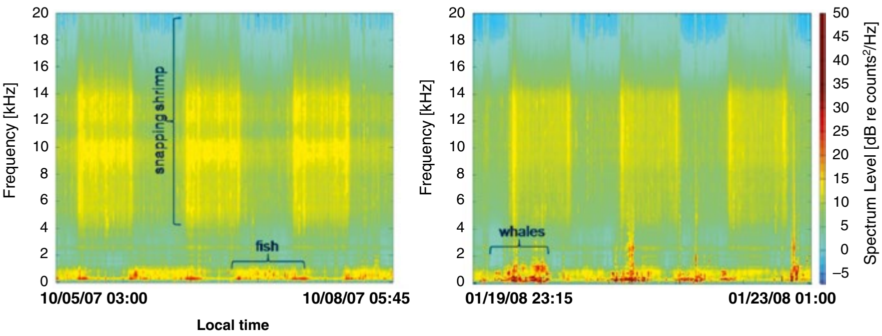

Fig. 4.5 Long-term spectrograms of 3-day periods from French Frigate Shoals during October 2007 (*left*) and January 2008 (*right*)

reduced snapping shrimp acoustic activity with lower water temperatures. In 2007–2008, only one month of warm period data (October) was obtained, which precluded comparison between warm and cold periods.

At frequencies below ~2 kHz, reef fish are the predominant source of acoustic signaling. Tricas and Boyle (2014) recently characterized the acoustic properties of 85 sounds produced by 45 species of Hawaiian reef fish. Of these, 95.3 % had peak frequencies below 1.4 kHz. Thus, it is reasonable to presume that the temporal patterns observed in the 0–1.25 kHz band most likely reflect the acoustic activity patterns of reef fish near the EAR. There was little variation between warm and cold-water periods in the diel pattern of the lowest octave band, suggesting that in aggregate, reef fish sound production is not a predominantly seasonal phenomenon. Small (1–2 dB) interannual variations were observed between deployments in this and also other bands, but it is not clear whether these reflect changes in acoustic activity from year to year or variations in hydrophone sensitivity between the EAR units used for each deployment. The minimum in ambient sound levels within the 1.25–2.5 kHz frequency band may reflect the transition from frequencies dominated by fish (and seasonally, humpback whales) to invertebrate-dominated frequencies.

4.2.2 Parrotfish Analysis

The data set obtained between September 2008 and July 2009 was examined for the presence of bite and scrape sounds produced by grazing parrotfish. To search for these sounds, EAR data were filtered using an eighth-order low-pass Chebyshev Type I filter with a cutoff frequency of 1600 Hz and downsampled to a new sample rate of 4 kHz (effective bandwidth = 2 kHz) prior to analysis. Due to the large volume of data, spectrogram data were searched manually for parrotfish sounds on a subset of data, every fourth day, and on that day each sound recording file was examined visually to detect potential parrotfish scrapes (Fig. 4.6), which were played back to the analyst to confirm identity as fish scrapes. The number of parrotfish scrapes within each file was recorded and given a subjective quality rating of 1 through 7, with 1 being the poorest quality (low SNR) and highest uncertainty (for example, not co-occurring with other scrape sounds or not audibly similar to known parrotfish scrapes), and 7 being the best quality (high SNR) and greatest confidence (occurrence with other sounds and resemblance to known parrotfish recordings and field observations). The highest uncertainty sounds were not included in further analyses. Parrotfish bite sounds were detected year-round at Rapture Reef (Fig. 4.7). Fish foraged most actively during the afternoon (Fig. 4.8), which is consistent with previous studies of parrotfish foraging behavior in other parts of Hawaii (Jayewardene 2009; Ong and Holland 2010).

Parrotfish are an important ecological component of tropical reef ecosystems. One potential application of PAM of fishes is estimating abundance, which would be a cost-effective and valuable management tool for ecologically important species such as parrotfish. As herbivores (and sometimes corallivores), parrotfish play a major role in algae removal, bioerosion of reef substrate, resilience, and benthic community structure (Mumby 2009; Rotjan et al. 2006). They are also heavily fished in many

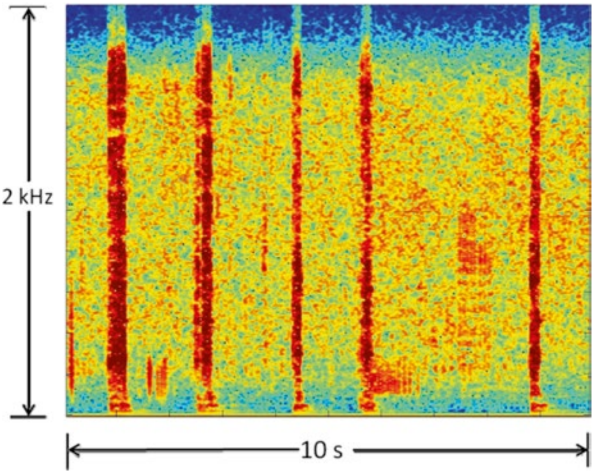

Fig. 4.6 Spectrogram of broadband parrotfish scrapes (at 1, 2.7, 4.4, 5.8, and 8.9 s), and other unidentified fish sounds below 1 kHz (at ~1.8, 6, and 7.7 s)

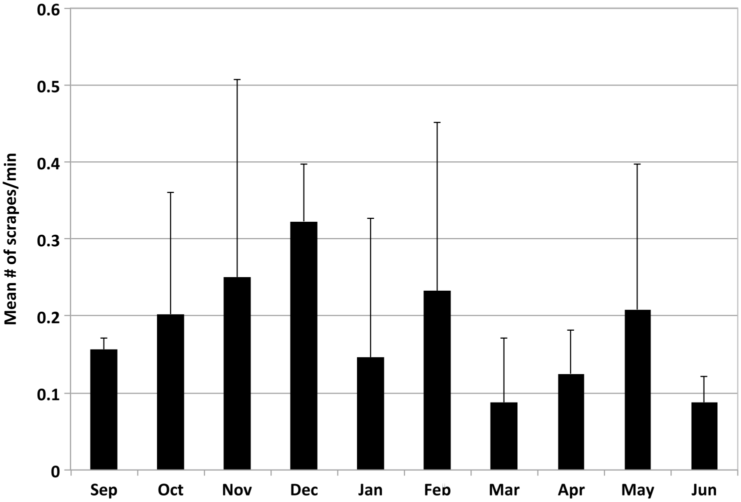

Fig. 4.7 Monthly mean and standard deviation of parrotfish scrapes per minute for the FFS EAR deployment made between September 2008 and July 2009

locations, which may lead to ecosystem-wide impacts such as increased algal cover. In the main Hawaiian islands, parrotfish are a high priority for resource managers, and population abundance is monitored by conducting visual surveys on SCUBA. However, parrotfishes are highly mobile and somewhat skittish around SCUBA divers, particularly in areas where fishing pressure is high, and are hence prone to being undercounted (Lobel 2005). Passive acoustic monitoring has potential as a tool for estimating abundance of parrotfish and other fish species of concern, and PAM could thus be a cost-effective tool for managers over long time periods and in remote areas.

In order to apply PAM as a tool for abundance estimation, further work is necessary to collect data on the characteristics and propagation distance of parrotfish

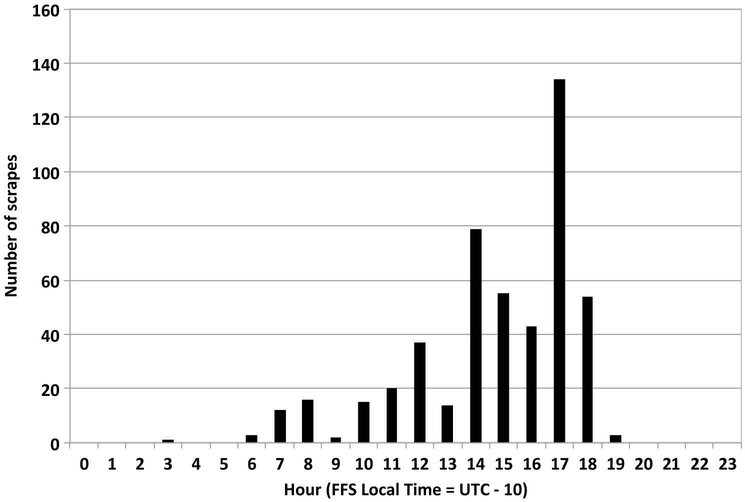

Fig. 4.8 Parrotfish scrape counts by hour of the day

foraging sounds. This information is required for acoustics-based abundance estimation using distance sampling methodology, similar to the methodology demonstrated for cetaceans using fixed passive acoustic sensors (e.g., Marques et al. 2009, 2011). Other required information for abundance estimates includes bite rates and the influence of covariates such as body size (Thomas et al. 2010), for which published information exists from visual surveys. Parrotfish bite rates and types (i.e., scraping versus excavating) vary by species, body size, and time of day (Ong and Holland 2010), and further characterization of the acoustic features of parrotfish bites may enable researchers to relate bite sounds to variables such as species and body size.

4.2.3 Cetacean Analysis

Data obtained from the EAR were processed for cetacean sounds using a custom (M. Lammers) Matlab™ script. The script was designed to identify periods of tonal signaling indicative of the presence of dolphin whistles and whale calls in the recordings (Lammers et al. 2008a). An automated short-time Fourier transform approach was used to find periods when tonal peaks greater than 3 dB above the averaged noise floor were present in the frequency spectrum. These periods were then summed for each recording, and those with tonality exceeding 1 % of the total recording time were visually examined to confirm the presence of cetacean signals. Recordings with confirmed dolphin or whale signals were designated "detections." In addition, to investigate the relative abundance of signals over time, 10 % of recordings from each site were randomly selected for each month and visually and aurally examined for the presence of signals. This provided a proportional measure of the number of recordings per month that contained certain kinds of cetacean

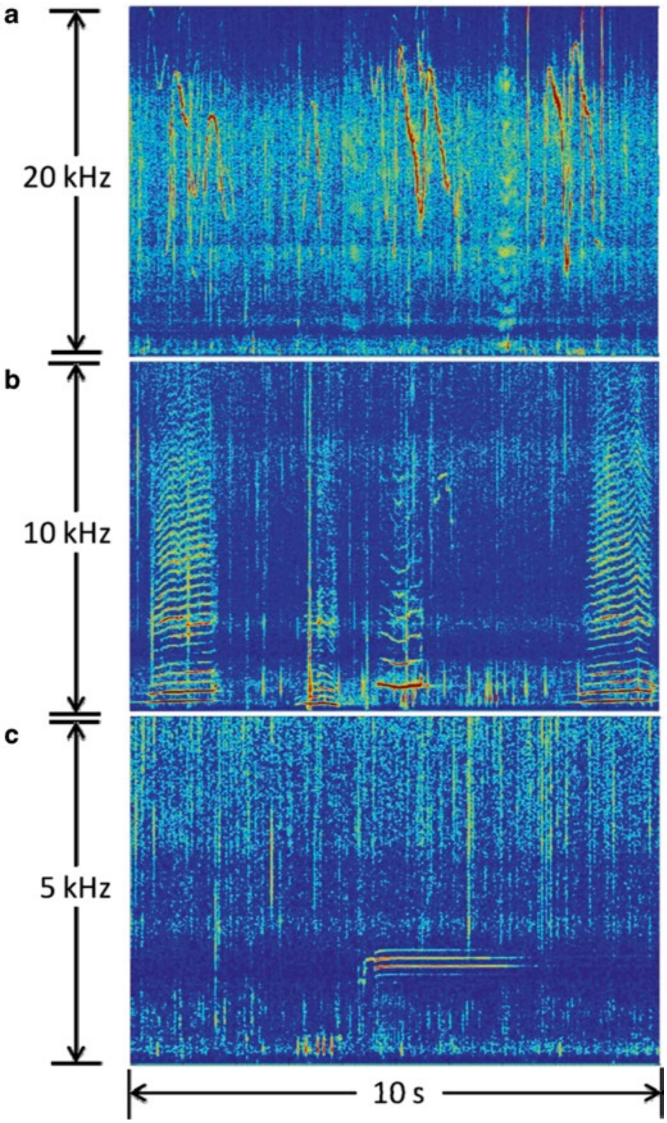

Fig. 4.9 Spectrogram examples of (**a**) dolphin whistles, (**b**) humpback whales song units, and (**c**) a minke whale boing call

signals. No attempt was made to identify calls below 50 Hz, such as those produced by blue whales (*Balaenoptera musculus*) and fin whales (*Balaenoptera physalus*), because such low-frequency signals do not propagate well in the relatively shallow waters in which the EAR was deployed (Urick 1983).

Three types of cetacean signals were found in the recordings: dolphin whistles (Fig. 4.9a), song units from humpback whales (Fig. 4.9b), and "boing" sounds produced by minke whales (Fig. 4.9c) (Rankin and Barlow 2005). The whistles produced by dolphins could not be identified to the species level. However, the frequency range of the majority of whistles was between 7 and 17 kHz. Of the delphinid species occurring in nearshore Hawaiian waters, this range is consistent with the whistles of spinner dolphins (*Stenella longirostris*), bottlenose dolphins (*Tursiops truncatus*), and/or spotted dolphins (*Stenella attenuata*) (Oswald et al. 2007).

4.2.3.1 Dolphins

The occurrence of dolphins was relatively common at Rapture Reef, with detections occurring between 12 and 64 % of days per month during the monitored periods (Fig. 4.10). In general, the month of December had the fewest days of dolphins detected, whereas the period between February and March had the highest occurrence.

Except during the months of January and May, the 2008–2009 deployment period had more days with dolphin signals present per month than the other two monitoring periods. Significantly more detections were made at night between the hours of 20:00 and 5:59 than 6:00 and 19:59 (2-sample *t*-test; $t=3.03$; $P=0.004$) (Fig. 4.11). Over the 3-year period, daytime detections were consistently low during midday hours (1100–1459) and high during the late afternoon (1500–1759). Periods of anomalously high dolphin activity were detected in February/March 2007, May 2007, October 2008, and February/March 2009, when the number of night and/or daytime detections was multiple times greater than the monthly median occurrence (Fig. 4.12).

The consistent occurrence of dolphins at Rapture Reef suggests that one or more species are resident in the area. Of the three species identified as the likely source of the signals, both bottlenose dolphins and spinner dolphins are known to occupy the nearshore waters of FFS (Andrews et al. 2010; Lammers, pers. obs.). The occur-

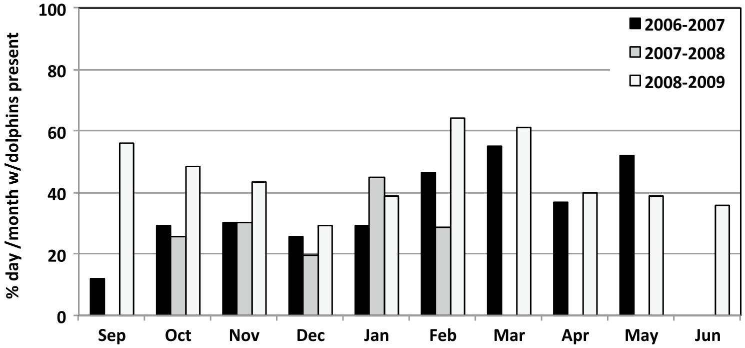

Fig. 4.10 Occurrence of dolphin whistles at Rapture Reef, FFS, measured by the percentage of days per month that dolphin whistles were detected in recordings between 2006 and 2009. *Note*: Months with no dolphin detections are due to an absence of recording effort in those months during those years, rather than to zero detections

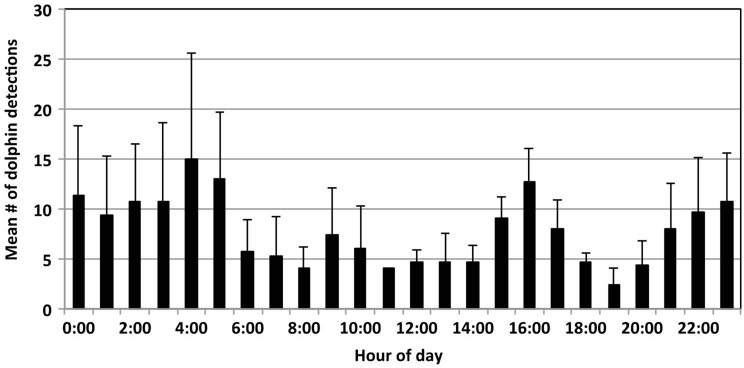

Fig. 4.11 The timing of dolphin whistles at Rapture Reef, FFS, detected by the automated algorithm separated hourly and averaged across the three deployment periods. Error bars represent standard deviations

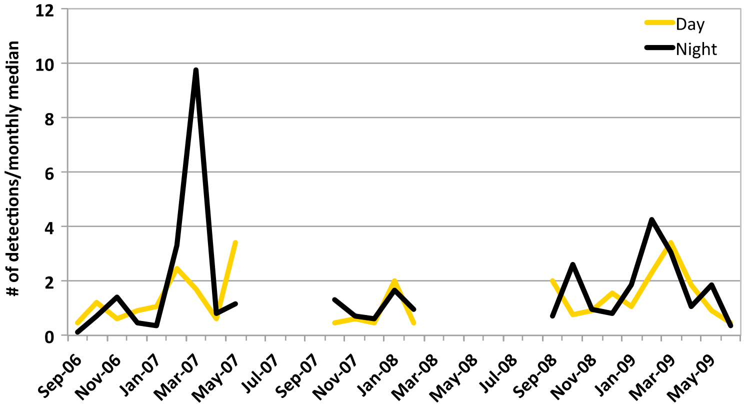

Fig. 4.12 The number of daytime and nighttime detections for each month normalized by the median of each category. High peaks indicated months that contained anomalously high numbers of dolphin acoustic detections

rence and timing of signaling in shallow waters are consistent with behavioral and acoustic patterns observed from spinner dolphins in the main Hawaiian Islands (MHI) (Lammers 2004; Lammers et al. 2008b). The low level of signal occurrence during midday hours followed by a late afternoon peak is characteristic of spinner dolphin acoustic behavior at resting locations (Lammers et al. 2008b). In both the MHI and NWHI, spinner dolphins seek out shallow water areas to rest during morning and midday hours and recover from nocturnal foraging activities (Karczmarski et al. 2005; Norris et al. 1994). In the late afternoon they become active again before moving offshore to begin foraging on the mesopelagic boundary community (MBC), a community of fish, shrimp, and squid that resides in deep waters during the day, but migrates both vertically toward the surface and horizontally toward shore at night (Benoit-Bird et al. 2001; Benoit-Bird and Au 2004).

Echosounder surveys conducted at FFS have documented the nocturnal migration of a strong MBC associated with the island slope (Lammers et al. 2006b). Although it cannot be established whether spinner dolphins or another species are the primary source of nocturnal signals observed at Rapture Reef, the high incidence of signaling at night does suggest that dolphins are likely feeding in the area. In the MHI, spinner dolphins follow the MBC as it moves inshore at night (Benoit-Bird and Au 2003). Therefore, the consistent occurrence of dolphins in the area during nighttime hours suggests that the MBC's nocturnal migration reaches the inshore waters of Rapture Reef. This is ecologically significant because the MBC is an important source of prey for many species of benthopelagic and pelagic fish (Benoit-Bird et al. 2001) and likely contributes to the nutrient cycle of nearshore ecosystems (Benoit-Bird and Au 2004). Of special note are periods of peak nighttime dolphin occurrence. During February/March 2007, October 2008, and February/March 2009 dolphins were detected more frequently than usual at Rapture Reef at night, suggesting that these periods may reflect episodes of high MBC occurrence in the area tied to "pulses" of food availability, which may in turn be indicative of oceanographic or ecosystem processes that concentrate food in the area. Continued acoustic monitoring for the occurrence of dolphins could, therefore, help inform a long-term perspective on patterns in food availability and energy flux at this location.

4.2.3.2 Humpback Whales

Humpback whale song occurrence was seasonal, with the first singing whales detected each year around mid-December and the last whales recorded at the end of April or beginning of May. During the 2006–2007 deployment, a steady increase in the number of days per month with whale song detected occurred between December and March, followed by a rapid decline in April (Fig. 4.13). During the 2007–2008 deployment, the EAR only recorded until February 2008, but a similar seasonal trend in song occurrence was evident as in the previous year. In 2008–2009, the months with the highest number of days with song shifted to January and February, which were nearly equivalent. In addition, month by month, there were more days with humpback whale song in 2008–2009 than each of the previous two deployment periods, except in March when the number was slightly higher in 2007.

A statistical analysis of randomly selected recordings for each month comparing the 2006–2007 and 2008–2009 deployment periods confirmed that the latter period had significantly more recordings with whale song (Paired t-test, $t=2.99$, $P=0.04$). The increase in humpback whale singing activity between the two periods is also evident in the overall sound levels presented previously (Fig. 4.3). The period between January and April 2009 had both higher overall dB RMS levels and greater variability in the lower frequency bands, reflecting more humpback whale song energy than the same period in 2007. Whether the increases in humpback whale

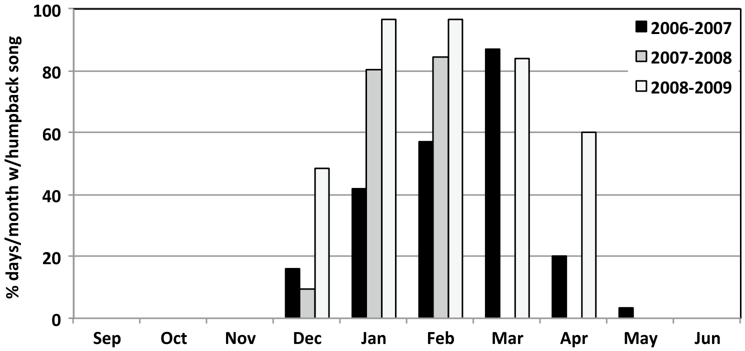

Fig. 4.13 Occurrence of humpback whale song units at Rapture Reef, FFS, measured by the percentage of days per month that whale song was detected in recordings between 2006 and 2009. *Note*: Months between March and May in 2007 without any detections are due to a lack of recording effort rather than an absence of detections

song observed at this location reflect changes in whale abundance at FFS is not clear, but certainly possible. The NWHI have been shown to be a more important wintering habitat than previously believed (Johnston et al. 2007; Lammers et al. 2011), so it is conceivable that the number of whales wintering at FFS increased proportionately to the estimated 6 % annual increase of the overall north Pacific population (Calambokidis et al. 2008). However, because these data do not allow us to localize or count singing animals near the EAR, the question cannot be directly addressed here.

4.2.3.3 Minke Whales

Minke whale boing sound occurrence was also seasonal and had a pattern similar to humpback whale song incidence (Fig. 4.14). However, whereas humpback whales were first recorded in December, minke whales began to be heard already in late October. In 2007–2008, the highest incidence of minke whale detections was evenly distributed between December and January. In both 2006–2007 and 2008–2009 there was an initial peak in January followed by a higher peak in March. In fact, in March 2009 minke whale calls were present nearly every day of the month. No diel variation in the occurrence of signals was evident. These data are the first long-term acoustic record of minke whale occurrence in the NWHI and suggest that this portion of the archipelago may be an important winter breeding area or a migration route. Of the approximately 19 species known or believed to regularly occur in the Hawaiian Archipelago (Barlow 2006), to date only spinner dolphin (*Stenella longirostris*) (Andrews et al. 2010; Karczmarski et al. 2005), humpback whales (Johnston et al 2007; Lammers et al. 2011), and false killer whales (Baird et al 2013) have received focused scientific attention in the NWHI. The data presented here suggest that minke whales also exploit the coastal waters of the NWHI and may be seasonally common near FFS.

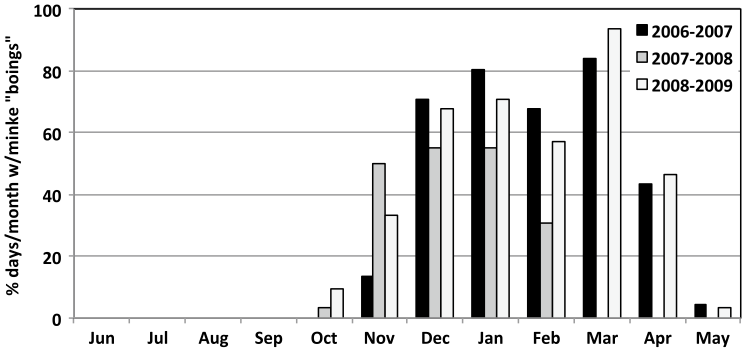

Fig. 4.14 Occurrence of minke whale boings at Rapture Reef, FFS, measured by the percentage of days per month that minke whale calls were detected in recordings between 2006 and 2009. *Note*: Months between March and May in 2007 without any detections are due to a lack of recording effort rather than an absence of detections

4.3 Discussion

The results presented in this chapter demonstrate the potential of using long-term PAM sensors in remote coral reef ecosystems to address biological questions relating to the acoustic environment and a variety of taxa, from primary consumers to apex predators. Temporal patterns in the ambient soundscape reveal variations between seasons and years at French Frigate Shoals, and show division of the soundscape into acoustic "niches" (frequency bands) used by different groups of animals. Examining these niches in more detail and relating observed variations with other biotic (e.g., fish biodiversity, chlorophyll levels) and abiotic (e.g., temperature, turbidity) factors is likely to yield new insights into patterns of biological activity on coral reefs and the mechanisms that drive them. In addition, we have provided a starting place for monitoring the abundance of an ecologically important herbivore, parrotfish, and have shared new information on the occurrence of cetaceans in the Northwestern Hawaiian Islands (NWHI).

We have shown how a single acoustic sensor can potentially provide information on species diversity, trends in abundance, behavior, temporal patterns of presence or activity, and ecologically relevant patterns of soundscape variation. When combined with other remotely sensed and in situ data sets, a comprehensive view can emerge for how temporal, environmental, and biological variables affect the acoustic behavior of reef animals. Moreover, spatial comparisons using additional PAM data sets could reveal how the acoustic features of an area might be used as indications of biodiversity (e.g., Riede 1993, 1997; Sueur et al. 2008) and ecosystem health or resilience.

The use of passive acoustics as a research tool for long-term monitoring of biological communities on coral reefs is a comparatively young field. The utility of PAM has been demonstrated for studying the behavior of fish species in many habitats and over a variety of time scales (e.g., Lobel 2002; Lobel et al. 2010; Locascio and Mann 2008, 2011; Luczkovich et al. 2008; Mann et al. 2009; Mann and Lobel 1995; Nelson et al. 2011; Van Parijs et al. 2009; Wall et al. 2013). However, many of the hundreds of sound-producing fish species are known only from laboratory studies, e.g., Fish and Mowbray (1970), and until recently, biological sounds have rarely been studied directly on coral reefs (Mann and Lobel 1995; Myrberg and Fuiman 2002; Tricas and Boyle 2014). There is a need for basic research to discover and further characterize the acoustic repertoires of coral reef fishes, as well as the behavioral context and temporal patterns in their sound production (Rountree et al. 2006). Similarly, more work needs to be conducted to identify other sounds on coral reefs to species, such as dolphin whistles and the sounds produced (directly or indirectly) by certain invertebrates (e.g., urchin skeletons rattling, Radford et al 2008).

More detailed studies are also needed in order to further utilize autonomous long-term recordings, particularly to develop techniques for abundance estimation using acoustic sensors. The data needs include the source levels of signals, information on propagation loss, background noise, the sound production rate of individuals, the behavioral contexts of sound production, and other biological and environmental covariates. Finally, another major challenge associated with long-term acoustic data collection is the processing and detection of signals of interest within large volumes of data. Much like the field of molecular biology decades ago, passive acoustic monitoring is presently still limited by the ability to process and interpret large data sets in a timely manner. This challenge will likely have to be solved by drawing from a combination of fields and technologies, including signal processing, computer science, and data mining.

Because of their reliance on sound as part of many biologically significant processes, marine organisms are vulnerable to acoustic disturbances, particularly from humans. These include short-term, local disturbances such as vessel transits, military sonar, seismic airgun exploration, industrial activities such as pile-driving and blasting, as well as long-term increases in ambient noise pollution due to increased human activity on a global scale (commercial shipping, industrial, etc.). As global climate change continues to drive changes in species distribution, disease, coral bleaching events, etc., continued monitoring of coral reefs and other environments is critical, and the use of PAM should be included as a tool in any comprehensive monitoring program, together with efforts to continue identifying and characterizing the vast number of sound sources in the ocean.

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Chapter 5
Studying the Biosonar Activities of Deep Diving Odontocetes in Hawaii and Other Western Pacific Locations

Whitlow W.L. Au and Giacomo Giorli

Abstract Ecological acoustic recorders (EARs) have been deployed at several locations in Hawaii and in other western Pacific locations to study the foraging behavior of deep-diving odontocetes. EARs have been deployed at depths greater than 400 m at five locations around the island of Kauai, one at Ni'ihau, two around the island of Okinawa and four in the Marianas (two close to Guam, one close to Saipan, and another close to Tinian). The four groups of deep-diving odontocetes were blackfish (mainly pilot whales and false killer whales), sperm whales, beaked whales (Cuvier and Bainsville beaked whales), and Risso's dolphin. In all locations, the biosonar signals of blackfish were detected the most followed by either sperm or beaked whales depending on specific locations with Risso's dolphin being detected the least. There was a strong tendency for these animals to forage at night in all locations. The detection results suggest a much lower population of these four groups of odontocetes around Okinawa and in the Marianas and then off Kauai in the main Hawaiian Island chain.

5.1 Introduction

The use of autonomous remote passive acoustic monitoring (PAM) continues to grow as new and varied devices become commercially available. These devices are extremely useful in order to collect long-term (months) acoustic data on the presence of marine mammals in any area of interests, especially remote areas and in areas that are difficult to get to on a regular basis. The advantages and disadvantages

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of using PAM including the early history of the use of PAM have been discussed in Chap. 1 of this book and will not be repeated here. However, we emphasize again that PAM represent one of the few ways to obtain data in remote locations of the world and over periods of months and years.

Our knowledge of the distribution of cetacean in a large part of the Pacific has come mainly from shipboard visual line-transect cetacean surveys for over 30 years and are now conducted with combined visual and acoustics methods for over several years (Rankin et al. 2008). However, these surveys tend to occur infrequently with surveys occurring at intervals between half a year to several years. Only a handful of surveys have been performed around the Hawaiian Islands and more research needs to be conducted. In recent years large ship surveys have been complemented by shall-boat surveys close to shore (Barid et al. 2013). Very little survey efforts have been spent in other areas of the Pacific west of Hawaii including the northwest Hawaiian Islands. This chapter focuses mainly on monitoring efforts around the island of Kauai (Au et al. 2013) in the main Hawaiian Island chain with additional data from Okinawa and the Marianas.

There are approximately 18 species of odontocetes and six species of baleen whales that can be found in Hawaiian waters (Baird et al. 2009). Except for spinner dolphins (*Stenella longirostris*) and humpback whales (*Megaptera novaeangliae*) the locations and time of occurrence of these cetaceans cannot be predicted with any degree of certainty. Knowing what animals are present in a given body of water at any given time is important in order to understand the overall cetacean population dynamics. Where and when animals might be present may provide insights as to how different species utilize a given habitat. For example, spinner dolphins in Hawaii typically rest during the day in several different known locations along a coast. In the late afternoon and at night they may travel along the entire coastline at varying distances from shore foraging for food. They move with the mesopelagic boundary community throughout the night to optimize their foraging effort (Benoit-Bird and Au 2003).

The presence of deep-diving odontocetes around the island of Kauai detected by a number of autonomous remote PAM devices operating nearly simultaneously has been studied by Au et al. (2013, 2014). The studies by Au and his colleagues have been focused on Blainville's beaked whales, *Mesoplodon densirostris*, Cuvier beaked whales, *Ziphius cavirostris* sperm whales, *Physeter macrocephalus*, short-finned pilot whales, *Globicephala macrorhynchus*, and Risso's dolphin (*Grampus griesus*). These species are known to be present in Hawaiian waters (Baird et al. 2009, 2013) and they typically forage at depths as far down to approximately 1200 m. To complicate the study of these animals beaked whales and sperm whales do not emit whistle signals but only click signals, most of which are biosonar click signals. The same type of studies have been conducted in the Marianas and off Okinawa, in waters used by the US military.

Kauai is of special interest to the Navy since the Pacific Missile Range facility (PMRF) underwater test range exists in waters along the west and southwest coast.

Our objectives were to determine the daily pattern of detection of different species, relative number of detections, and the seasonal and diurnal patterns at five locations around Kauai. The diurnal behavior of biosonar activity was previously reported by Au et al. (2013, 2014). The Marianas is also of special interest to the US Navy with bases and facilities on the island of Guam with training exercise areas in the waters of Saipan and Tinian. The US Marines are presently on Okinawa although they will eventually close their bases there in the near future.

Our knowledge of the behavior of deep-diving odontocetes has expanded manyfold with the introduction of the D-tag (digital acoustic recording tag) developed at Woods Hole Oceanographic Institute (Johnson and Tyack 2003). DTAGs have been used to study deep-diving odontocetes such as Blainville's and Cuvier beaked whales (Johnson et al. 2004; Madsen et al. 2005), sperm whales (Miller et al. 2004), and short-finned pilot whales (Aguilar de Soto 2006; Aguilar de Soto et al. 2008). These same species are also present in Hawaiian waters (Baird et al. 2009, 2013).

Beaked whales, sperm whales, short-finned pilot whales, and Risso's dolphin are some of the deep-diving odontocete species that forage in a depth regime between several hundred meters down to slightly over 1200 m using their biosonar to hunt for prey (Johnson et al. 2004; Aguilar de Soto 2006). Johnson et al. (2004, 2006) reported that beaked whales can dive to depths on the order of 1200 m but do not emit biosonar signals until they descend below approximately 200 m below the surface. DTAG data collected by Miller et al. (2004) showed the steady use of regular biosonar clicks with creaks produced during the deepest part of dives by sperm whales. Aguilar de Soto et al. (2008) reported that short-finned pilot whales forage at depths between 250 and 1000 m using their biosonar to detect prey. Deep-diving odontocetes such as pilot whales, sperm whales, beaked whales, and Risso's dolphins prey on squids and deep-dwelling demersal fish.

Another device that has contributed to our expanding knowledge of deep-diving foraging odontocete is the autonomous high-frequency acoustic recording package (HARP) developed at the Scripps Institute of Oceanography (Wiggins and Hildebrand 2007). Use of the HARP was also accompanied by research to identify odontocetes by their biosonar signals. The use of a HARP off the Cross Seamount (Johnston et al. 2008; McDonald et al. 2009) and another in the waters of Palmyra Atoll (Baumann-Pickering et al. 2010) have successfully confirmed the presence of foraging beaked whales in both locations. Soldevilla et al. (2008, 2010) reported on the presence and behavior of Risso's dolphin (*Grampus griesus*) and Pacific white-sided dolphin (*Lagenorhynchus obliquidens*) in the Southern California Bight. These studies have demonstrated that some species of echolocating odontocetes can be identified by characteristics of their biosonar signals and autonomous remote recorders can collect data to study the long-term behavior of deep-diving odontocetes in a single location. Chap. 2 will be devoted to important findings from the use of Harps.

5.2 Identifying Odontocete Species by Their Biosonar Signals

The prevalent notion for many years was that species and groups of odontocetes could not be identified by their broadband biosonar clicks. Beam pattern measurements on the bottlenose dolphins (*Tursiops truncatus*), a false killer whale (*pseudorca crassidens*) and a beluga whale (*Delphinapterus leucas*) summarized in Au (1993) indicated that signals measured at angles away from the beam axis were distorted when compared with the signals measured on the beam axis. Not only were the off-axis signals distorted but the waveform and spectrum varied almost randomly as a function of angle in three-dimensional space. Measurements done in the field on the white-beaked dolphin (*Lagenorhynchus albirostris*) by Rasmussen et al. (2002), killer whale (*Orcinus orca*) by Au et al. (2004), Atlantic spotted dolphin (*Stenella frontalis*) by Au and Herzing (1997), dusky dolphins (*Lagenorhynchus obscurus*) by Au and Würsig (2004), and spinner dolphin (*Stenella longirostris*) and pantropical spotted dolphin (*Stenella attenuata*) by Schotten et al. (2003) all indicated that off-axis signals were distorted. However, measurements of biosonar signals produced by odontocetes that forage at deep depths indicate that these animals can be identified by their biosonar signals.

Sperm whales, being the largest of all odontocetes, should produce the biosonar signals with the lowest peak frequency (frequency of maximum energy). Madsen et al. (2002) and Mohl et al. (2003) reported peak frequency between 8 and 15 kHz for sperm whales. The physics of sound production indicate that sperm whales are probably the only animals that can produce biosonar clicks with such low peak frequency. Therefore, detected biosonar signals with peak frequency in this frequency range can only be produced by sperm whales. Beaked whales are the only odontocetes known to consistently produce biosonar signal that is frequency modulated (Johnson et al. 2004; Madsen et al. 2005; Zimmer et al. 2005). The spectra of Risso's dolphin biosonar clicks typically have a rippled feature between 20 and 30 kHz (Soldevilla et al. 2008). The biosonar signals of the Pacific white-sided dolphin (*Lagenorhynchus obliquidens*) also have a similar rippled structure between 20 and 30 kHz (Soldevilla et al. 2008); however, this species has not been seen in Hawaiian waters. According to Bauman-Pickering et al. (2011) the biosonar clicks of short-finned pilot whales and false killer whales (*Pseudorca crassidens*) have a peak frequency close to 30 kHz and it is often difficult to tell the two species apart acoustically. However, the sighting rate of false killer whales on visual surveys around the Hawaiian Islands is approximately 10 % of short-finned pilot whale sightings (Barid et al. 2013). Representative signals and spectrum from a sperm whale, a Risso's dolphin, and a short-finned pilot whale are shown in Fig. 5.1. The waveform and Wigner-Ville distribution showing frequency versus time distribution of a beaked whale biosonar signal are also shown in Fig. 5.1. In this chapter, no distinction is made between Blainville's and Cuvier's beaked whales. Both species are lumped into a single category.

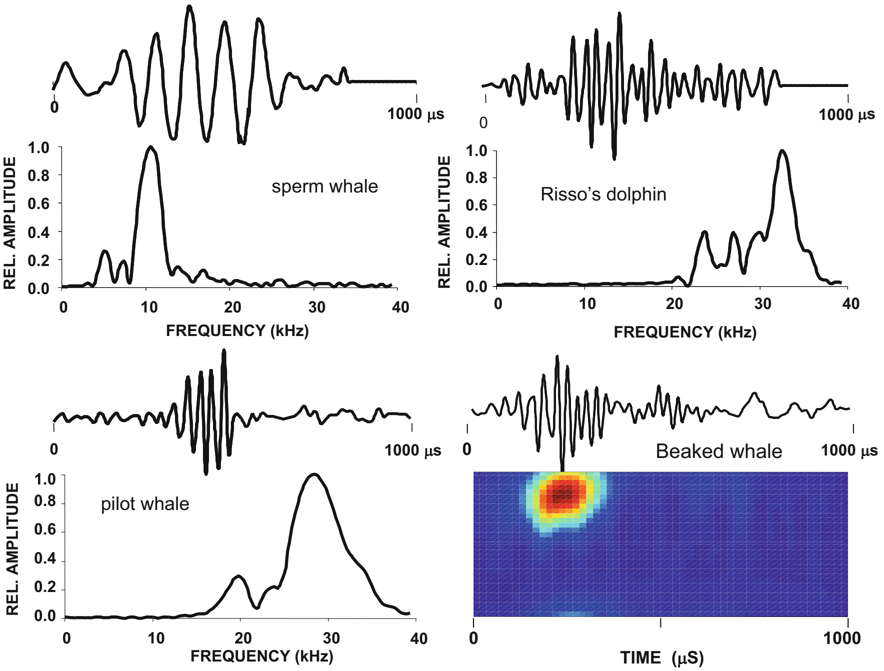

Fig. 5.1 Examples of waveforms and frequency spectra of biosonar clicks produced by sperm whales, short-finned pilot whales, and Risso's dolphins. The waveform and Wigner-Ville time-frequency distribution are shown for a representative beaked whale signal. All signals were extracted from EAR recording being discussed in this manuscript

5.3 Marine Mammal Monitoring on Navy Ranges (M3R) Software

The acoustic data of Au et al. (2013, 2014) were analyzed with the class-specific support vector machine (CS-SVM) portion of the M3R software (Jarvis et al. 2008; Jarvis 2012) and custom Matlab programs. The M3R (Jarvis et al. 2008; Jarvis 2012) is the primary Navy software used to detect and identify deep-diving odontocetes at the following US Navy ranges: AUTEC (Atlantic Undersea Test and Evaluation Center), SCORE (Southern California Offshore Range), and PMRF (Pacific Missile Range Facility). It has undergone detailed testing and found to be reliable and robust. The CS-SVM portion of the M3R software uses nine-dimensional feature vectors formed by computing the time between 6 zero crossings about the peak and 3 normalized envelope amplitude peaks. M3R software contain templates of biosonar signals from the short-finned pilot whale, Risso's dolphin, sperm whales, Cuvier and Blainville beaked whales, and spinner dolphins (*Stenella longirostris*). A preliminary performance check can be found in Jarvis et al. (2008) and a more detailed performance evaluation can be found in Jarvis (2012). Au et al. (2013,

2014) performed separate validation test of the M3R performance using a totally different method than that used by Jarvis (2012). The classification precision of the M3R on test data sets for all the species was high, 85 % or higher depending on the species (Jarvis 2012). We combined the Cuvier and Blainville beaked whales together under the beaked whale category. We also combined all dolphin biosonar signals except those of the short-finned pilot whales and Risso's dolphins as unknown dolphins, which would include a number of inshore species that typically do not dive to deep depths but their biosonar clicks can occasionally be detected by a deep-moored PAM.

5.3.1 Independent Validation Test of M3R

Validation test of the M3R algorithm was conducted by Jarvis et al. (2008) and Jarvis (2012) using test data that contained the biosonar signals of specific species. An independent validation test was performed in the study of Au et al. (2014) using data collected by one of our EARs using a completely different technique than Jarvis (2012). The validation test consisted of examining 100 files per species for each of the four species, sperm whales, short-finned pilot whales, Risso's dolphins, and beaked whales that were detected by the CS-SVM algorithm. The waveform, frequency spectrum, and the Wigner-Ville time-frequency distribution for each biosonar click were displayed on a computer monitor and a decision made by a human operator as to the species producing the signal. The frequency spectrum was used to determine the presence of sperm whales, short-finned pilot whales, and Risso's dolphin. The Wigner-Ville distribution was used to determine the presence of beaked whales. The time waveform was also used for further confirmation of the presence of a particular species. If the visual inspection indicated that at least five signals were from the designated species then that file was accepted as a correctly identified file. The specific clicks detected by the M3R algorithm were not singled out so that the clicks used to identify the desired species were not necessarily the same clicks detected by M3R. The results of the validation tests are shown in Table 5.1.

Not surprising is that all the files in which M3R indicated the presence of sperm whales were verified since Jarvis (2012) also had 100 % correct detection for sperm whales. Sperm whale biosonar clicks are probably the most unique of all odontocetes

Table 5.1 Visual validation test results of M3R performance from 100 files per species that were designated as containing biosonar signals

Species	Correct detection (%)	False alarm (%)
Pilot whale	97	3
Sperm whale	100	0
Risso's dolphin	85	15
Beaked whale	97	3

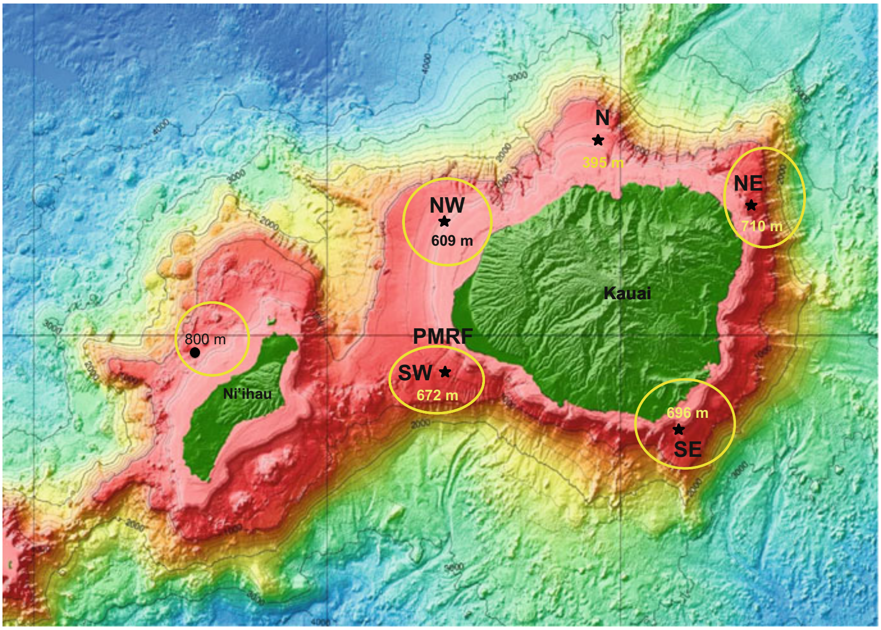

Fig. 5.2 Location of EARs around the islands of Kauai and Ni'ihau. The depth of each EAR is shown next to the *symbol* marking its location. The general area of the Pacific Missile Range Facility (PMRF) is also shown (courtesy of the Hawaii Mapping Group, U. of HI)

since it is the only species with clicks that have peak frequencies between approximately 5 and 15 kHz (Mohl et al. 2003). There is a remote possibility that highly off-axis clicks from bottlenose dolphin (*Tursiops truncatus*) could be confused with clicks from short-finned pilot whales. Examples of the clicks measured at aspect angles of ±90° by Au et al. (2012a, b) have a peak frequency close to 20 kHz, similar to the spectrum in Fig. 5.2 for the short-finned pilot whale. However, at such a wide off-axis angle, the signal level is 45–55 dB below the on-axis source level. With an EAR at depths below 600 m, it is highly unlikely that such extreme off-axis clicks from bottlenose dolphins at shallow depths would be regularly detected in comparison to the signals of short-finned pilot whales which consistently forage at much deeper depths. The M3R software was originally developed to analyze data from deep bottom-mounted hydrophones on Navy acoustic ranges.

Another independent validation study was conducted by Bio-wave Inc. under contract to HDR Inc. to visually examine some randomly selected EAR files collected off the island of Niihau. This analysis concentrated on beaked and sperm whales. When the same data set used by Bio-wave Inc. was analyzed with the M3R algorithm, performance accuracy was 99.4 % correct on the 746 files used to look for *Ziphius* signals and 98 % correct on the 748 files used for *Mesoplodon*.

5.4 Deployment of Deep EARs in Western Pacific

Five EARs were deployed around the island of Kauai in the approximate locations shown in Fig. 5.2 between February 2009 and January 2011. These were refurbished by swapping out the batteries and the laptop disk used to store the data at intervals of approximately 4–5 months. One was deployed off Ni'ihau in June 2010 and retrieved in December 2010. The depth of the EARs at the different locations is indicated in the figure. The original data acquisition rate for the EARs around Kauai was 64 kHz but was eventually modified to 80 kHz (Au et al. 2013). Only data collected at a sample rate of 80 kHz have been used in the M3R program. The sample rate for the EAR off Ni'ihau was 80 kHz. All of the EARs acquired data over a 30-s period every 5 min. After collecting data for 30 s, the EAR would enter a "sleep" mode to conserve battery and storage and wake up 4.5 min later.

Three EARs were deployed in waters of Okinawa, Japan, between November 2011 and May 2012. However, only two of the EARs were in deep waters (greater than 400 m). The western site was designated as Le Shima (in the East China Sea) and the eastern site (in the Philippines Sea) as Schwab South. Deep EARs were also deployed in the Marianas, in waters off Guam, Saipan, and Tinian between September 2011 and September 2012. The approximate location and depth of the EARs deployed off Okinawa (deep EARs only) and in the Marianas are shown in Fig. 5.3. The depth of each EAR is shown in the figure. In order to increase the

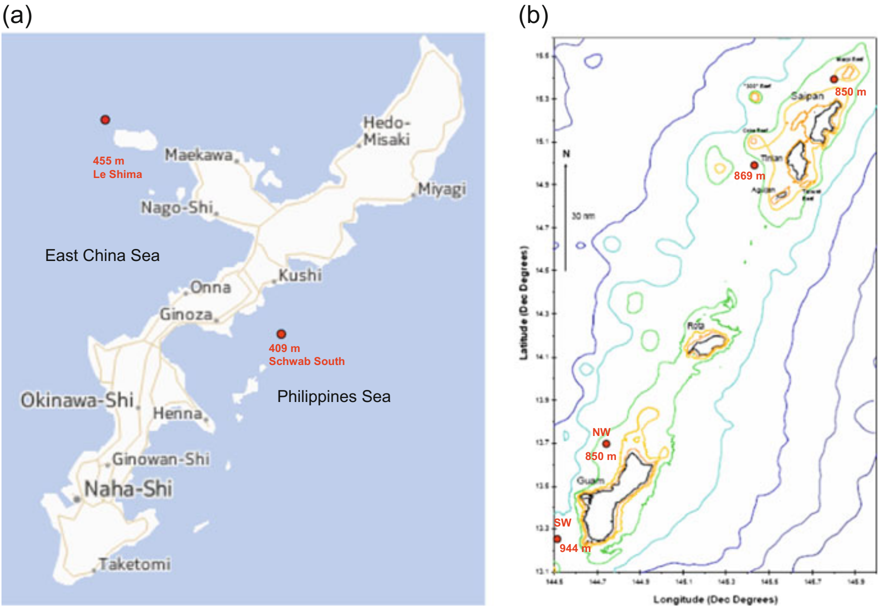

Fig. 5.3 (**a**) Location of EARs around the island of Okinawa, (**b**) location of EARs in the Marianas. The most northern location is off the island of Saipan, one next to the south is off the island of Tinian, and two were off Guam, one in the NW, and one in the SW

recording time, the duty cycle for the EARs in the Marianas was changed to 30 s of recording every 10 min instead of every 5 min.

Detection of deep-diving odontocetes was reported by Au et al. (2013, 2014) in terms of the number of 30-s files that contained biosonar signals from the different species. Each file can be considered an observation period (OBSP) and if the 30-s data acquisition period occurred every 5 min, then there were 288 OBSP per day. The EARs in the Marianas had a duty cycle of 10 min so that there were 144 OBSP per day. The longer duty cycle was used in order to extend the battery life of each EAR.

5.5 Daily Pattern of Biosonar Detections

5.5.1 Off the Island of Kauai

The results for the four groups of deep-diving odontocetes listed in Table 5.1 along with a group denoted as unknown dolphins are shown in Fig. 5.4 for the SW location of Kauai during the period between January 26 and May 4, 2010. The plots all have the same vertical scale so that a quick visual inspection will portray the relative number of detection between the species. The results indicate that at least one of the species of interest was detected every day. There were many days in which multiple species were detected. The daily occurrence of at least one group is typical for all sites regardless of the time period. The data indicate that pilot whales were detected most often followed by sperm and beaked whales. The highest detection rate occurred on April 23 with a rate of 52 %. This means that of the 288 observation periods during that day, 150 contained biosonar signals of pilot whales. However, the daily number of detection also varied considerably. Two days before the day of highest detection only 8 % or 23 of the OBSP and 2 days after only 6 % or 17 of the OBSP contained pilot whale biosonar signals. At least six dolphin species can be lumped into the unknown dolphin category, Pacific bottlenose dolphin (*Tursiops truncatus gilli*), Hawaiian spinner dolphins (*Stenella longirostris*), pantropical spotted dolphin (*Stenella attenuata*), striped dolphin (*Stenella coeruleoalba*), rough-toothed dolphin (*Steno bredanensis*), and Fraser's dolphin (*Lagenodelphis hosei*). These dolphins emit very similar and highly variable biosonar signals that are not species specific and at this time impossible to separate (Au 1993; Au and Hasting 2008; Schotten et al. 2003).

The graphs in Fig. 5.4 also show a pattern of detection that was similar for the five groups of odontocetes. There were periods of relatively high detection in March and after the first week in April for all groups. The pattern may be difficult to visualize because of the day-to-day variations in detecting the biosonar signals of the five groups of odontocetes. Furthermore, the two peaks in detection occurred at approximately the same days.

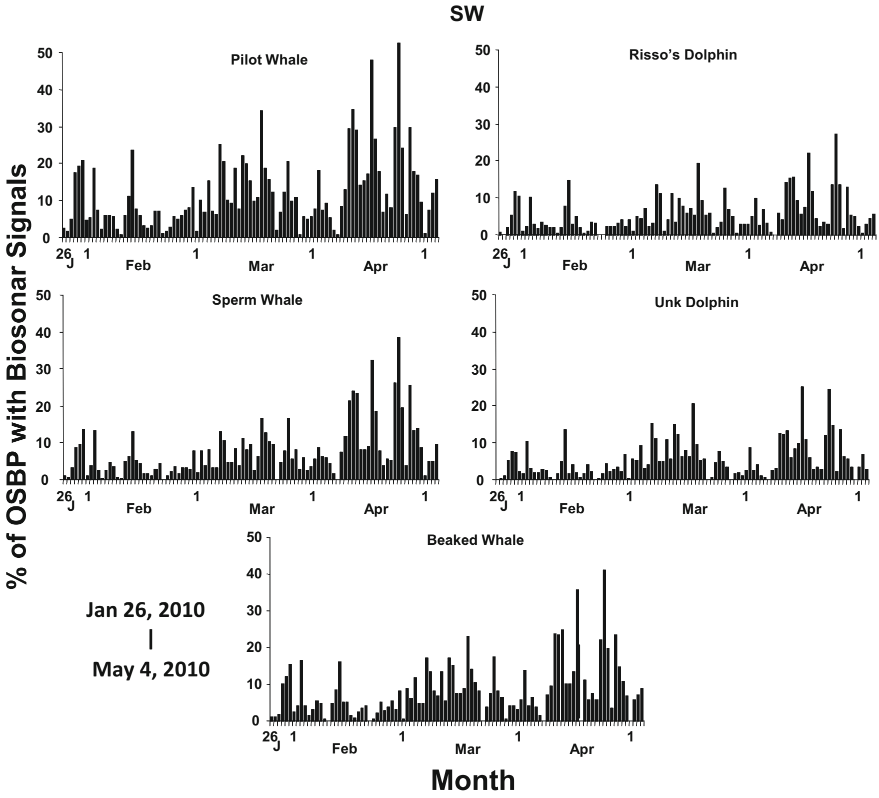

Fig. 5.4 The percent of daily observation periods (OBSP) that the biosonar signals of different species of deep-diving odontocetes were detected at the SW location between Jan 26 and May 4, 2010

The spatial distribution of detected biosonar clicks for pilot whales and beaked whales at the four EAR locations are shown in Figs. 5.5 and 5.6, respectively, for one deployment period.

Similar graphs can be drawn for the other species but short-finned pilot whales were chosen because they had the highest detection levels and beaked whales were chosen because of the high interest in beaked whales close to PMRF in the waters of SW and NW Kauai. The results in Fig. 5.5 clearly indicate that short-finned pilot whales were detected most often at the SW and NW locations. The results in both Figs. 5.5 and 5.6 clearly indicate that more biosonar signals were detected on the west side of Kauai than on the east side. The average percent of OBSP with biosonar signals had its highest value in April and June for all species at the SW location. The April value at the NW location was higher for all the species than during any months at the NE and SE locations.

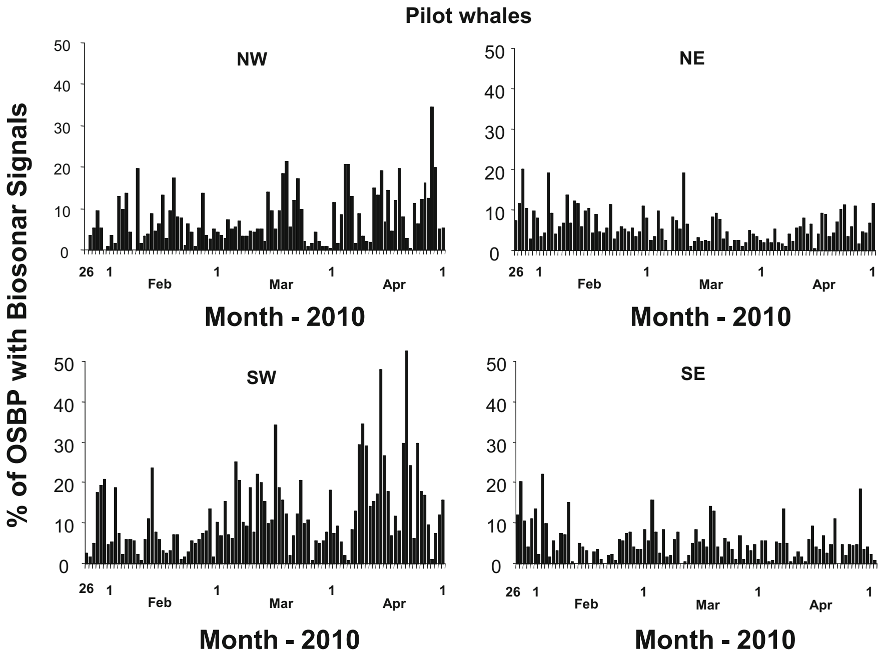

Fig. 5.5 The percent of OBSP containing short-finned pilot whale biosonar signals at four EAR locations for the time period between Jan 26 and May 4, 2010

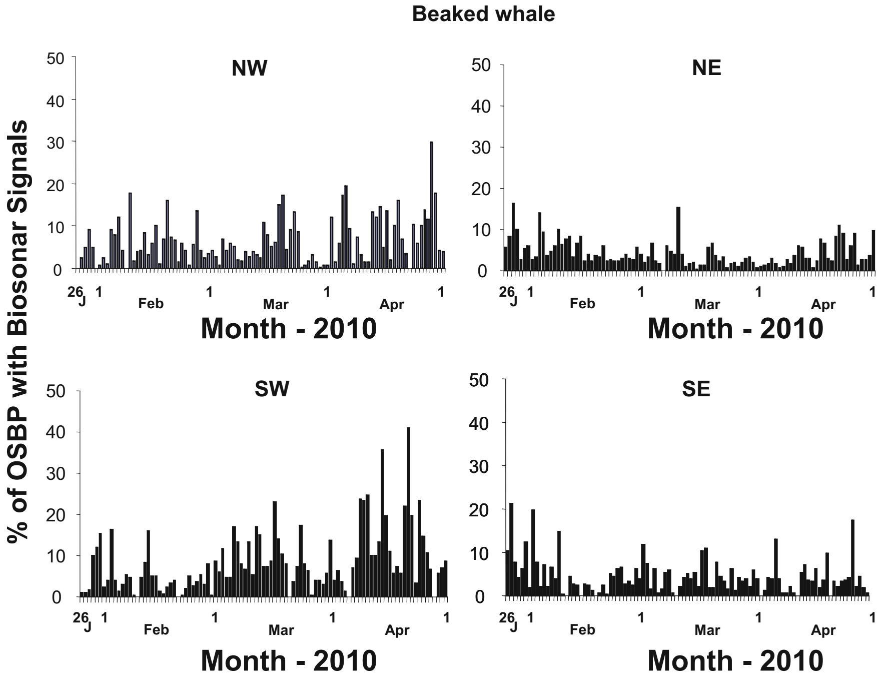

Fig. 5.6 The percent of OBSP containing beaked whale biosonar signals at four locations for the time period between Jan 26 and May 4, 2010

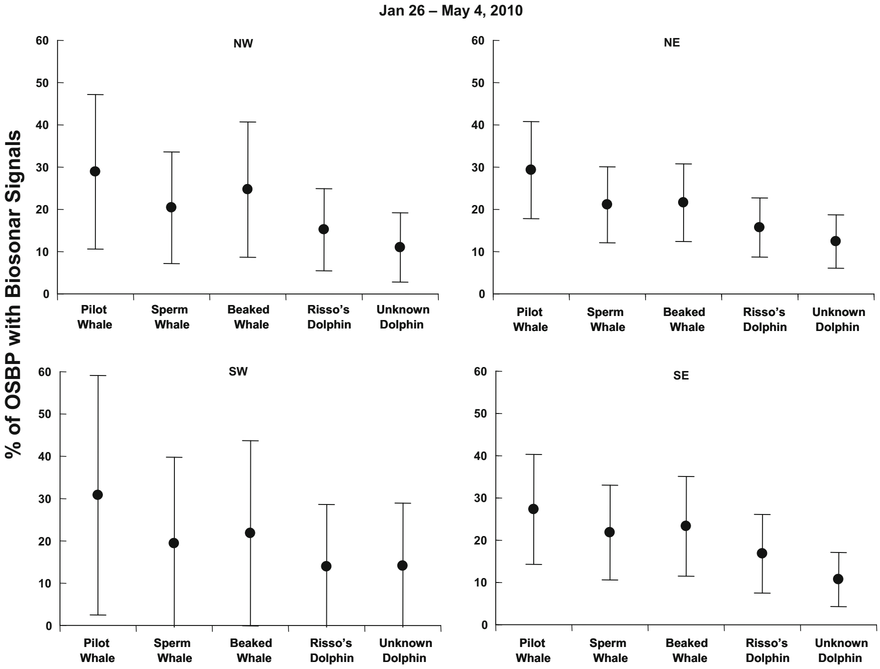

Fig. 5.7 The average and standard deviation of the daily detection for each odontocete group and each location during the Jan 26 and May 4, 2010, time period around the island of Kauai

The percentage of observation periods per day during the January 26 to May 4, 2010, time period that contained biosonar clicks at the different locations and different groups of odontocetes is shown in Fig. 5.7. Biosonar signals of short-finned pilot whales were detected the most at all locations although the mean values of detection of pilot whale signals were very similar at all locations, approximately 30 % of all OBSP. Biosonar signals of sperm and beaked whales were close to 20 % and there were no significant difference between the percent of sperm and beaked whale signals detected at all locations during this time period.

5.5.2 *Off Okinawa and in the Marianas*

The percent of the observation periods with biosonar detected on a daily basis at the two locations in Okinawa was similar to Fig. 5.3 for the island of Kauai with detections made every day during the time period of March 2 to May 17, 2012. Instead of presenting the daily distribution results, the averaged daily results are shown in Fig. 5.8. In this figure, the pilot whale designation was changed to "blackfish," a group of odontocetes that include short-finned and long-finned pilot whales, false killer whales, and melon-headed whales. Unlike the water in the main Hawaiian

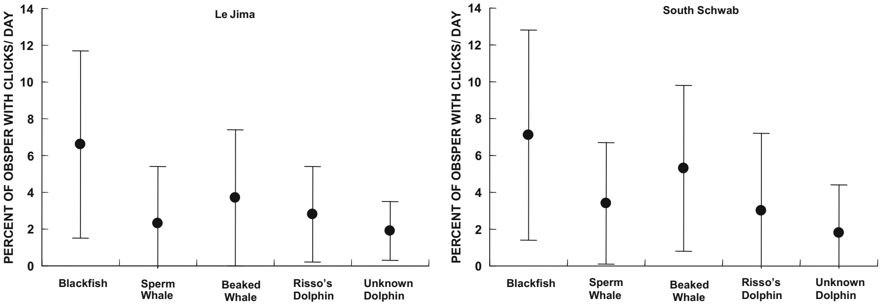

Fig. 5.8 The average and standard deviation of the daily detection for each odontocete group and each location during the Mar 2 to May 17, 2012, time period around the island of Okinawa

Island, it is not known if pilot whale abundance is considerably higher than the other species in this category as is in Hawaii.

Although the biosonar signals of at least one species of deep-diving odontocetes were detected every day, the actual numbers of observation periods for all species were much smaller than off Kauai. The mean values for detection of pilot whale signals were close to 30 % or about four times more in the waters of Kauai compared to about 7 % in the waters of Okinawa. Approximately six times more files with sperm whale clicks and about five times more with beaked whale clicks were detected off Kauai than Okinawa. The detection rate at Le Shima was about the same as at Schwab South for the four groups of odontocetes being compared.

The average and standard deviation of the percent detections at the four locations in the Marianas are shown in Fig. 5.9 within the time period of Sept 11, 2011, and Jan 6, 2012. The EAR at Tinian started recording on September 11 while the other three started recording on September 12. Although the EARs were programmed to record over the same time period, the number of days of recordings varied with 106 days at Saipan, 78 days at Tinian, 118 days at NW Guam, and 108 days at SW Guam because of variations in the battery life. Nevertheless, the daily average of detection shown in Fig. 5.9 should be a good representation of the biosonar activity by the different groups of deep-diving odontocetes at the four different locations.

The duty cycle for the results shown in Fig. 5.9 was 10 min versus 5 min for all the other EARs used in Hawaii and Okinawa, so caution must be taken in comparing the results obtained in the Marianas with results obtained in the other locations. It would be expedient to discuss the possible effect of having a lower duty cycle for the Marianas data at this time so that more confidence can be placed on the meaning of the results. Assume that we have two EARs, one with a 5-min duty cycle (EAR-1) and the second with a 10-min duty cycle (EAR-2) both with the same period so that EAR-1 will have two data sample periods for each of EAR-2. Therefore, any signals detected by EAR-1 during the first sampling period will also be detected by EAR-2 while any signals detected during the second sampling period of EAR-1 would not be available to EAR-2. Assuming a random detection rate, there is a 50 % probability that signals detected by EAR-1 will be during the first sampling period. Therefore, EAR-2 will have approximately one-half the number of OBSP with detections than

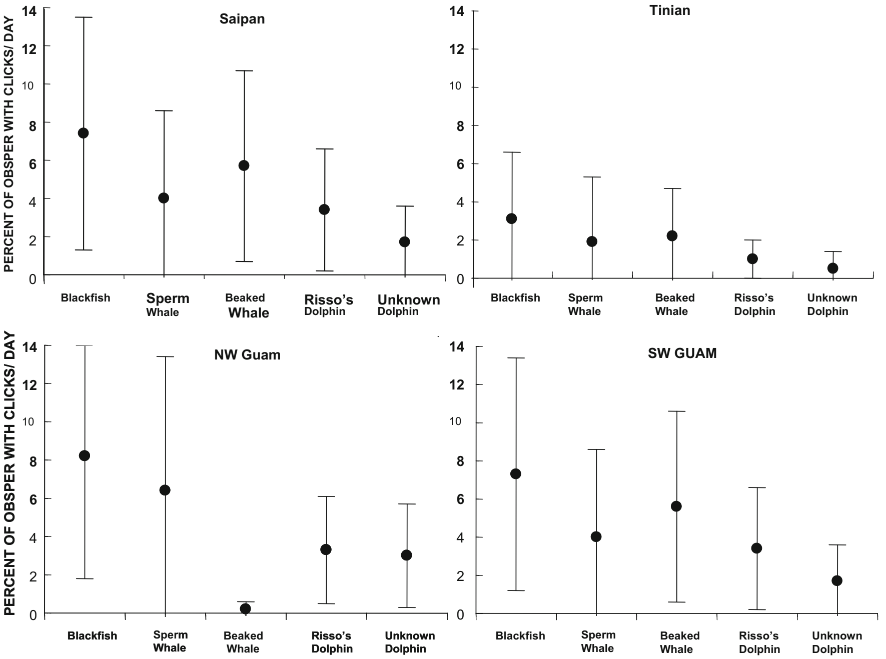

Fig. 5.9 The average and standard deviation of the daily detection for each odontocete group and each location during the Sept 11, 2011 to Jan 6, 2012, time period in the Marianas

EAR-1 and since EAR-2 will have ½ the total sampling periods per unit time, the percent of OBSP with biosonar clicks will be the same as for EAR-1. Now if it turns out that there is a slight imbalance in detection so that 55 % of all the clicks detected by EAR-1 occurs in the second sampling period and 45 % in the first sampling period then percent of OBSP for EAR-2 will only be 3.5 % lower than for EAR-1. The reverse could also happen where first sampling period of EAR-1 detects 55 % of all the click for EAR-1 and the second period detects 45 %; then EAR-2 will report a 3.5 % higher detection rate than EAR-1, again a relatively small difference. Therefore we should have good confidence that the low percentage of detection of deep-diving odontocetes in the Marianas is real and that like Okinawa, the detection percentage in the Marianas is approximately 4–7 times lower than off Kauai. The number of detections of the four groups of animals off Tinian was much lower than for the other locations in the Marianas. The number of detections of beaked whales off NW Guam was very low, indicating nearly an absence of beaked whales at that location. Finally, blackfish had the most detections in all four areas. The data indicate a trend in which the number of deep-diving odontocetes around Okinawa and in the Marianas is considerable lower than around the island of Kauai in the main Hawaiian Island chain. If the percent of detection per OBSP is related to the abundance of the different group of odontocetes, then the population of deep-diving odontocetes in this part of the Pacific Ocean is much lower than in Hawaii.

5.5.3 Diurnal Pattern Biosonar Detections

The diurnal behavior of foraging by deep-diving odontocetes off Kauai and Ni'ihau was examined by Au et al. (2013) by dividing the 24 h in a day into two 12-h periods. The dawn-dusk-night or twilight-night period was defined from 6:00 PM until 6:00 AM and the day period between 6:00 AM and 6:00 PM. At the latitude of the main Hawaiian Islands (19°–22° N) the time difference between sunrise on the longest day and the shortest day is only about 1 h. An example of average number of files in which signals from the various species were detected is shown in Fig. 5.10 for the time period between October 20, 2010, and January 11, 2011, at the SW Kauai location.

The shaded areas on each histogram plot represent the twilight-nighttime period. The twilight period is often referred to the crepuscular period where many animals display increased activity. The shaded block with a percentage value attached to each histogram is the percentage of time that files with biosonar signals were

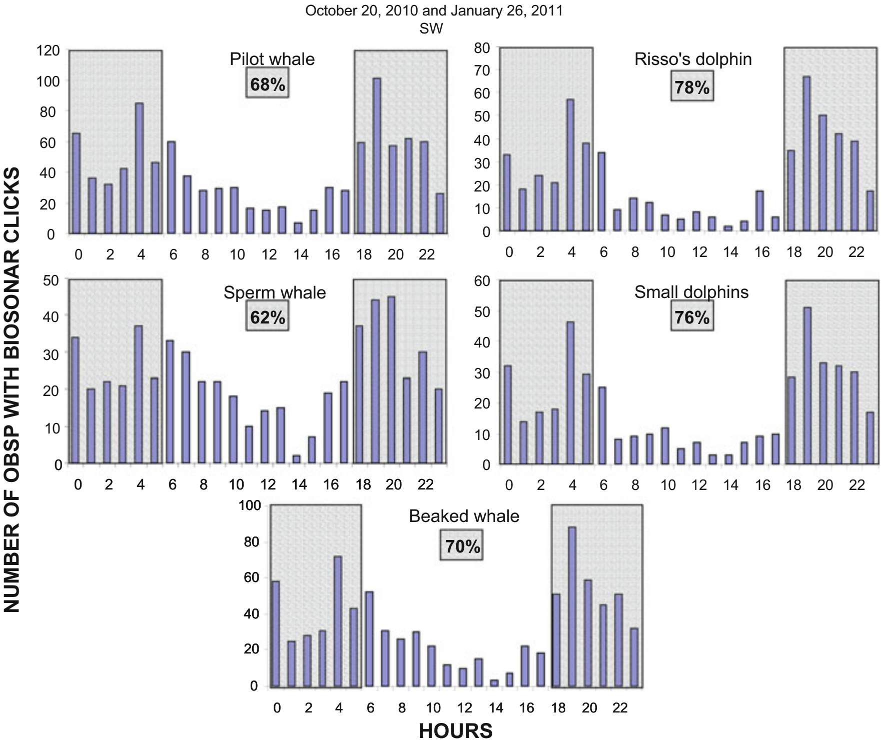

Fig. 5.10 An example of the average number of files in which foraging clicks from the different species were detected on an hourly basis for the time period between Oct 20, 2010, and Jan 26, 2011, at the SW location of Kauai. The percentage of twilight-night detection is shown in the shaded block of each histogram

Table 5.2 The percentage of files with biosonar clicks detected during the twilight-nighttime period from the different species and different locations around Kauai and one location off Ni'ihau

Location	Pilot whale (%)	Sperm whale (%)	Beaked whale (%)	Risso's dolphin (%)	Unknown dolphin (%)
Jan 25–May 3, 2010					
NW	72	69	72	80	72
NE	79	79	83	90	88
SE	80	80	83	90	88
SW	70	68	73	84	78
Jun 13–Sep 19, 2010					
NW	68	71	67	72	71
NE	80	86	79	92	83
SE	72	68	72	86	80
SW	68	57	72	81	71
Oct 20, 2010–Jan 26, 2011					
NE	80	80	86	89	85
SE	62	62	70	80	74
SW	68	62	70	78	76
Jul 17–Dec 17, 2010					
Ni'ihau	78	77	89	83	85

detected during the twilight-nighttime period. The percent of observation periods with biosonar clicks detected during the twilight-night period at the different EAR locations and for different deployment periods is summarized in Table 5.2 for the locations around Kauai and one at Ni'ihau.

The results in Table 5.2 are consistent with the results of Fig. 5.10 in that most of the foraging clicks were detected at night, although there was a fair amount of variability depending on location, time period, and species and without any other obvious trends. For example, the smallest percentage of foraging clicks detected during the twilight-nighttime period was 57 % for sperm whale at the SW location during the Jun 13 to Sept 19, 2010, period. Yet at the NE location for this same time period, the highest percentage of nighttime foraging clicks of 86 % for sperm whale was recorded. During the Oct 20, 2010 to Jan 26, 2011, time period, the smallest percentage of nighttime foraging clicks for short-finned pilot whale was 62 % at the SE location while during this same time period the highest percentage was 80 % occurred at the NE location. Beaked whales also had a strong tendency to forage at night with foraging mainly occurring 80 % or greater in 7 out of 12 cells in Table 5.2.

In order to obtain a broad and general appreciation of the amount foraging during the twilight-nighttime period around Kauai and Ni'ihau, the total number of files detected for each day and for all time periods and locations was summed for each species. The corresponding number of files that pertained to the twilight-night period was summed and the percent of detection of foraging clicks during twilight-night period is summarized in Table 5.3. The results clearly show a definite preference for twilight-nighttime foraging by the different species.

Table 5.3 The overall percentage of twilight-nighttime detection for all the locations and time period

	Pilot whale (%)	Sperm whale (%)	Beaked whale (%)	Risso's dolphin (%)	Unknown dolphin (%)
Overall	73	70	76	84	79

Table 5.4 The overall percentage of twilight-nighttime detection for the two locations in Okinawa

	Pilot whale (%)	Sperm whale (%)	Beaked whale (%)	Risso's dolphin (%)	Unknown dolphin (%)
Le Shima	62	54	64	71	69
Schwab S	70	70	74	71	75

Table 5.5 The overall percentage of twilight-nighttime detection for the four locations in the Marianas

	Pilot whale (%)	Sperm whale (%)	Beaked whale (%)	Risso's dolphin (%)	Unknown dolphin (%)
Tinian	73	71	70	94	87
Saipan	77	74	78	86	88
NW Guam	69	61	71	84	80
SW Guam	77	68	78	79	88

The diurnal variation in foraging behavior by deep-diving odontocetes in the waters of Okinawa was examined by dividing the 24 h in a day into two 12-h periods in the same manner as for the Kauai data. Sunrise on 15 December 2011 in Okinawa occurred at approximately 07:00, so the dusk-night-dawn period was defined from 19:00 until 07:00 AM and the day period as 07:00–19:00. The average numbers of observation periods in which signals from the various species were detected during the twilight-nighttime periods are shown in Table 5.4. The percentage of observation periods with biosonar clicks detected during the twilight-night periods was considerably higher than the day-time period for each of the five groups. Foraging also occurred during the day, but not as much as during the night.

The EAR at the Schwab South location had a stronger tendency for nighttime foraging than the Le Shima location. Sperm whales had only a slight tendency to forage at night at the Le Shima location but a strong tendency for nighttime foraging at Schwab South location in the Philippine Sea.

The detection of biosonar clicks by the EARs deployed in the Marianas is summarized in Table 5.5. The tendency for nighttime foraging was strong at the four locations for all the marine mammal groups considered. Sperm whales detected at the NW Guam location had the lowest tendency for nighttime foraging but yet 61 % of sperm whale clicks detected at this location occurred at night.

The amount of nighttime clicks was extremely high at all locations for Risso's and unknown or unidentified small dolphin species in the Marianas and were highest than all the locations in Okinawa, Kauai, and Ni'ihau.

5.6 Percentage of Biosonar Signals by the Different Species

A general insight into the relative number or the relative biosonar activity of the different groups of deep-diving odontocetes can be obtained by examining the percentage of biosonar clicks detected for the different groups at a specific site. This approach was taken by Au et al. (2014) for all the locations around Kauai. The results of Au et al. (2014) separated into four locations around Kauai are shown in Fig. 5.11. An interest feature of Fig. 5.11 is the similarity of the results showing very little differences in the four locations. The percent of biosonar clicks for the short-finned pilot whale varied between 27 and 31 %. The percentage values varied from 19 to 22 % for sperm whales, 22–25 % for beaked whales, and 14–17 % for Risso's dolphins.

The number of observation periods containing beaked whales and sperm whales clicks was almost even with beaked whales having a slightly higher detection rate. The unknown dolphin category had the least number of clicks which is not surprising because the animals in the unknown category are usually found close to shore and do not normally dive to deep depths. The rate of detection of Risso's dolphins was only slightly higher than that of unknown dolphins. The largest variation was only 4 % and most locations had no more than 3 % variation. Since the variations in the percent of detections for each species were so small at all locations, a gross estimate of the percentage of signals emitted by the different species around Kauai was calculated based on all the deployment periods and all the locations summed together.

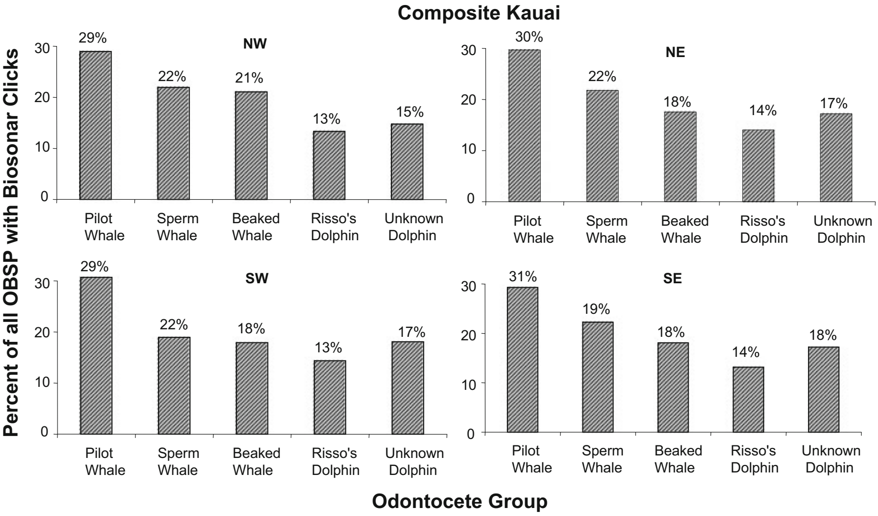

Fig. 5.11 The percentage of biosonar signals detected per species at the different locations during the deployment between January 26, 2010, and January 26, 2011

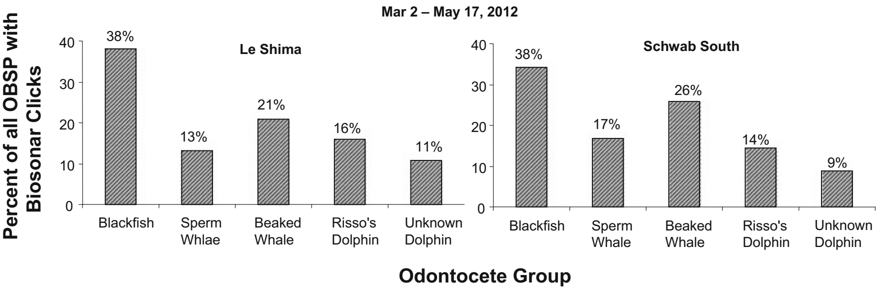

Fig. 5.12 The percentage of biosonar signals detected per group at the EAR locations off Okinawa

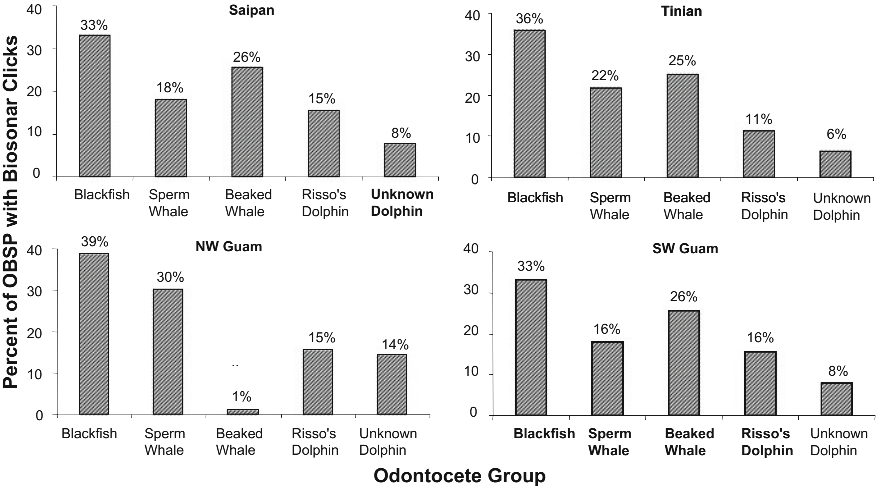

Fig. 5.13 The percentage of biosonar signals detected per group at the EAR locations during the Sept 11, 2011 to Jan 6, 2012, time period in the Marianas

The percentage of observation periods containing biosonar clicks emitted from the different groups of animals at the two locations in the waters of Okinawa is shown in Fig. 5.12. Unlike the Kauai results, there are larger variations between species for this data set. The percentage of clicks attributed to blackfish is 8 % higher off Okinawa than for pilot whales off Kauai.

The amount of clicks attributed to sperm whales and beaked whales was higher at Schwab than at Le Shima suggesting that sperm and beaked whales made up a higher percentage of deep-diving odontocetes at Schwab South than at Le Shima. The percentage of clicks attributed to the unknown dolphin category in both locations was much lower than off Kauai.

The percentage of observation periods containing biosonar clicks emitted from the different groups of animals at the four locations in the Marianas is shown in Fig. 5.13.

The amount of biosonar signals attributed to the different groups of deep-diving odontocetes had larger variations in the Marianas than either Kauai and Okinawa. The amount of clicks attributed to sperm whales at the NW Guam location was highest for all locations in Kauai, Okinawa, and the Marianas. Biosonar clicks attributed to blackfish had the higher rate of detection of all clicks detected in the Marianas. Sperm whales at the NW Guam location emitted approximately 30 % of the clicks detected which is at least 8 % higher than the locations around Kauai and 13 and 17 % higher than the Le Shima and Schwab South locations, respectively, off Okinawa. Conversely, the proportion of clicks attributed to beaked whales of 1 % was the lowest of all the locations around the Marianas, Kauai, and Okinawa.

5.7 Seasonal Variations of Foraging

The time period of EAR data collected off the island of Kauai was 1 month short of a year but nevertheless the results can provide some insight into how foraging behavior varies during the course of a year. Data from Okinawa and Guam did not extend beyond several months and so these data cannot provide any seasonal insights. The monthly averages of the percent of OBSP per day with biosonar signals are shown in Fig. 5.14 for the different groups of odontocetes. The vertical scale of each plot is the same so that the relative number of occurrences over the same time period at the different locations can be easily observed. The number of days during the beginning and end of each deployment period was limited. There were 7 months in which data existed for every day of the month. Only 5 days of data existed for January 2010 and 4 days for May 2010 and so these are not shown in the figure. The other 4 months had approximately 2 weeks of data associated with them and should serve as a good representation of that particular month.

Each species at the different locations seems to follow a general pattern specific to each location suggesting some general and common conditions (the availability of prey and environmental conditions) that influence each animal group. However, each location had its own trend. At the NW location, the peak monthly average occurred in April 2010. Unfortunately, the EAR did not surface after the second deployment so data and use of that EAR were lost for the rest of the project. The monthly averages showed little variations at the NE location with very small peaks in February and July 2010 and January 2011. At the SE location, two peaks can be seen, one in August and the other in January. There were two peaks, one in April and the other in June for the SW location.

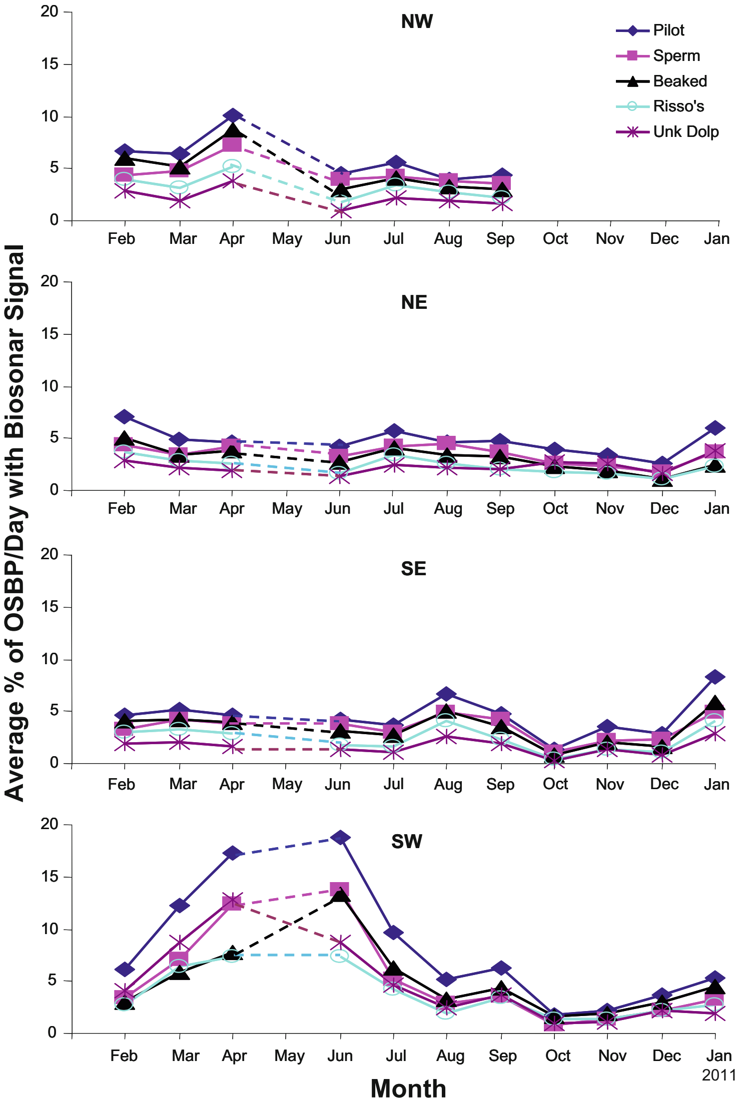

Fig. 5.14 Average of the percent of OBSP per day containing biosonar signals between Jan 2010 and Jan 2011 for the five odontocete groups and four locations around Kauai

5.8 Discussion and Conclusions

5.8.1 Occurrence

The daily occurrence of at least one group and on most days several groups of deep-diving odontocetes at some locations around Kauai was unexpected and the results suggest that these animals are around a given body of water more often than previously realized. Unfortunately there are no data on visual sighting rate of these animals over periods greater than several weeks. These results strongly suggest that the use of remote acoustic recorders is a good method to obtain quantitative information of which type of animals frequent a particular location. In addition, the data provide daily occurrence pattern and daily behavior of some species of odontocetes. Barlow and Taylor (2005) found that sperm whales were detected more often acoustically than visually. The acoustic detection ranges were also much larger than the visual detection ranges. Au et al. (2013a, 2014) have shown that most of the biosonar click detections occur during the twilight and nighttime hours when visual surveys are not possible. This pattern of foraging behavior could not possibly be uncovered without long-term acoustic monitoring spanning several months.

One of the important considerations to keep in mind is the fact that food resource is extremely important to any animal and that animals tend to congregate in area of high prey level. In the case of the odontocetes being considered here, their diet consists mainly of squid and some demersal fish that inhabit deep depths. Since these deep-diving odontocetes use their biosonar to forage, other animals in the vicinity should know that foraging is taking place and by knowing the length of foraging bouts and the level of biosonar activity these other animals can ascertain the relative abundance of prey in an area. Furthermore, since odontocetes have a directional hearing system, they can probably localize the depth and locations where different animals are foraging. This type of activity will probably attract them into the area and perhaps prompt them to begin foraging.

It is not obvious why these deep-diving odontocetes would favor certain locations around an island such as the western side of the island of Kauai. The trade winds generally come from a northeast direction so that the western side of the island may be slightly calmer than the eastern side but the difference is not enough to significantly affect the noise received by the EARs. The SW location is directly opposite from the northeast direction of the trade wind and most detections were obtained at this location. Little or no research has been done on whether dolphins and whales prefer calm or rough ocean conditions. It is also not obvious why the population of the four groups of deep-diving odontocetes investigated around Okinawa and in the Marianas is so much lower than around Kauai and why the population at Tinian is so much lower than in other locations in the Marianas. Different prey distribution and behavior will definitely affect which areas they forage in and at this time there is little information on the distribution and behavior of the prey fields that these deep-diving odontocetes feed on in Hawaiian waters or any place in the world. However, other oceanographic conditions such as water temperature, salinity, bottom conditions, and noise conditions are among some of the variables; in addition, the availability of prey should also affect the size of a population in a given body of water. Finally, the presence of predator could affect the population of odontocetes in different sites.

A peculiarity of the results around Kauai is the seemly low seasonal variation in most locations. There was an indication at the SW location of Kauai of a fairly large seasonal variation that was not present at the other locations. Between the months of March and June, the detection rate was much higher at this location than then at any time in the other locations. Between the months of July 2010 and January 2011, the detection rate was similar for the SW, SE, and NE locations. The reasons for such a seasonal variation are not known.

One of the difficulties in analyzing acoustic data recorded remotely is in obtaining an accurate identification of the whale or dolphin species that emitted the sounds. This applies to both whistle and echolocation signals. To complicate matters, in the marine environment it is often difficult to obtain visual validation or confirmation of the species emitting the sounds. Finally if most of the sounds are emitted at night, the problem of assessing the accuracy of the acoustic identification becomes almost impossible. In general whistles are easier to identify than clicks since clicks are very short in duration and the waveform and the subsequent spectrum will vary according to the geometry between the marine mammal and the sensor. On the positive side, there are some species of odontocetes that emit relatively low-frequency biosonar signals that seem to be species specific and these animals can be identified by their click emissions. However, there are some serious issues involving species identification. In the study of Au et al. (2013, 2014), biosonar clicks identified as originating from Risso's dolphins consisted of approximately 15 % of all clicks by deep-diving odontocetes around the island of Kauai. However, Risso's dolphins are not detected very often in visual surveys conducted in Hawaiian waters (Barid et al. 2013). So we are left with a conundrum in regard to this species. The M3R has been validated by two independent methods and with different data sets and shown to accurately label Risso's dolphins. We cannot deny that clicks that best represent Risso's dolphins were detected about 15 % of the time and that the clicks cannot at this time be assigned to other species of dolphins. We could choose to assign these clicks to the unknown dolphin category. However, these clicks were very consistent in their characteristics and to the best of our knowledge resemble Risso's dolphin signals. Therefore, we chose to assign the signals to Risso's dolphins. Other investigators may choose to assign them to the unknown dolphin category and that would be their prerogative.

One should keep in mind the situation with minke whales and boing sounds. Boing sounds have been detected in Hawaiian waters as early as the 1950s (Wenz 1962). Yet it was not until 2002 that it was confirmed by visual and acoustic recordings that boing sounds were produced by minke whales (Rankin and Barlow 2005). Not one single minke whale was sighted during more than 10 years of aerial survey effort over Hawaiian waters (Mobley et al. 2000; Mobley 2004). Additionally, despite significant shipboard survey efforts, there have been only a handful of verified sightings in Hawaiian waters. A juvenile minke whale was observed riding the bow wave of a navy ship in the 1970s (Balcomb, pers. comm.), long-line fishery observers have reported four confirmed minke whale sightings (Carretta et al. 2005), three minke whales were encountered in Hawaiian waters during a 5-month visual and acoustic survey of marine mammal abundance (Barlow et al. 2004), and one minke whale was sighted during a 1-week visual and acoustic survey focused on minke whales in waters offshore of Oahu and Kauai (Rankin et al. 2008). The minke whale experience can be summarized by the statement “just because you can’t see them doesn’t mean that they are not there, especially if you can hear them.”

Discrepancies between visual surveys and sighting and results from acoustic recordings are expected since both the methodologies have their own strengths and weaknesses (Barlow and Taylor 2005; Barlow and Rankin 2007). For example, Barid et al. (2013) reported that the sighting rate of short-finned pilot whales around Kauai was much lower than for other areas around the main Hawaiian Islands. Yet our results indicated that short-finned pilot whales were detected the most often of all the deep-diving odontocetes. For the most comprehensive understanding of the relative abundance of marine mammals including their distribution, time of occurrence, and movement patterns both visual and acoustic data should be collected and their results should be considered complementary rather than contrary. The “dual” approaches have been used for several years by NOAA, pioneered by Dr. Jay Barlow and Shannon Rankin at the Southwest Fishery Science Center in La Jolla, outside of San Diego, California.

It is important to emphasize that in order to make more progress in the field of acoustically identifying odontocetes by their biosonar signals more data in field need to be collected. In previous measurements of biosonar signals in the field, the focus was to obtain clicks that were emitted along the major axis of the animal’s beam. Those efforts should continue since there are many species from which biosonar signals have not been collected. However, field efforts should also include the collection of off-axis signals and laboratory effort should include measurements around the bodies of animals as was done by Au et al. (2012a, b) for *Tursiops truncatus*. A priority of laboratory measurements should be on different species including porpoises and dolphins that emit narrow-band biosonar signals.

The distribution of deep-diving odontocetes and their seasonal variations could only be obtained with remote autonomous PAM devices. Having visual survey teams at multiple locations that operated around the clock would be prohibitively expensive. Furthermore, many detections of these deep-diving odontocetes occurred at night (Au et al. 2013). It would also be very expensive to have a system in which hydrophones are connected to shore by cables as in the hydrophone arrays on the PMRF range. Finally, battery-operated radio telemeter systems (modified sonobuoys) powered by photovoltaic cells on the surface would be subject to theft or damage by boaters and their anchor cables could possibly be hazardous to the marine mammals that frequent the area.

5.8.2 Relative Abundance

The percentage of clicks from the different groups can be used to provide a first-order or ballpark estimate of the relative abundance of these deep-diving odontocetes. However, to go beyond this is not warranted. There are many criteria that need to be satisfied before a definitive statement can be made. The source levels of the different species would need to be almost the same and there are no data to support this criterion. The higher the source level the greater distance clicks can be detected and more clicks can also be detected. The beam pattern of each group of animals should be similar in order to estimate relative abundance. Once again, there is no data to support this contention. The beam pattern has been measured completely around an echolocating *Tursiops truncatus* (Au et al. 2012a, b) and estimates have been made of the beam pattern for *Ziphius cavirostris* by Zimmer et al. (2005) and by Shaffer et al. (2013) for *Mesoplodon densirostris*. The results of Au et al. (2012a) indicated that for large angles from the beam axis the source level can vary by as much as 50–60 dB! Another criterion that should be satisfied for an accurate abundance estimate has to do with the depth of the echolocating animal. The transmission loss may be different depending on the depth of the animal. Finally, the group size of the different animals would need to be similar since the greater the group size the more signals may be detected.

The results shown in this chapter clearly indicate that biosonar signals from short-finned pilot whales were detected the most often at all locations around Kauai and Okinawa and in the Marianas. Sperm whale and beaked whale clicks were detected almost equally around Kauai and other western Pacific locations but were detected less often than pilot whale clicks. Blackfish biosonar signals were also detected the most for EARs deployed near the Josephine Seamount off Portugal (Giorli et al. 2015). It is interesting that in very vastly separated locations that the biosonar signals of blackfish were detected the most of all the different deep-diving odontocetes.

Although PAM technology can provide valuable information about the occurrence of marine mammals and indications of the relative abundance of different species, there some serious limitations with the use of a single device which will hopefully be addressed in future generations of remote recorders. The range at which biosonar signals are being detected, the number of animals being detected at a given time, the depth at which different animals are detected, the relationship of the depth of foraging animals as a function of the time of day, and the movement pattern of foraging animals are but some of the few questions that should be addressed. To address some of these questions, array of remote recorders in which the data acquisition sample process is synchronized need to be developed. Such arrays exist in Navy ranges; however, these facilities not being available to most researchers present some serious problems and the hydrphone spacing and array configuration may not be optimal to address some questions. Therefore, the advancement in technology that is required has to do with being able to localize and track animals over a scale of several kilometers in three dimensions.

5.8.3 Diurnal Variation

There is a strong inclination of different deep-diving echolocating odontocetes to foraging at night. Johnston et al. (2008) using a HARP reported that beaked whales at the Cross Seamount foraged mainly at night. Soldevilla et al. (2010) using recording from six HARPs moored between 300 and 1300 m found that Risso's dolphins in the southern California Bight forage mainly at night. However, data from tagged beaked whales have shown no difference between day and night in the foraging patterns of beaked whale in the Tongue of the ocean, Bahama (Hazen et al. 2011), and off El Hierro, in the Canary Islands (Arranz et al. 2011). Baird et al. (2008) using time-depth recorders on six Blainville and two Cuvier's beaked whale off the Hawaii Island also found that deep foraging dives occurred at the same rate during the day and night. The Seaglider experiment off the Kona coast of Hawaii Island indicated that Cuvier's beaked whales and sperm whale did not display any difference between day and night foraging patterns (Klinck et al. 2012). It should be recognized that different types of information on odontocete foraging behavior are being gathered by PAM devices, time-depth recording, acoustic tags, and ocean gliders. Tags can obtain detailed temporal and spatial information on a few subjects for a short period of time whereas PAM devices sample a population for an extended period of several months. The differences between PAMs, tags, and ocean gliders can lead to different results and conclusions.

The results obtained with EARs around Kauai and in other western Pacific locations strongly indicate that deep-diving odontocetes forage mainly at night. The nighttime foraging behavior applies to four groups of deep-diving odontocetes, blackfish, sperm whales, beaked whales, and Risso's dolphin. Sperm whales exhibited the lowest tendency to forage at night but the results are highly variable. Overall, the results for sperm whale indicated that approximately 70 % of their foraging activities occur at night but there were at one location (Le Shima off Okinawa) in which only 54 % of the foraging was done at night.

The foraging pattern of any animal is dependent on the dynamic behavior of the prey and in order to obtain an appreciation of the foraging process, an understanding of the prey field is required. Research in the Hawaiian Islands has shown that the dynamic behavior of the mesopelagic boundary community (MBC) consisting of myctophid, shrimp, and small squid has an overriding influence on the natural history of spinner dolphins (Benoit-Bird et al. 2001; Benoit-Bird and Au 2003).

The prey field essentially dictates where on the coast spinner dolphins rest, where they forage, how they forage, and when they forage. A similar type of relationship would not be surprising between deep-diving foraging odontocetes and the prey they depend on for their survival. Unfortunately there is a poor understanding of the dynamic behavior of the prey fields of the deep-diving odontocetes and the rationale for nighttime foraging is much more difficult to understand. Short-finned pilot whales, sperm whales, Risso's dolphins, and beaked whales all feed mainly on squids and occasionally on some unspecified species of fish. Seagars and Henderson (1985) reported that short-finned pilot whales in the Pacific west coast feed primarily on neritic squid Loligo sp. Mintzer et al. (2008) found that oceanic squid Brachioteuthis riisei was the main prey of short-finned pilot whales in the Atlantic; however *Taonius pavo* and *Histioteuthis reversa* were also a part of their diet. Sperm whales feed mainly on mesopelagic and benthic habitats on squids of different species and occasionally fish. Giant squid (*Architeuthis* sp.) and jumbo squid (*Dosidicus* sp.) and Antarctic colossal squid (*Mesonychoteuthis hamiltoni*) (Clarke et al. 1993;

Whitehead 2003) are some prey species of sperm whales. Risso's dolphins feed mainly on squid and other cephalopods (Clarke and Pascoe 1985). Off the California coast the jumbo squid (*Dosidicus gigas*) and the California market squid (*Loligo opalescens*) are common prey (Orr 1966; Kruse 1989). Beaked whales tend to prefer deepwater squid but there exist sufficient data to suggest that the prey specimens include a variety of demersal and mesopelagic fishes (Mead 2002; Pitman 2002; Ohizumi et al. 2003).

Although the habitat of the deep-diving odontocetes consists of the mesopelagic and upper bathypelagic zones of the ocean, it would not be surprising if some sort of habitat partitioning occurs as a function of depth. We can assume that sperm whales must forage for larger prey than the smaller odontocetes. Short-finned pilot whales and beaked whales are of similar size and it is conceivable that the prey species may be similar. Risso's dolphins weigh approximately 1/2 that of short-finned pilot whales and it would be reasonable that they would forage for smaller prey. It would not be surprising that there are niches mediated by bottom depth for the different species of squids. Yet the various prey species behave in such a manner as to make it advantageous for the different species of deep-diving odontocetes to forage at night.

At the current level of understanding we can only speculate on the advantages of nighttime foraging. There has not been much research done on the foraging ecology of deep-diving odontocetes. It is well known that the deep scattering layer (DSL) and other mesopelagic layer of organisms migrate vertically towards the surface. However, scientific echosounder result indicates that the biomass structure in the offshore mesopelagic region can be very complicated.

Echosounding data obtained off the Kona coast of Hawaii Island shown in Fig. 5.14 indicate that there are usually two strong mesopelagic layers: one at deep depth on the order to 400–600 m and a shallower layer between 0 and 250 m.

The data also indicate that the layer structure is often complex with several "weaker" layers between the two strong layers. The surface layer became more dense at night with the vertical migration beginning at dusk as early as 17:10–20:00 HST. The organisms migrated from the surface to a deeper forging layer at dawn starting at 4:00–5:50 HST. A portion of the deep layer does not migrate vertically very much, remaining within a small range of depth. The depth of this deep layer appears to be relatively independent of the bottom depth. As depth increases beyond 600 m, the spacing between the deep layer and the bottom increases. The sloping bottom dropping off the chart can be seen in the echogram of Fig. 5.15 with the deep layer remaining relatively constant in depth. Echosounding inshore (approximately 1000 m bottom depth) and offshore (3000 m plus bottom depth) indicated that the biomass tends to be denser closer to shore. The peak densities of the top and bottom layer are approximately the same although the deep layer is considerably wider in depth.

The question is how does the migration of mesopelagic organisms affect the squid species and consequently the top marine mammal predators. If the squid prey also migrate from deep waters to forage on the organisms of the DSL, the squids would rise into depth strata that would be more beneficial for deep-diving odonto-

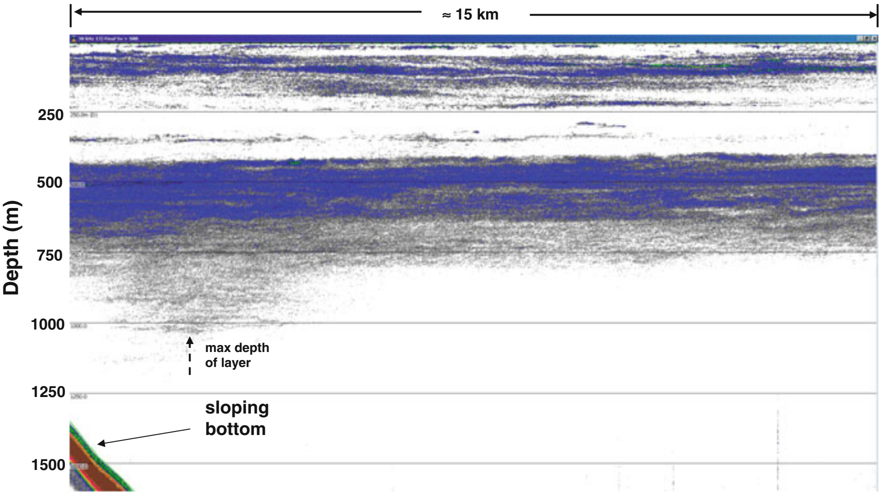

Fig. 5.15 EK-60 echograms during a deepwater day transect showing the bottom (*left side*) at about 1350 m slopping out of range 1500 m while the deep layer remained relatively constant in depth. Patches of organisms can be seen below the densest part of the deep layer (courtesy of Adrienne Copeland)

cetes to forage on them. Furthermore, not all species of squid will behave in the same manner. Smaller species may migrate vertically higher in the layer than layer species of squid, which would create a partitioning of the prey field for deep-diving odontocetes. Arranz et al. (2011) have found that Blainville's beaked whales spend most of their foraging time in the lower part of the DSL or near the bottom in the Canary Islands. From a biosonar perspective, the DSL represents a volume reverberation environment and finding prey within such a layer of scatterers would represent a difficult sonar task. To detect and localize targets below the DSL or even off the bottom may be a simpler task than attempting to do so in the DSL. Andrews et al. (2011) using satellite time depth recorders found that short-finned pilot whales off the island of Hawaii do most of the foraging at night and that the night dives are slightly but not statistically significantly shallower than the daytime dives. The mean depth of dives for eight subjects varied between 293 and 502 m. However, more data from more species are needed in order to draw stronger conclusions about the diving and foraging behavior of not only pilot whales but the other deep-diving odontocetes. Other species of deep-diving odontocetes may not vary their foraging depth between day and night hours. Until data can be obtained from tag animals in different locations around the world, our understanding of the foraging ecology of deep-diving odontocetes will be severely limited. The one solid piece of knowledge that we have is the fact that there is a strong bias by these animals to foraging at night and dive to deep depths beyond 200 or so meters.

5.9 Closing Remarks

The data collected by a stationary PAM device such as the EAR make it possible to study the diurnal foraging behavior of deep-diving odontocetes over a long time period. Other instruments such as acoustic and time-depth recording tags and acoustic gliders have not uncovered the twilight-night foraging behavior of deep-diving odontocetes. The Seagilder experiment found a twilight-nigh sound emission for delphinids but these were probably from spinner dolphins which are known to forage mainly at night in swallow waters. The Seaglider experiment was also performed off the Kona coast of Hawaii Island instead of Kauai and geographic differences may have been a factor in not detecting a strong twilight-nighttime foraging tendencies in sperm and beaked whales. Nevertheless, the results of this study indicate a strong tendency for twilight-nighttime foraging by deep-diving odontocetes around Kauai and Ni'ihau. The reasons for this foraging behavior are not known and will continue to be an area of interesting research.

The results collected by deep-moored EARs in the western Pacific are new and were obtained with a relatively new measurement technique and a signal processing technique (CS-SNM portion of the M3R algorithm) to identify species by the clicks they emit. In this type of situation, a considerable amount of consternation can arise among those not familiar with passive acoustic methods leading to much skepticisms. That is not a bad thing in science. However, in this case, it is a relatively simple process to detect the presence of biosonar clicks. It is also very easy to identify clicks from sperm and beaked whales. Sperm whales are the only species that emit click with peaked frequency between 5 and 15 kHz. Beaked whales are the only odontocetes that emit clicks with fm modulation. As best as we know, short-finned pilot whale and Risso's dolphins emit clicks with characteristics that are unique to them. Needless to say, more research in this area is warranted.

This chapter has illustrated how PAMs can be valuable instruments to determine the presence of sound-producing marine mammals. In this chapter, the diurnal and seasonal patterns of deep-diving odontocetes were examined. Yet the use of a single hydrophone can be a serious limitation. On one hand, an EAR can provide valuable information but on the other hand the limitation of the information provided can trigger deeper questions that are important to understand the behavior of marine mammals in a given body of water. Questions like how many animals are present, how far away are they, and how deep are they diving to cannot be addressed by present single hydrophone PAMs.

The results of our use of EARs in the western Pacific Ocean suggest that future studies of deep-diving odontocetes should have a strong ecological emphasis. The composition and dynamics of the prey field need to be examined more deeply. How the prey field of squid interacts with the mesopelagic layers is one area of study that is important and basis in order to understand the foraging behavior of deep-diving odontocetes. The role of the bottom topography is also a factor that should be considered in future studies. The bottom off the Hawaiian Islands rises steeply from the deep into the air as can be seen in Fig. 5.1. This type of topography is rather different than a seamount which basically represents submerged isolated bathymetric feature on the abyssal plane. Canyons, like the one at the AUTEC range, have steep walls that rise to an underwater plateau on both sides. The oceanographic conditions for these bottom types can be expected to be very different and these differences will affect the dynamic behavior of squid and fish prey. There are also many other factors that affect prey behavior that we can only speculate on without any detailed measurements. Furthermore, the geographic locations and atmospheric and oceanic patterns will all be contributing factors in a complex interactive web of variables that affect squid and fish prey behavior. In the end, the general prey field behavior around Pacific islands like Kauai, Ni'ihau, Okinawa, Guam, Tinian, and Saipan is such that deep-diving odontocetes must have a distinct advantage foraging at night rather than during the day. In summary, better and more sophisticated PAMs are needed and complementary ecological studies should be conducted with PAMs being but one of the instruments involved. PAMs definitely have a role in studies to understand the foraging behavior of deep-diving odontocetes.

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Chapter 6
Environmental Acoustic Recording System (EARS) in the Gulf of Mexico

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Abstract The Littoral Acoustic Demonstration Center (LADC) was formed in early 2001 to utilize Environmental Acoustic Recording System (EARS) buoys developed by the Naval Oceanographic Office (NAVOCEANO) which has provided technical guidance and support to LADC. The purpose of LADC is to make environmental measurements, which is not part of the mission of NAVOCEANO. This chapter describes the Gulf of Mexico marine mammal measurements and related data analysis of LADC. LADC has also used the buoys to characterize the three-dimensional acoustic field of a seismic airgun array and to analyze the noise

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due to nearby storms. LADC is a consortium of scientists from universities and the U.S. Navy. The following institutions are or have been represented: initially, the University of New Orleans, the University of Southern Mississippi, and the Naval Research Laboratory-Stennis Space Center; and then the University of Louisiana at Lafayette, the Applied Research Laboratories at the University of Texas at Austin, and Oregon State University. The scientists are listed in the first section of the chapter. A technical overview of EARS technology is given in Sect. 6.2. The current Generation 2 EARS buoys can record four channels of up to 25 kHz each or one channel up to 96 kHz.

LADC has conducted marine mammal experiments in the Gulf of Mexico in 2001, 2002, 2007, and 2010. The 2007 experiments were at sites 9 and 23 miles from the Macondo Well Oil Spill. These sites as well as the 2001 and 2002 sites were recorded in the 2010 experiment to measure changes related to earlier measurements. LADC has also done seismic airgun array experiments in 2003 and 2007. The marine mammal experiments are summarized in Sect. 3, where experiments in the Mediterranean Sea, which had LADC participation, are also listed.

The remaining Sects. 6.4 through 6.11 describe the analysis to date of LADC data and also the analysis by LADC scientists of workshop data for detection, classification, and localization purposes. Section 6.4 describes sperm whale click structure analysis for click-train demarcation and identification of individual whales. The tendency of whales diving together to establish different cadences for their echolocation clicks to keep from interfering with each other is presented in Sect. 6.5. The identification of individual whales by clustering echolocation clicks of sperm and beaked whales and coda clicks of sperm whales is discussed in Sect. 6.6.

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The application of click change detection to know if the same or a different whale are speaking on successive clicks is described in Sect. 6.7. This method allows one to follow a turning sperm whale. A technique for localizing individual clicking whales is presented in Sect. 6.8. The integration of the above techniques is discussed in Sect. 6.9, which also suggests how whales might identify each other. Sperm whale coda classification and repertoire analysis are the subject of Sect. 6.10. Finally, statistical modeling for population estimation is given in Sect. 6.11.

6.1 Littoral Acoustic Demonstration Center (LADC)

The Littoral Acoustic Demonstration Center was formed in early 2001 to utilize U. S. Navy technology to advance the science of underwater acoustics. Specifically, the technology is the autonomous Environmental Acoustic Recording System (EARS) buoy, developed by the Naval Oceanographic Office (NAVOCEANO) at Stennis Space Center, MS. EARS are described in Sect. 6.2 of this chapter. It was decided that LADC would be a consortium of scientists from Gulf State Universities and the U. S. Navy.

Mr. Craig Peterson represented the Naval Oceanographic Office, which supplied technical support and guidance. The cooperating scientists included the following, almost all of whom are still participants: Dr. Grayson Rayborn of the Department of Physics and Astronomy (and later also of the Signal Research Center) of the University of Southern Mississippi (USM), Dr. Stan Kuczaj of the Department of Psychology of USM, Dr. George Ioup and Dr. Juliette Ioup of the Department of Physics of the University of New Orleans (UNO), Dr. Joal Newcomb of the Naval Research Laboratory at Stennis Space Center (NRL-Stennis) (now at NAVOCEANO) and Mr. Robert Field of NRL-Stennis (now retired). Later these scientists were joined by Dr. Natalia Sidorovskaia of the Physics Department at the University of Louisiana at Lafayette (UL Lafayette), Dr. Christopher Tiemann of the Applied Research Laboratories of the University of Texas at Austin (ARL-UT) (now at R2Sonic), Dr. James Stephens of the Department of Physics and Astronomy and the Signal Research Center of USM (now at the Southwest Mississippi Community College), Dr. Arslan Tashmukhambetov of the Department of Physics at UNO (later at G Geophysics and now at LLOG), and Dr. Azmy Ackleh of the Department of Mathematics at UL Lafayette. Recently Dr. David Mellinger and Ms. Sara Heimlich of the Cooperative Institute for Marine Resources Studies at Oregon State University and Adm. Ken Barbor and Dr. Danielle Greenhow of the Department of Marine Science of USM have joined the group. These scientists have joined over the years for specific exercises and for equipment development and maintenance by many other scientists and engineers, technicians, graduate students, and crew members, to whom an immense debt of gratitude is owed. LADC's development is described in the remainder of this section. EARS technology is elucidated in Sect. 6.2 and LADC

Marine Mammal Experiments are described in Sect. 6.3. The remaining Sects. 6.4 through 6.12 contain the results of data analysis.

The initial scientific purpose of the group was to study ocean ambient noise and upslope propagation. When it was learned in early 2001 that the Minerals Management Service (MMS), with other sponsors, intended to have an exercise conducted in the Northern Gulf of Mexico (GoM) in the summer of 2001 to study endangered sperm whales, LADC added marine mammal bioacoustics to its areas of interest and determined to deploy EARS moorings that summer to record sperm whales as well as ambient noise and upslope propagation. An area was chosen that had a very large number of sperm whale sightings, and EARS technology was extended to higher frequencies (~6000 Hz) by NAVOCEANO to record the whales. (Originally EARS was developed to measure ambient noise, and its upper frequency limit was 1000 Hz.) Some of the highest quality recordings of sperm whales up to that time were made. The deployment was repeated in the summer of 2002. These exercises are referred to as LADC01 and LADC02 and were supported by ONR.

When LADC learned that MMS intended to conduct a controlled exposure experiment (CEE) for sperm whales in the Northern GoM in 2003, using a seismic source vessel supplied by the Industry Research Funders Coalition (IRFC) through the International Association of Geophysical Contractors (IAGC), it approached the IRFC through the IAGC for funding to measure the acoustic field of the seismic airgun array, adding an additional LADC research interest. LADC deployed a co-located sensitive hydrophone buoy and a desensitized hydrophone buoy (to avoid clipping), and the plan was to have the source vessel run lines over this mooring if its schedule permitted. On the last afternoon of its availability, the vessel had time to shoot five parallel lines over the mooring. This experiment, called Airgun03, is described and the data are analyzed and modeled in "Three-dimensional seismic array characterization study: Experiment and modeling," Arslan M. Tashmukhambetov et al. (2008).

EARS technology was extended to measure up to 25 kHz for the airgun experiment. Because of increasing U. S. Navy interest in beaked whales, the technology was further developed so that EARS buoys could measure up to 96 kHz in single-channel mode or 25 kHz per channel in four-channel mode. These are Generation 2 buoys. In 2007, LADC conducted the Source Characterization Study 2007 (SCS07) to completely characterize the three-dimensional (3-D) primary acoustic field of a seismic array, using Generation 2 EARS buoys in the four-channel mode. These were deployed as 20 pairs of moored hydrophones (one each, sensitive and desensitized) at different depths. Four pairs of hydrophones were suspended from a ship. This work was sponsored by the Joint Industry Programme (JIP) through the International Association of Oil and Gas Producers (OGP). Its findings will impact regulations for the protection of marine mammals and other marine life.

Also in 2007, LADC conducted an exercise, sponsored by SPAWAR, to record primarily not only beaked whales but also sperm whales and dolphins in the Northern GoM. The Generation 2 EARS buoys were used in the single-channel mode. It made the first recordings of beaked whales in the GoM. By coincidence, the two sites selected for deployment, based on a high density of beaked whale sightings, are 9 and 23 miles from the location of the BP oil spill in 2010. Therefore, LADC received funding in 2010 from NSF and Greenpeace to go back to the two sites and to LADC01 and LADC02 sites to measure marine mammal activity after the spill and compare it to the measurements made in LADC07 and earlier. Some abundance analysis results appear in Ackleh et al. (2012) and in this Chapter. More recently, LADC has received 3 years of funding (2015 through 2017) from the Gulf of Mexico Research Initiative (GoMRI) RFP IV to conduct two exercises to compare sperm and beaked whales and dolphin measurements using moored buoys, autonomous surface vehicles, and gliders.

All of the existing marine mammal recordings are still being analyzed. Many of our results are summarized in the following sections of this Chapter.

6.2 Environmental Acoustic Recording System (EARS) Buoys

Environmental Acoustic Recording System (EARS) buoys were developed as autonomous moored underwater recording systems by the Naval Oceanographic Office (NAVOCEANO) to make long-term ocean ambient noise measurements. When LADC was formed, the buoys were capable of measuring up to 1000 Hz for 1 year. When LADC added listening to sperm whales to its noise and propagation measurement missions, NAVOCEANO quickly modified the buoys to measure up to 5859 Hz for 36 days. The buoys, moored at depths from 550 to 950 m in the Gulf of Mexico, produced exceptionally clear recordings of sperm whale echolocation and coda clicks and recordings of other whales. EARS Generation 2 buoys are now capable of recording one channel to 96 kHz, or 4 channels to 25 kHz. All buoy designs include high quality omnidirectional hydrophones (Figs. 6.1 and 6.2).

Overview: (Environmental Acoustic Recording System (EARS) BUOY

- Developed by NAVOCEANO
- Autonomous Self-recording Buoy
- Small, Easily Deployable Package
- 16-bit Sigma-Delta A/D
- First-Generation Attributes (at peak of development)
    - 1–4 channels (limited spatial separation)
    - Sampling rates from 200 Hz to 25 kHz
    - 4 Disk Drives
    - Hard disk data storage from 80 to 128 GB per disk >66 days recording
- Second-Generation Attributes
    - 1–4 channels
    - Sampling rates from 78 to 200 kHz
    - 4 Disk Drives
    - Hard disk storage from 240 GB to 1 TB per disk

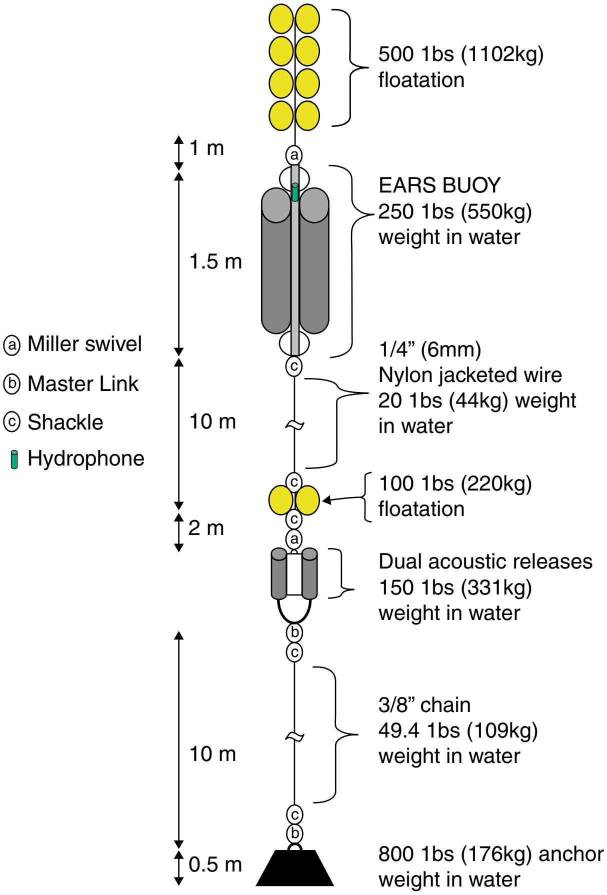


Fig. 6.1 Components of an EARS mooring. These include flotation, the EARS buoys, dual acoustic releases, an anchor chain, and an anchor. Aside from the chain the remaining components are connected by faired cable, to minimize cable strum

Fig. 6.2 EARS mooring components on deck, before deployment. The floats are *yellow*. The faired cable is *white*. The EARS buoys are *black cylinders*

  - Choice of hydrophone sensitivity/System gains
  - Delayed start available
  - More compact due to higher energy efficiency
  - Recording time dependent on disk size

Summary of Current Technology

- Microprocessor:
  - Two stereo a/d boards (total of four 16-bit sigma-delta a/d)
- Maximum sample rate:
  - 50 kHz/channel in 4-channel mode
  - 100 kHz/channel in 2-channel mode
  - 192 kHz in single-channel mode
- Storage media:
  - 2.5 in. hard drives (four each)
  - Flash drives (future)
- Max storage:
  - Hard drive dependent
  - Current: 4 × 120 GB drives (480 GB)
  - Available soon: 4 × 250 GB (1 TB) up to 4 × 1 TB
- Number of bits: full 16 bit
- Size: 2 m long, 0.425 m diameter, 110 lbs
- Average power supply/consumption:
  - Currently the EARS are storage limited, not battery limited

Cost of EARS buoys

- Approximate cost of Generation 2 EARS buoys considering different configurations
  - LADC paid $23.4K per buoy with a single hydrophone in our configuration (group of 10)
  - Add $950 per hydrophone and $33/m for cabling to build two or four channel arrays

6.3 LADC Marine Mammal Acoustic Experiments

Experiments in the Gulf of Mexico and the Ligurian Sea have targeted both sperm and beaked whales. Audio results and visualizations of these recordings reveal rich detail of *Odontocete* clicks and enable new analyses such as the identification of individual whales from the properties of their clicks. Beginning with experiments in 2001, LADC scientists have studied sperm whale clicks and clicking behavior. In 2007, the study was extended to beaked whale clicks.

LADC has led or participated in seven experiments for the study of marine mammal acoustics. They are:

1. LADC 01—Gulf of Mexico
2. SIRENA 02—Ligurian Sea w/NURC
3. LADC 02—Gulf of Mexico
4. SIRENA 03—Ligurian Sea w/NURC
5. ZIPHIO 06—Ligurian Sea w/NURC
6. LADC 07—Gulf of Mexico
7. LADC 10—Gulf of Mexico

Experiments 1, 3, 6, and 7 were performed by LADC, and the remaining experiments were led by the NATO Undersea Research Centre (NURC) (now the Centre for Maritime Research and Experimentation (CMRE)) with LADC participation. All experiments used EARS buoys.

1. LADC 01

- Northeastern Gulf of Mexico.
- July 16 through Aug 21, 2001. The acoustic recordings spanned 36 days.
- Buoys moored upslope off mouth of Mississippi River in water depths of 600, 800, and 1000 m.
- Buoys moored 50 m above bottom.
- During the experiment, Tropical Storm Barry passed within 100 nmi of the EARS buoys.

3. LADC 02

- North central Gulf of Mexico.
- August 19 through September 15 planned, retrieval 23–24 October, 2002; 22–57 days recorded.
- Buoys moored upslope off mouth of Mississippi River in water depths of 600, 800, and 1000.
- Buoys moored 50 m above bottom.
- Tropical Storm Isidore passed with 73 nmi of the EARS buoys, and Hurricane Lili passed within 116 nmi.

LADC 01 and LADC 02

- Three Single-Channel G1 EARS Buoys.
- 11.7 kHz sampling rate.

6. LADC 07

- Gulf of Mexico south of Gulfport, MS, at 1550 m contour.
- July 3 to July 14, 2007.
- Six Single-Channel G2 EARS buoys on bottom-mounted moorings.
- Three moorings at north site 3 km separation.
- Three moorings at south site 5 km separation.
- 750–800 m hydrophone depths.

- 192 kHz sampling rate.
- 2.2 TB recorded (9 days, ~¾ capacity).

7. LADC 10

- Six Single-Channel G2 EARS buoys on bottom-mounted moorings.
- Two buoys at LADC 07 north site buoy locations, two buoys at LADC 07 south site buoy locations, and two buoys at deepest site for LADC 01 and 02.
- 192 kHz sampling rate.
- The buoys recorded for 12 days.
- Deployments were done from 9 September through 12 September 2010.
- Recording depths of 1000 m for the LADC 07 sites and 800 m for the LADC 01-02 site.

Recently, LADC has received funding from the Gulf of Mexico Research Initiative (GoMRI) RFP IV for two exercises to compare sperm and beaked whales and dolphin measurements using ten single-channel Generation 2 moored EARS buoys, hydrophone arrays towed by autonomous surface vehicles (ASV's), and hydrophone arrays towed by gliders, and a test cruise in the off year between the two exercises. All measurements will be made at the three sites of the LADC 10 experiments. The first exercise will begin with a cruise to deploy the hydrophones and operate the ASV's and glider in June of 2015. A retrieval cruise will take place in October 2015. Tests of equipment upgrades will be made on a cruise in July 2016. The second field exercise will begin with deployment in April of 2017 and retrieval in August of that year. Again, ASV's and gliders will be tested. Funding is also included for equipment upgrades, experimental planning, and data analysis.

Figure 6.3 shows the locations of all GoM exercises. The green circles are the LADC 01 locations and the yellow circles are the LADC 02 locations; the yellow

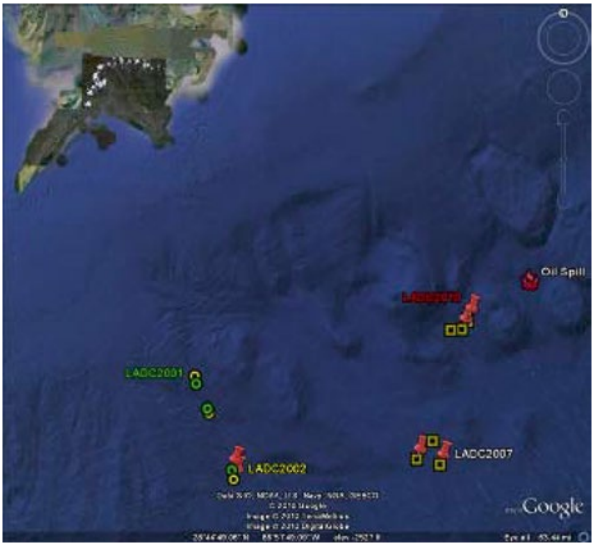


Fig. 6.3 The locations of all GoM exercises. The *green circles* are the LADC 01 locations, the *yellow circles* are the LADC 02 locations, the *yellow squares* show the north and south buoy sites of the LADC 07 exercises, and the *pink pushpins* show the LADC 10 locations. The *red flame* shows the site of the BP oil spill

squares show the north and south buoy sites of the LADC 07 exercises, and the pink pushpins show the LADC 10 locations. The red flame shows the site of the BP oil spill.

Acoustic data from any single LADC experiment can support a variety of marine mammal related studies, often in parallel and complementary to each other. For example, several techniques were explored for individually identifying clicking sperm whales, and simultaneous results compared. Other research regarding acoustic behavior and population estimation is summarized below as well.

6.4 Click Structure Analysis and Sperm Whale Identification

The ability to acoustically discriminate one clicking sperm whale from another is a challenging problem yet an important one to solve if acoustics are to be used to passively study these animals' behavior. For example, associating all the clicks from just one individual whale while multiple animals are clicking concurrently is an important first step in the passive acoustic localization and tracking of sperm whales. There is also the question of whether these animals can distinguish each other through the individual characteristics of their clicks. The LADC group explored several techniques in parallel for grouping click sequences from individual whales, as described below and in subsequent sections.

6.4.1 Click Structure Analysis

The click production mechanism of the sperm whale results in a "click" that is not just a single impulse but rather has a structure from the sum of multiple reflections internal to the whale's head (called the *p0*, *p1*, and *p2* pulses), and the recorded click structure will vary depending on the animal's aspect to the receiver. It has been LADC's experience that any change in recorded click structure as an animal moves relative to the receiver happens slowly compared to the rate in which clicks are made. Thus, when trying to match click events from the same individual, adjacent clicks that have a consistent periodicity and structure (and frequency spectra) are likely matches from the same individual. As an example, when time series of clicks assumed to be from the same individual are time aligned and stacked, their persistent, or slowly evolving, shapes become visually apparent. Figure 6.4 illustrates this in two waterfall plots of evolving click shapes from two different sperm whales with unique click structures. These two click trains overlapped in time and had slightly different average interclick intervals.

While manually associating clicks via visual inspection and periodicity clues is possible over short time spans, it is too laborious a method to apply to hours or days of acoustic data, suggesting the need for an automated solution, as explored in the following sections.

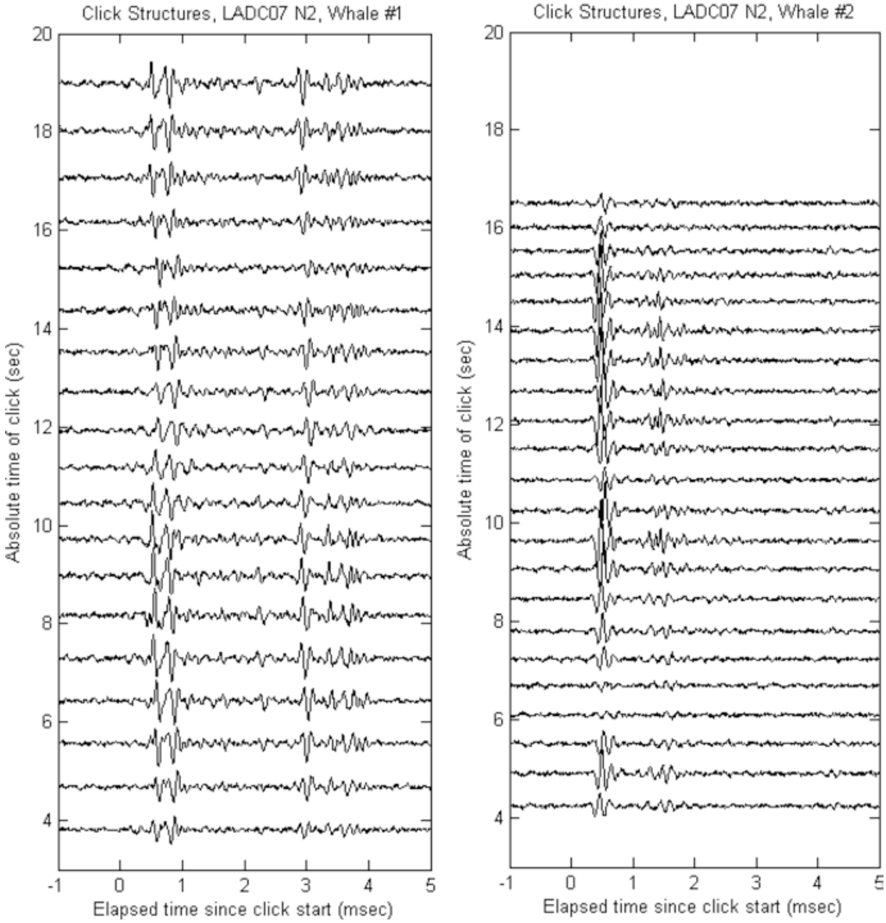


Fig. 6.4 Time-aligned and stacked time series of clicks from two different whales clicking concurrently, as recorded by sensor N2 during LADC07. The slowly evolving shapes of the click structures and consistent interclick interval allow association of each click to an individual whale when manually inspected

6.5 Cadence Frequency Analysis and Identification of Individual Clicking Whales

The Cadence Frequency Analysis (CFA) algorithm was developed as a part of the LADC integrated software package to identify individual sperm whales. The algorithm allows the determination of the number of simultaneously phonating animals in a group and the identification of the click trains of an individual animal in the group of interleaving click trains. It also tests the hypothesis that simultaneously phonating animals in a group will adjust their clicking rhythms to efficiently scan the environment and distinguish among clicks emitted by different group members (Sidorovskaia et al. 2009a, b, c, 2010; Tiemann et al. 2011).

The CFA method can quickly and reliably associate clicks with individuals in a group of whales who are phonating simultaneously. It can be of interest also for developing technology associated with real-time passive acoustic monitoring from autonomous mobile platforms. The method is robust against environmental changes, signal-to-noise ratio, and surface and bottom reflections, and is species independent. The algorithm performance is independently validated by identifying individual click trains using two other techniques: the Passive Acoustic Localization using the Time Difference of Arrival (TDA) method (Tiemann et al. 2006; Tiemann et al. 2008; Van der Schaar et al. 2009) and cluster analysis. These techniques are described in Sects. 6.8 and 6.6 of this chapter.

Diving marine mammals produce echolocation clicks to orient themselves in the ocean, find prey, and perform short-range localization and tracking for prey capture. Many types of marine mammals dive in groups and echolocate simultaneously. The development of the CFA algorithm is based on the hypothesis that each animal in a group has the ability to slightly vary its interclick interval (frequency of clicks) to avoid interference with signals produced by nearby divemates. Logically it would also allow them to utilize clicks produced by other animals in the group to extract information about the surroundings with higher efficiency. The concept of rhythmic identity measurements was previously discussed by Andre and Kamminga (2000). They also mentioned anecdotal evidence that drummers from African tribes, trained at early ages to play individual rhythms in a group, could easily determine how many rhythmic themes were preset in a playback of overlapping click trains. The authors proposed that marine mammal click production can be rhythmically modulated to prevent interference among individuals, and such rhythmic patterns could serve as acoustic signatures of individuals. Andre and Kamminga used a cross-correlation analysis of time domain signals for sperm whale clicks and codas to reveal rhythmic modulation. Despite the similarity of initial hypotheses, the CFA algorithm is fundamentally different and originated from an algorithm developed for human motion analysis (Ekimov and Sabatier 2008, 2011). The CFA algorithm does not have some common shortcomings of the other two methods.

1. The CFA algorithm is species and environment independent. Reflections do not degrade the algorithm performance.
2. The CFA algorithm is dynamic and follows the rhythm evolution during a dive.
3. The CFA algorithm allows for multiple frequency band selections and can serve as a simultaneous detector and classifier.
4. The CFA algorithm is robust to low signal-to-noise ratio due to band selectivity.
5. The implementation of a concurrent "cleaning" procedure reveals rhythmic patterns of strong and faint click trains simultaneously.

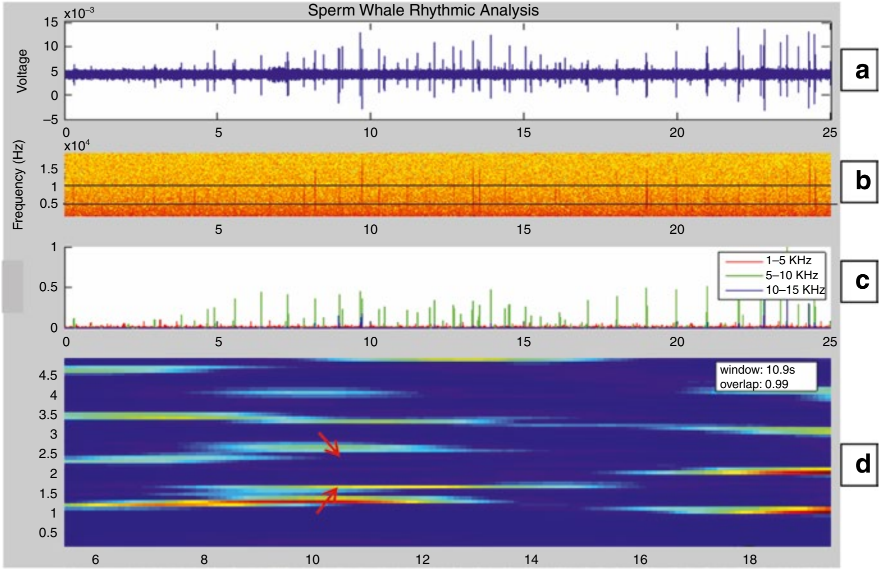


Fig. 6.5 The Cadence Frequency Analysis algorithm is applied to LADC Gulf of Mexico 2007 PAM data. (**a**) Raw temporal broadband acoustic signal of 25 s duration. (**b**) Spectrogram of the acoustic signal with *vertical lines* corresponding to sperm whale clicks. (**c**) Normalized band-limited energy function vs time obtained by incoherently summing spectrogram frequency components over the chosen band. (**d**) Spectrogram of the energy function for the 5–10 kHz band with sliding window of 11 s. The *arrows* indicate two whales phonating with offset interclick frequencies of 1.2 and 1.6 Hz. The temporal evolution of the interclick interval for the 1.2 Hz individual can be also seen

The algorithm consists of two main steps: (1) formation of a band-limited energy function, and (2) frequency analysis of the band-limited energy function (Fig. 6.5). Figure 6.5a shows the raw temporal PAM signal recorded by the Environmental Acoustic Recording System (EARS) Buoy during July 2007 in the Northern Gulf of Mexico. The signal contains multiple sperm whale echolocation clicks. The sampling frequency of the EARS buoy continuous recordings was 192 kHz and provided reliable discrimination among different marine mammal species present in the area (sperm whales, beaked whales, pilot whales, and dolphins). A sliding window Fourier transform is applied to the temporal data to obtain the spectrogram shown in Fig. 6.5b. The sliding window length is approximately the duration of the expected clicks (4 ms for sperm whales). The bright vertical lines on the spectrogram represent sperm whale clicks. The main energy of the sperm whale clicks is concentrated in the 5–10 kHz band; this band is chosen for energy function formation. The energy of all spectral components in the chosen band is summed for each temporal point of the spectrogram. The temporal evolution of the normalized energy functions for three different frequency bands are shown in Fig. 6.5c. The 5–10 kHz band energy function characteristic of sperm whale clicks is analyzed next to reveal different rhythmic patterns of simultaneously phonating sperm whales.

The second step of the CFA algorithm consists of obtaining a spectrogram of the band-limited energy function, as shown in Fig. 6.5d. The cadence frequency spectrogram in Fig. 6.5d shows two sperm whales clicking simultaneously at 1.2 and 1.6 Hz (as indicated by arrows). The dynamic evolution of the lower frequency to 1 Hz at time marker 16 s can also be seen. The higher frequency content of the cadence frequency spectrogram (above 2 Hz) does not represent any new information. The prominent frequency components above 2 Hz are amplitude-modulated harmonics of the fundamental cadence frequencies due to properties of the Fourier Transform. It should be noted that a careful record of time axis resolutions has been kept for associating time points in the raw signal, energy function, and cadence frequency spectrograms. The algorithm is not affected by the multipulse structure of sperm whale clicks or reflections because they will have the same cadence frequency. These may appear in later iterations of the CFA algorithm when the strong clicks of an individual whale (following the cadence spectral line) are removed from an original raw signal to reveal low amplitude phonations. The number of whales in a group and the click association with a particular whale will remain unchanged.

The method was applied to a 90-s segment of the experimental dataset collected in the Northern Gulf of Mexico in 2007 by the Littoral Acoustic Demonstration Center (LADC) and verified by comparison with results provided by two independent algorithms: manual association of clicks from the time difference of arrival maps (Tiemann et al. 2006), and self-organizing map clustering based on three click attributes (temporal structure, spectral structure, and wavelet transform structure) (Ioup et al. 2004). Figure 6.6 shows the cadence analysis final time-frequency maps for three hydrophones N1, N2, and N3 (N1 and N2 are about 2 km apart, N1 and N3 are about 2 km apart, and N2 and N3 are 4 km apart). Eight iterations of CFA are applied to the data from each hydrophone. The iteration number is identified by a colored arrow, and the same color-coded symbols correspond to the click time and cadence frequency pair. Hydrophone N2 clearly shows three whales phonating at 1.0, 1.2, and 1.6 Hz (1, 0.83, and 0.62 interclick intervals (ICI), respectively) during the first 30 s. The same cadence frequency pattern is seen on hydrophone N1. The distant N3 hydrophone does not pick up all three whales, probably due to click directionality. To verify the cadence frequency-whale association made based on the results produced by the CFA, we compared it with the manual click association from the TDA and the self-organizing map methods for the same segment of data. Results show over 80 % agreement among all three methods in associating clicks with individuals and their click production times (see Fig. 6.7). Due to the cleaning algorithm and iterative approach, the CFA algorithm is much more sensitive to weak signals, which explains why many CFA click detections are unmatched by the TDA and self-organizing map algorithms in Fig. 6.7.

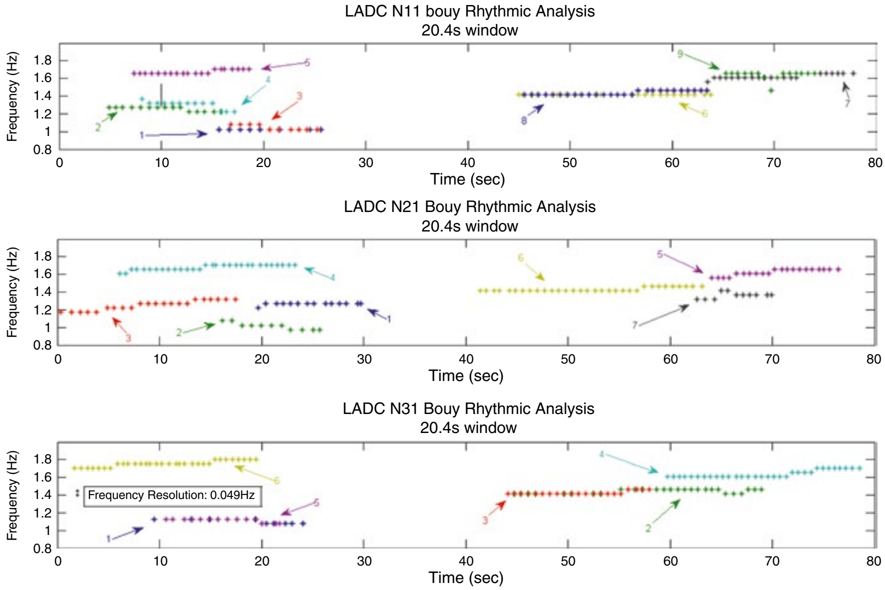


Fig. 6.6 Eight iterations of Cadence Frequency Analysis are applied to the data from three recording EARS buoys of the 2007 experiment. *Star symbols* identify the time and interclick frequency of sperm whale clicks. Three individuals phonating with slightly offset interclick intervals are easily identified on N11 and N21 buoys in the first 30-s of the analyzed segment. Only two individuals are identified on the N31 buoy

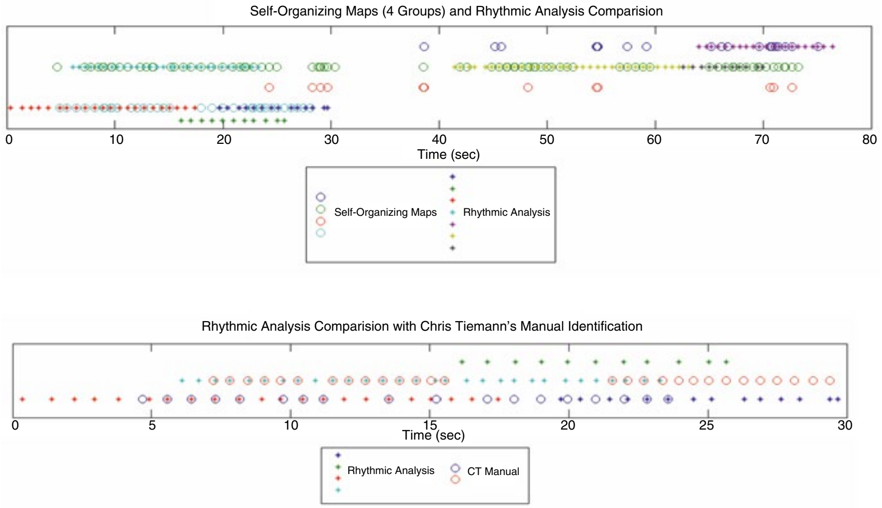


Fig. 6.7 Comparison of CFA individual animal click production time results with self-organizing map clusters (**a**), and TDA results (**b**). *Horizontal lines* correspond to the individuals identified by the algorithms. *Symbols* are located at times of individual clicks

In summary, the CFA algorithm shows good agreement with other algorithms targeting identification of individuals in a group of simultaneously phonating marine mammals. It also supports the hypothesis of "polite speakers," i.e., sperm whales adjust their interclick intervals so that they do not overlap with the interclick intervals of divemates.

6.6 Identification of Individual Whales from Click Properties by Clustering

The initial motivation for working with individual clicks came when G. Ioup and J. Ioup noticed that all the clicks in a sperm whale coda were similar both in the time and frequency domains, but that they could differ from coda to coda. Coda clicks are used for communication, and they occur in groups of 6–15 clicks with an interclick interval of approximately 40 ms and a click duration of 3 to 6 ms. It has been shown that the time difference between peaks (intraclick interval) within a sperm whale echolocation click is related to the size of the whale (Norris and Harvey 1972; Møhl et al. 1981; Gordon 1991; Goold 1996; Rhinelander and Dawson 2004; Teloni et al. 2007; Growcott et al. 2011). The observation that coda clicks from a given whale are similar to each other but differ from the clicks of other whales is consistent with the connection of click properties to the size of the whale.

Baggenstoss (2011, 2013) has developed sophisticated mathematical approaches to associate echolocation clicks into click trains originating from individual sperm and beaked whales. The methods can break down if there are too many overlapping click trains and/or if some of the click trains are sparse. Baggenstoss has advanced his method by using the cross-correlations among the clicks to assist in associating the clicks into click trains. His work provides another independent confirmation that properties of clicks differ from one individual whale to another.

Figure 6.8 displays one minute of EARS recorded underwater acoustic data from 2001. The top graph is an amplitude proportional to pressure plotted versus time. The middle figure is a data spectrogram showing frequencies up to 6000 Hz on the vertical axis and time on the horizontal axis. Color gives the intensity of the transform, with red indicating the highest intensity. The bottom figure is the 0–1000 Hz portion of the spectrogram. The 6000 Hz spectrogram shows that there are many echolocation clicks and some codas. The lower spectrogram shows clearly the seismic airgun firing every 11 s. The source ship was 107 km from the EARS buoy.

Figures 6.9a, b show the time domain signals and the spectrograms of two segments of four seconds of sperm whale clicks; each contains a coda. As in Fig. 6.8, the top figure in each group of three is proportional to the pressure plotted versus time. The middle figure shows the spectrogram with frequency to 6000 Hz on the vertical axis and time on the horizontal axis. Color indicates the magnitude of the transform. The bottom figure shows the frequency to 1000 Hz.

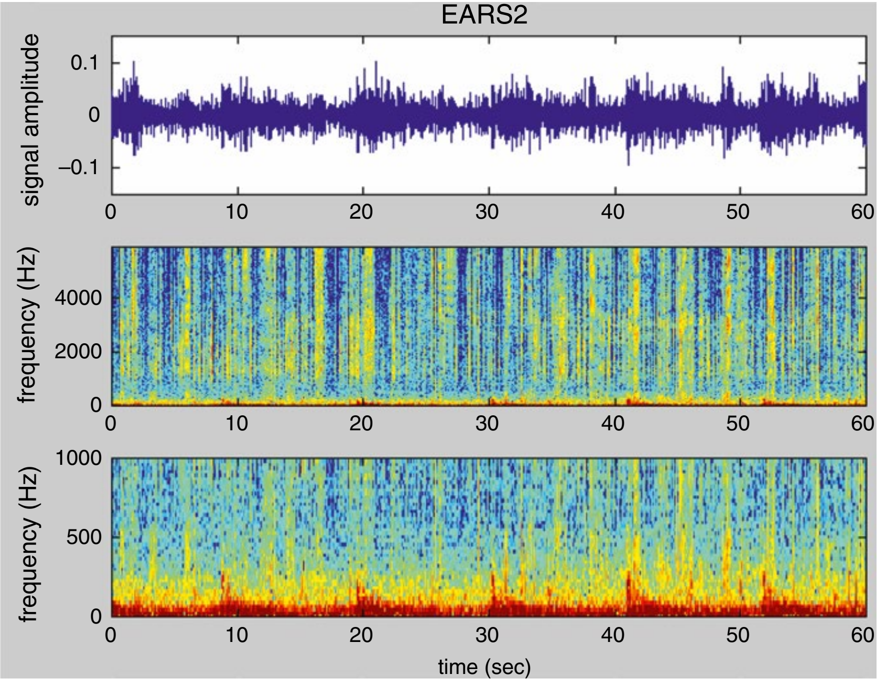


Fig. 6.8 One minute of recorded data. The *top graph* is an amplitude proportional to pressure plotted versus time. The *middle figure* is a data spectrogram showing frequencies up to 6000 Hz on the vertical axis and time on the horizontal axis. *Color* gives the intensity of the transform, with *red* indicating the highest intensity. The *bottom figure* is the 0–1000 Hz portion of the spectrogram. The 6000 Hz spectrogram shows that there are many echolocation clicks and some codas. The lower spectrogram shows clearly the seismic airgun firing every 11 s. Reprinted from G.E. Ioup et al. (2009)

Figure 6.10 shows an overplot of the magnitude spectra of all the clicks in a coda for five different codas. The similarity for clicks within a coda is striking. Figure 6.11 shows an amplitude versus time overplot of the clicks within a coda offset in the vertical axis, with similarity among the clicks evident.

As has been pointed out by Tiemann (see, for example, Sect. 6.4), identification of sperm whale echolocation click trains by humans is far too laborious when needed for many days or even hours of recordings. Baggenstoss' (2011, 2013) automated methods are one approach to solving this problem for sperm and beaked whales echolocation trains. The method of cadence analysis, Sect. 6.5, is another. A method of associating clicks with individuals, which avoids the need for click-train identification, and also applies to sperm whale coda clicks, is clustering of clicks. Clustering (Hartigan 1975; Seber 1984; Spath 1985; Estivill-Castro 2002) means putting clicks which closely resemble each other into individual clusters (classes), each of which presumably represents the clicks from one whale. Clustering is normally performed by computer analysis. The fact that the whale clicks have some natural biological variation from click to click for the same animal, and also

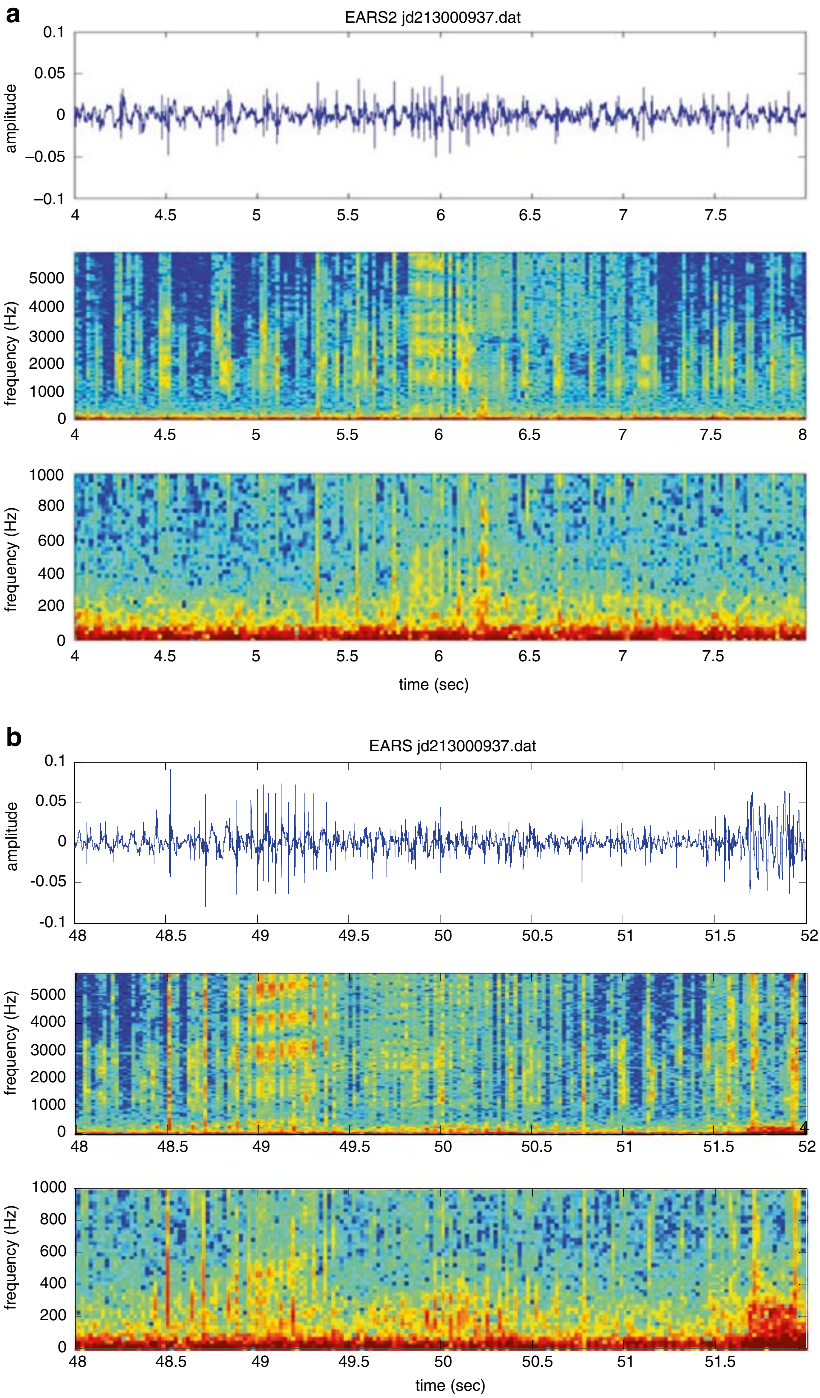


Fig. 6.9 Two 4-s segments of acoustic recordings from the Gulf of Mexico, containing sperm whale codas. (**a**, **b**) Time domain signals and the spectrograms of two different segments of four seconds of sperm whale clicks; each contains a coda. The *top figure* in each group is an amplitude proportional to the pressure plotted versus time. The *middle figure* shows the spectrogram with frequency to 6000 Hz on the vertical axis and time on the horizontal axis. *Color* indicates the magnitude of the transform. The *bottom figure* shows the frequency to 1000 Hz. Reprinted from Tiemann et al. (2011)

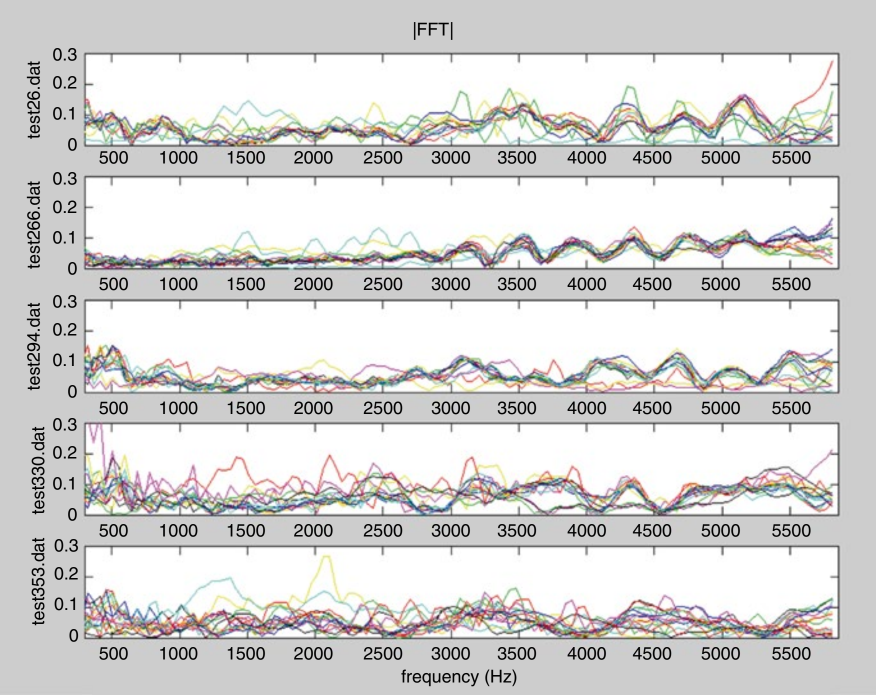
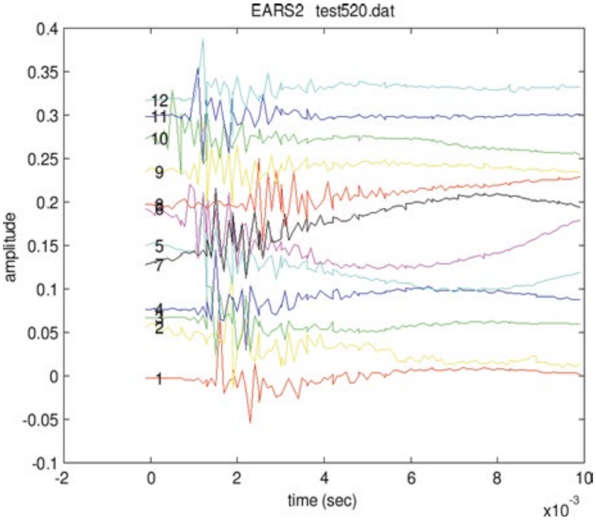


Fig. 6.10 Overplot of the magnitude Fourier spectra versus frequency for all the clicks in five sperm whale codas. Each *panel* is one coda, with individual clicks in each coda in a different color. Note that the shapes for the clicks in one coda are quite similar to each other, but that they can be distinctly different from those in other codas. A few overlapping echolocation clicks from other whales are also included in these plots. Reprinted from Tiemann et al. (2011)

Fig. 6.11 Amplitude versus time for all the clicks in one coda from Fig. 6.10 plotted. Amplitude in each click is offset for clarity. Reprinted from Tiemann et al. (2011)



changing physical parameters, such as whale depth and aspect between the whale and the receiver (the latter especially important for sperm whale echolocation clicks), means that the received signal from one whale will change over time and that the clustering must be designed with these factors in mind.

Clustering methods, mainly K-means (Lloyd 1982; Seber 1984; Spath 1985) and Self Organizing Maps (SOM) (Kohonen 1989; Pandya and Macy 1995), have been compared for application to whale clicks. SOM has been found to be more useful. It is iterative and allows straightforward incorporation of stopping criteria such as minimizing the Euclidean distances within a cluster and maximizing the Euclidean distances between cluster centers. It adds new clusters as it iterates. If adding a new cluster worsens the quality measures, the iterations are terminated and SOM gives the number of clusters needed. This number has turned out to be a good first estimate of the number of whales present.

SOM has been applied to both sperm whale coda and echolocation clicks and beaked whale echolocation clicks. LADC scientists have been using cluster analysis since 2004 (Ioup et al. 2005, 2009, 2010; Tiemann et al. 2011). The coda clustering results are shown in Fig. 6.12, which gives the results of clustering 43 sperm whale codas occurring over a 3-min interval for data collected in 2001 in the northern Gulf of Mexico. The clustering is done by taking an average click for each coda and clustering the 43 codas using the average click for each. Figure 6.12a shows the clustering results based on the time data. Figure 6.12b is based on clustering the magnitude of the discrete Fourier transform (DFT), and Fig. 6.12c is obtained by clustering the discrete wavelet transforms (DWT) of the time signals. As stated above, SOM algorithms determine how many clusters are needed to obtain optimum results. The time and wavelet clustering found that four clusters (four whales) were optimal, whereas the Fourier clustering put two codas in a fifth cluster. The time and wavelet clustering agreed completely; the Fourier clustering disagreed for three codas out of the 43 total codas. More recent work has shown that if clustering is done with the complex DFT instead of simply using the magnitude, better agreement is obtained with the time and wavelet clustering.

Tiemann used 46 sperm whale echolocation clicks from the LADC07 data to do a click-train analysis. He concluded that there were two whales clicking. When the same 46 clicks were clustered using SOM, the output showed three clusters. This is still a grey area in clustering, as sometimes minor differences in clicks will lead to the creation of an additional cluster when none is needed. It is hoped that incorporating click change detection (Sect. 6.7) into clustering will make the cluster count more accurate. In this case, to compare the clustering to Tiemann's manual click-train analysis, the maximum number of clusters was set to two in SOM. The results are shown in Fig. 6.13a, b, c. Figure 6.13a gives the two clusters for the time signals, (b) displays the two clusters for the complex DFT (showing only the magnitude), and (c) shows DWT clusters. Figure 6.14 shows the average click for each cluster, overplotted. The top figure is the time signal, the middle is DFT magnitude, and the bottom is the DWT. All amplitudes are normalized to one. Figure 6.15 shows the comparison of the SOM clustering to Tiemann's identification. The top figure shows the DFT classes (clusters) and the bottom shows the classes of Tiemann. There is 85 % agreement.

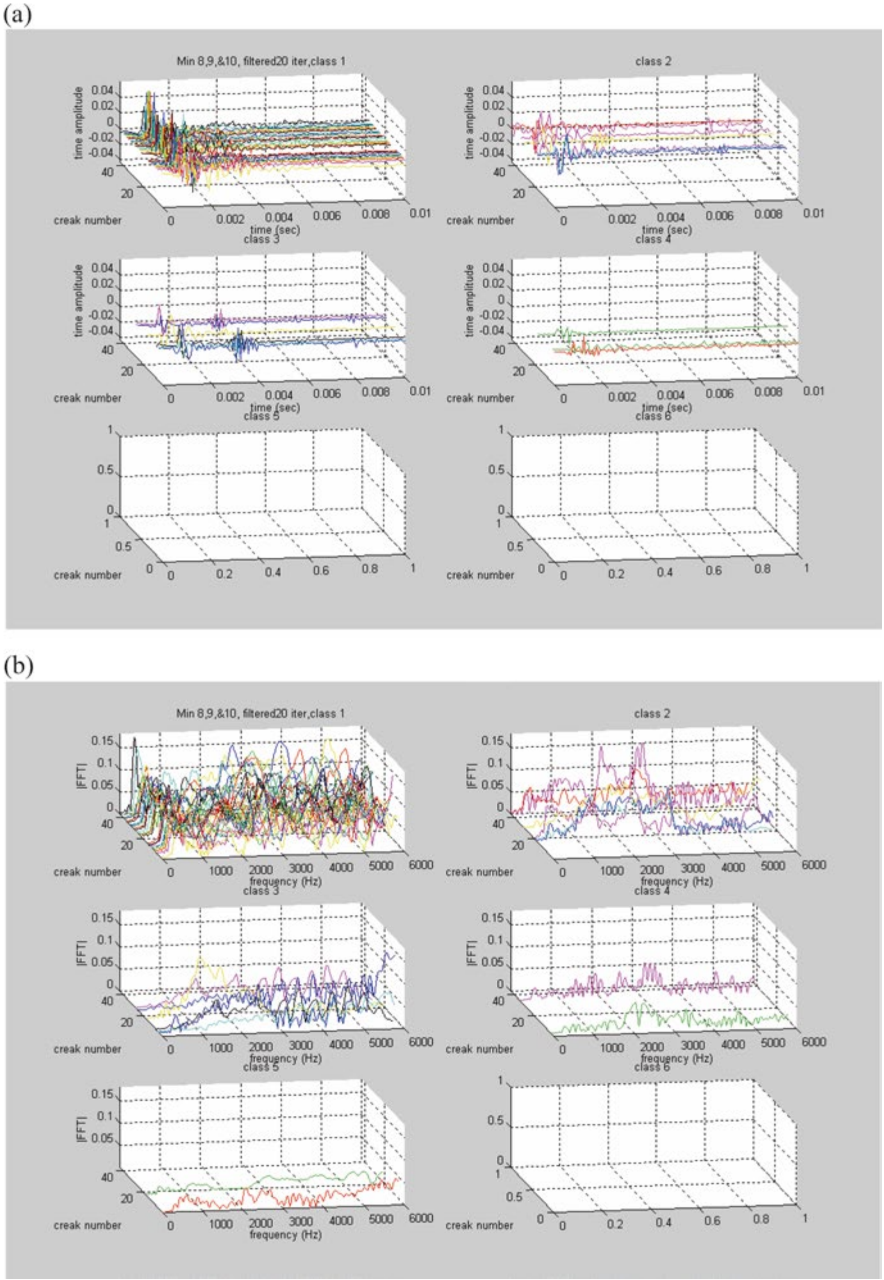


Fig. 6.12 The results of clustering 43 average coda clicks, one from each of 43 sperm whale codas. (**a**) displays the clicks in four clusters determined by SOM using the time signal; (**b**) shows the five classes found by SOM based on the DFT magnitude; and (**c**) gives the four classes resulting from applying SOM to the DWT, which are the same results as in (**a**)

(c)

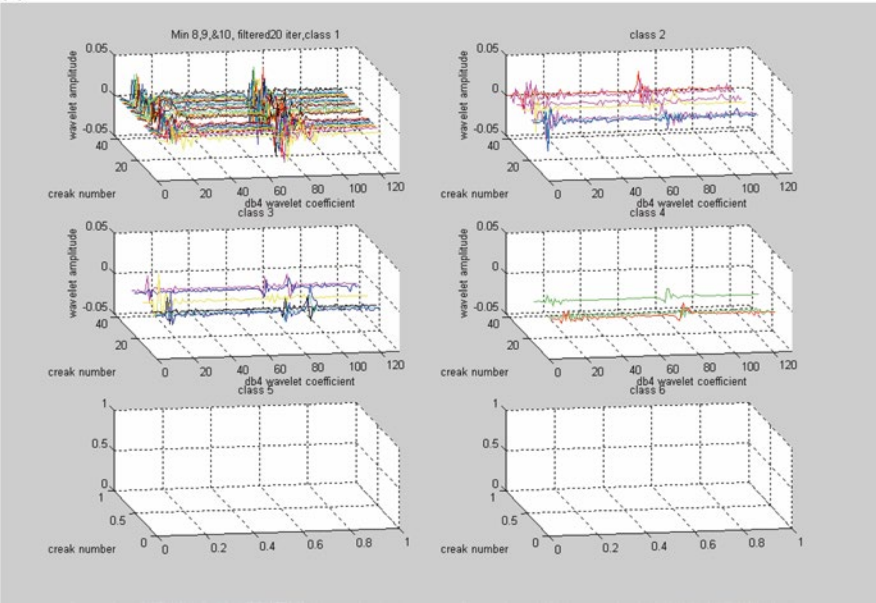


Fig. 6.12 (continued)

Figure 6.16 shows the clustering of Cuvier's beaked whale data from the Third International Workshop on Detection and Classification of Marine Mammals using Passive Acoustics, Boston, July 2007. The data were provided by Johnson of Woods Hole Oceanographic Institution and the reference for the data is Zimmer et al. (2005b). SOM found that six clusters were needed for these clicks, implying that six whales are present. Although the figures are quite busy, it can be seen that the clicks within each cluster generally match in shape. Clustering on the linear amplitude of the DFT proved to be much more satisfactory than clustering on the DFT given in dB.

6.7 Click Change Detection

Tiemann has analyzed clicks collectively by doing manual click-train identification (see, for example, Sect. 6.4). This involves following the click sequence of an echolocating whale, including the identification of multiple reflections, and distinguishing it from overlapping click sequences of other whales. He has developed several tools to facilitate the difficult work.

Meanwhile G. Ioup and J. Ioup have led the investigation of click change detection (CCD) (Ioup et al. 2010, 2011) to deal with the problem of turning sperm whales, which change their aspect with respect to the detector and therefore the properties of their received clicks (Møhl et al. 2003). Starkhammar et al. (2011) have independently

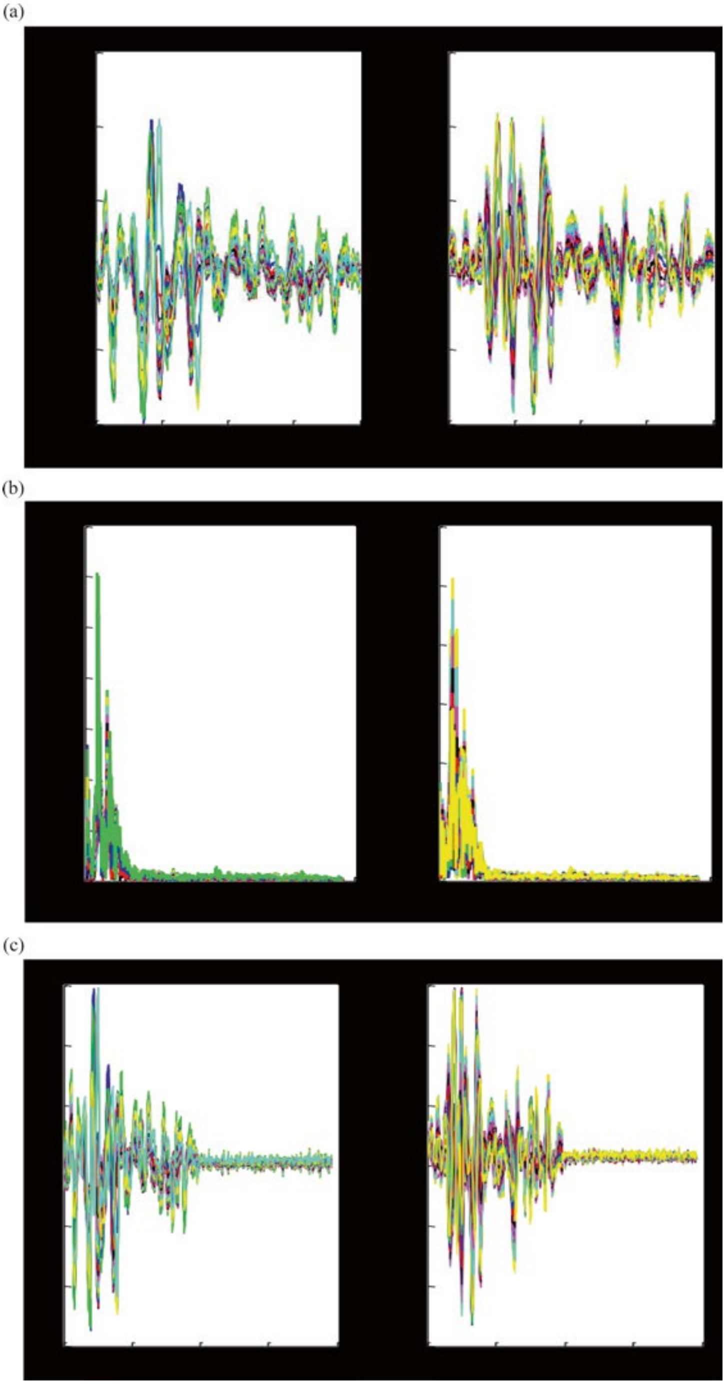


Fig. 6.13 SOM clustering results for 46 sperm whale echolocation clicks, which were also analyzed by Tiemann to determine click trains present. (**a**) Shows the two clusters resulting from using the time signal, (**b**) gives the results of clustering based on the complex DFT, with the magnitude shown in the graphs, and (**c**) displays the results of clustering the DWT. Clicks from LADC07 data sets

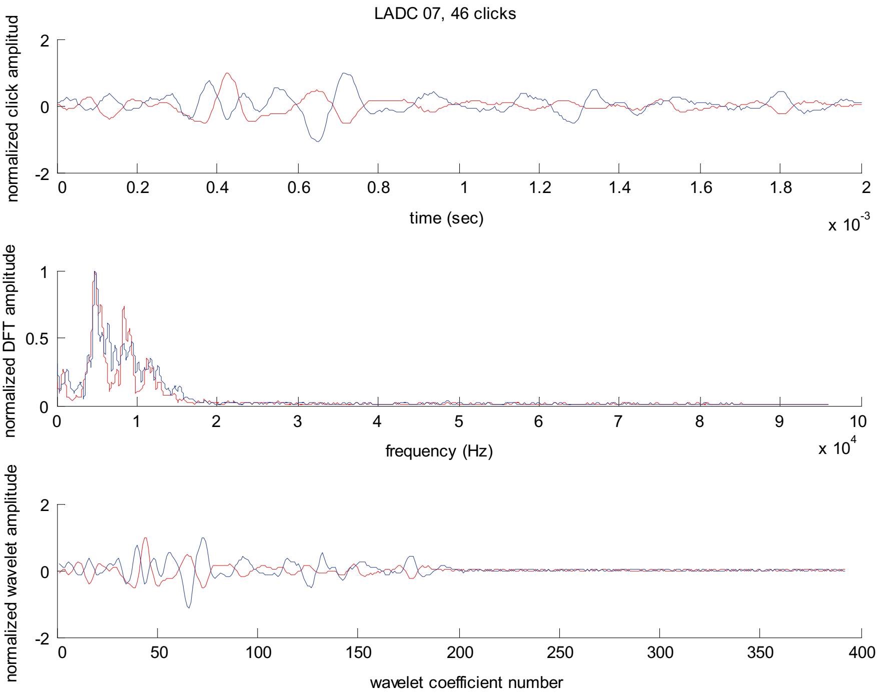


Fig. 6.14 Average clicks for each of the two SOM clusters found for 46 sperm whale echolocation clicks. The *top graph* gives the cluster average time signals; the *middle plot* shows the magnitudes of the cluster average complex DFT; and the *lower figure* contains the cluster average DWT's

developed a click change approach. Click change detection is also helpful in dealing with the change of clicks with depth (pressure) for diving whales and with the natural click-to-click variation for an individual whale.

The click change detection method used to determine whether the successive clicks are from the same or a different whale is based on taking successive cross-correlation maximum values and comparing these values to a threshold. Proper normalization of the cross-correlation is essential. For this purpose, division by the product of the square root of the energy of each click gives the normalization needed. The normalization expression is

$$\mathrm{CC}_{\max} = \left| \Sigma_i X_i Y_{i-j} \Big/ \left[\left(\Sigma X_i^2 \right) \left(\Sigma Y_i^2 \right) \right]^{1/2} \right|_{\max}$$

and $\mathrm{CC}_{\max}$ value is between 0 and 1. The threshold value, based on analysis of the data and on comparison with Tiemann's results, is 0.4.

The data used by Tiemann for sperm whale click-train identification is from data given in conjunction with the 4th International Workshop on Detection, Classification and Localization of Marine Mammals Using Passive Acoustics, University of

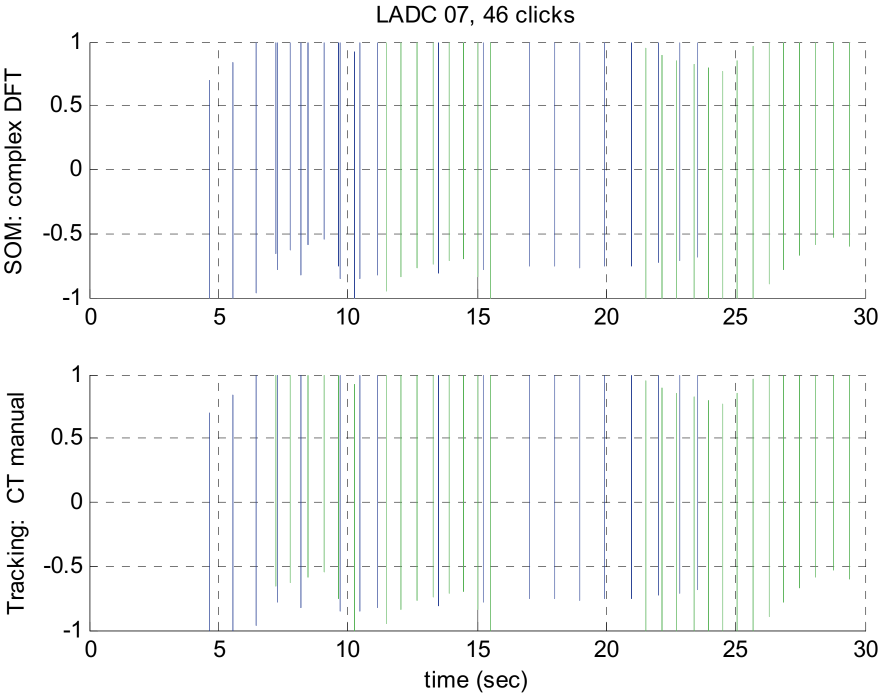


Fig. 6.15 Comparison of SOM clustering with manual click-train identification. Two classes or clusters (*two colors)* represent two whales. The *top figure* gives the SOM identifications and the *bottom figure* the click-train identifications of the two whales. There is 85 % agreement. Reprinted from G. Ioup et al. (2009)

Pavia, Italy, in September 2009. Dataset 3—NEMO ONDE deep-sea platform—was Sperm whale sounds recorded at 96 K sampling rate—four hydrophones on a tetrahedron placed at 2000 m depth, 25 km off Catania (Eastern coast of Sicily, Italy). Most files contain sperm whale sounds; one contains other clicks, similar to those emitted by Cuvier's beaked whales.

Tiemann has selected 550 successive sperm whale echolocation clicks for analysis. By grouping the clicks into trains, he is able to identify which whale is producing any given click. In particular, his analysis can be used to determine whether any click comes from the same whale as the preceding click in time.

The normalized cross-correlation was then calculated between each click and the preceding click and the maximum value of these cross-correlations is plotted versus time, as shown in Fig. 6.17. The plotted points are also color-coded. Green is used when, according to Tiemann's analysis, $\text{class}(i) = \text{class}(i-1)$ (where i is the time index), and red is used when $\text{class}(i) \neq \text{class}(i-1)$.

As can be seen in Fig. 6.17, almost all the green points are above the selected threshold of 0.4 and almost all the red points are below the threshold. Click change detection agrees with manual click-train analysis 98.5 % of the time. This is strong

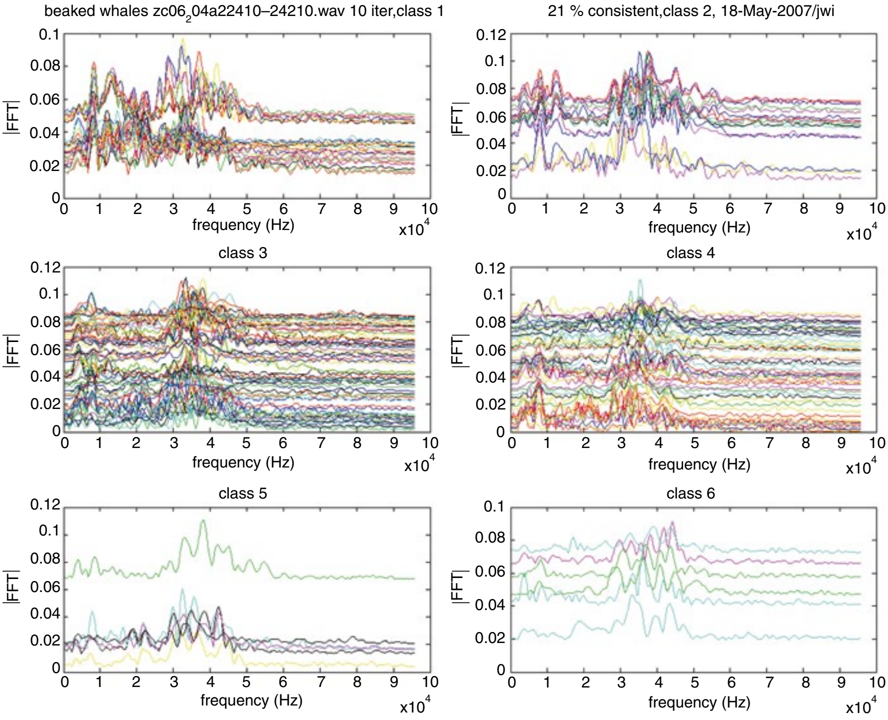


Fig. 6.16 SOM clustering for Cuvier's beaked whale clicks. Clustering is based on the magnitude of the DFT. Six clusters resulted. Data are from the Third International Workshop on Detection and Classification of Marine Mammals using Passive Acoustics, Boston, July 2007, and were supplied by Johnson of Woods Hole Oceanographic Institution. Data are filtered with a 20–60 kHz Butterworth filter

evidence that the cross-correlation analysis does a very good job identifying whether the same or a different whale produces a succeeding click.

As part of his analysis, Tiemann identified about 30 successive clicks, as shown in Fig. 6.18, between 125 and 145 s, which appear to be coming from a turning whale. Although there is a significant amount of change in click structure over that period, because sperm whales turn slowly, the amount of change from one click to the next is small. Therefore, click change detection applied to these clicks shows all clicks to be from the same whale. Not only are the cross-correlations above the minimum of 0.4, they are all greater than or equal to 0.5. Click change detection, at least in this case, has successfully dealt with the problem of a turning sperm whale.

While the success of click change detection is notable, it is not by itself capable of identifying which whale is clicking. It remains to be combined with clustering, or otherwise advanced, to accomplish identification.

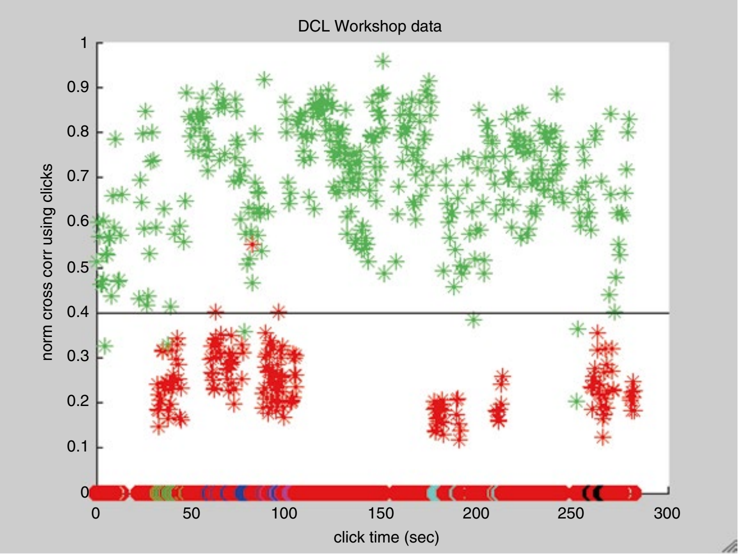


Fig. 6.17 Normalized cross-correlation value plotted versus click time. Chris Tiemann click-train analysis results indicated by *red* and *green star colors*. Click of speaking whale unchanged from previous click colored *green*, and click of speaking whale changed from previous click colored *red*, summarized as *green*: CT class(i) = CT class($i-1$); *red*: CT class(i) not equal to CT class($i-1$). For more than 98.5 % of the clicks, *green stars* are above the threshold and *red stars* are below. Reprinted from Tiemann et al. (2011)

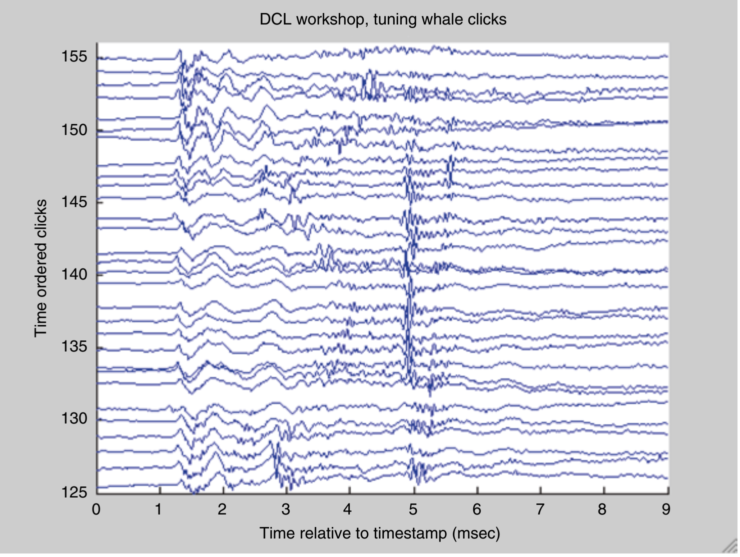


Fig. 6.18 A sequence of about 30 clicks (part of the 550 clicks analyzed) identified by Tiemann as being emitted by a turning sperm whale

6.8 Passive Acoustic Localization

Passive acoustic localization includes various methods to estimate the position of a phonating marine mammal, relative to a receiver or array, using only an acoustic record without the benefit of tags or visual observations (Tiemann et al. 2006, 2011; Tiemann 2008; Baggenstoss 2011, 2013). Benefits of acoustic localization include the ability to monitor whale behavior continuously and relatively inexpensively, even in times of reduced visibility. While localization and tracking are useful in studies of marine mammal behavior, they can also be considered another identification tool complementary to the others; acoustic localization is a way to sort or associate acoustic events geographically. For example, the estimated source positions for several consecutive sperm whale clicks should form a continuous track of animal motion. If they do not, there has likely been an error during click association. When used in that manner, localization serves as a way to check the results of any click associations derived through the methods above.

The passive acoustic localization of marine mammals is frequently accomplished by measuring the time of arrival of a given animal phonation at different acoustic sensors. The differences in arrival times, or time lag, can then be used to geometrically estimate an animal's position at the time it made the sound. A common technique called hyperbolic fixing uses a measured time lag to trace out candidate source positions on hyperbolic paths relative to a receiver pair. As time lags for the same sound event are measured by other receiver pairs, more candidate source positions can be defined. Finally, a candidate source position shared by all time lags is declared the most likely whale position. As an example, Fig. 6.19 shows the candidate locations for a clicking sperm whale estimated by time lags measured at two receiver pairs for a single click event. The intersection of the hyperbolic paths of possible source positions indicates the most likely whale location approximately 6 km from the hydrophone array.

6.9 Identification Cues and Their Integration

The developments summarized in Sects. 6.4 through 6.8 can all be used to help identify individual clicking whales. Consideration of these results has led to these research questions:

1. How can the methods of 6.5, 6.6, and 6.7 be verified?
2. How can the methods be made more robust and perhaps more efficient?
3. What do the results tell us about how whales identify each other?

Investigation of these topics is still very much work in progress, but some observations can be made at this stage.

Although coupling the methods of Sects. 6.5, 6.6, and 6.7 with visual identification may provide verification in the future, this has not been possible for LADC

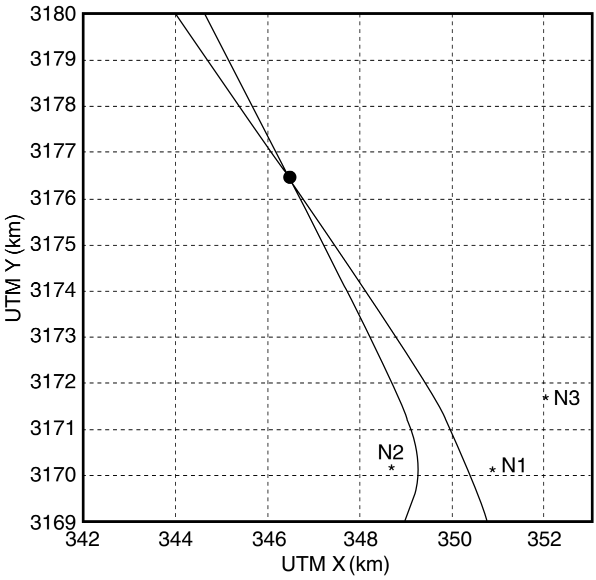


Fig. 6.19 Hyperbolic curves trace out candidate whale positions associated with a single sperm whale click recorded by the northern receiver array during LADC07. The intersection of the curves represents the most likely whale position

cruises to date. The most promising approaches for verifying cadence analysis, clustering, and click change detection have been manual (or, in the future, automated) click-train analysis and click localization. The work of Tiemann and colleagues (Sects. 6.4 and 6.8, and Tiemann and Porter 2003; Tiemann et al. 2006, 2011, Tiemann 2008), Baggenstoss (2011a, b, 2013, 2014, 2015), and Nosal and colleagues (2006, 2007a, b, 2008, 2013a, b; Young et al. 2013) is the key for progressing in this direction. One of the main challenges with LADC data is having enough sequential clicks from one whale (especially for beaked whales) to identify click trains, and having detection on more than one sensor to do tracking. (Single sensor tracking, Tiemann et al. 2006, is not applicable unless there are enough multiple reflections, usually present with a hard ocean bottom and not in the Gulf of Mexico.) LADC deployments have been mainly for detection, but future exercises will have one site with six clustered hydrophones, to achieve better localization and click-train identification. Thus far, click-train analysis by Tiemann (Sect. 6.4) has been compared to cadence analysis (Sect. 6.5), clustering (Sect. 6.6) and to click change detection (CCD) (Sect. 6.7) for echolocating sperm whales. The results are excellent for CCD and very good for cadence analysis and clustering.

Increasing the robustness and perhaps the efficiency of the identification methods will be important, but it will be difficult to do until verification is used to get confidence in the accuracy of the methods. Verification will also guide the combining of methods for increased accuracy.

It is likely that whales use elements of all of the methods described in Sects. 6.4 through 6.8 to identify and locate each other. Binaural hearing can give good enough localization to distinguish separated speakers. If better localization is needed, a few directed echolocation clicks, coupled with the whales' superb echolocation abilities, could locate companions.

It seems fairly certain that whales know which whale is speaking. Mothers and calves identify each other, and whales synchronize their dives. Whales have highly developed cochlea and copious ganglia (Ketten 1994; and references cited therein). As mentioned, their ability to echolocate prey is advanced. Although humans might be misled by the shortness of whale clicks, it is quite possible that whales know which one is phonating just from listening to individual clicks.

It is instructive to consider an analogy with human hearing, which may offer guidance, although the analogy could break down for several reasons. Humans are known to need about three cycles to identify a low frequency tone (50 Hz), about 20 cycles to identify a mid-frequency tone (2000 Hz), and about 250 cycles to identify a high frequency tone (10 kHz) (Bürck et al. 1935; Rossing et al. 2002). Sperm whale clicks can have energy up to 25 or 30 kHz, but the bulk of the energy is below 17 kHz. At 10 kHz, which is roughly mid-frequency, a 6 ms click contains 60 cycles. For beaked whales, which have click duration between 240 and 900 μs and a click frequency range from 20 to 60 kHz, a mid-frequency 40 kHz signal will have 24 cycles in 600 μs. Therefore, the possibility that sperm and beaked whales can identify individuals from the properties of single clicks merits investigation. Data analysis by LADC scientists and others provides important supporting evidence.

For diving whales, whose click properties change due to changing pressure (Thode et al. 2002), it is plausible that the whales use some form of click change detection (CCD) to keep track of which companion is phonating. The same is possible for turning sperm whales, whose click properties change slowly with time at a receiving point.

Since whales foraging together appear to have the ability to adopt different cadences for their echolocation click trains probably to reduce interference with each other, the cadence of an individual can be a component of identifying echolocating companions for each whale.

6.10 Sperm Whale Coda Classification and Repertoire Analysis

As noted in Sect. 6.3 and 6.1, during the summer of 2001, the Littoral Acoustic Demonstration Center (LADC) conducted the acquisition, deployment, and retrieval of three bottom-moored environmental acoustic recording system (EARS) buoys in the Northern Gulf of Mexico (GoM). The original focus of the project was to investigate ambient noise and upslope propagation in the area, but after consultation with the Minerals Management Service (MMS) Sperm Whale Acoustic Monitoring Program (SWAMP), the focus was expanded to include an examination of sperm whale acoustic behavior. The data collected during the summer of 2001 have been used in several studies examining the contributions of marine mammals and offshore drilling to the ambient noise level at the edge of the continental shelf in the Northern Gulf of Mexico (e.g., Newcomb et al. 2004, 2002a, b, c; Snyder et al. 2003). The project presented here is focused on identifying the coda repertoire of sperm whales in the area.

6.10.1 Location

EARS buoys, as described in Sect. 6.2, were used for the measurements in 2001, which produced the data analyzed in this section. The buoys were deployed from a ship on July 16th–19th. The deployment site was chosen to optimize LADC's goal of measuring noise propagation up the continental slope, as well as maximizing exposure to the largest concentration of previous sperm whale sightings in the general area. This area has been identified as an area rich in sperm whale activity, specifically around the 1000 m depth contour south/southeast of the Mississippi River delta (Mate et al. 1994; Würsig et al. 2000). The first buoy, EARS 1, was moored at approximately 28° 15′ N and 88° 50′ W. The other two buoys, EARS 2 and EARS 3, were deployed along a 43 km line extending from the 200 m contour to just beyond the 1000 m contour, along which oceanographic data were collected. Data were also collected along a cross track. The LADC01 and 02 buoy locations shown in Fig. 6.3. are specified in greater detail in Fig. 6.20. Total separation between buoys was approximately 25 km with roughly 7 km separating EARS 2 and EARS 3. The buoy closest to land, EARS 3, was located approximately 55 km from the Louisiana shore. EARS 1 was moored at a depth of approximately 1000 m, EARS 2 at 800 m, and EARS 3 at 600 m.

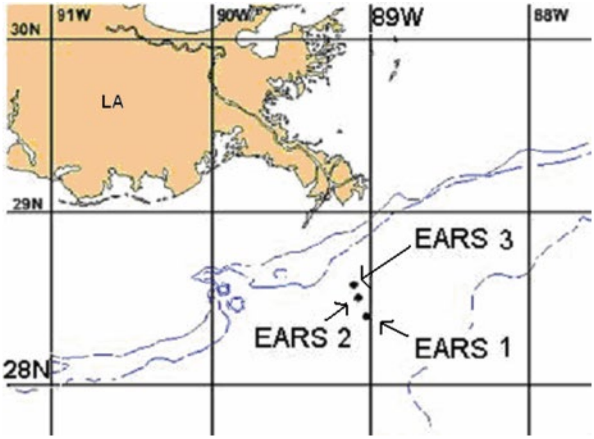


Fig. 6.20 The EARS deployment sites in the Northern Gulf of Mexico. Adapted from image provided by Joal Newcomb

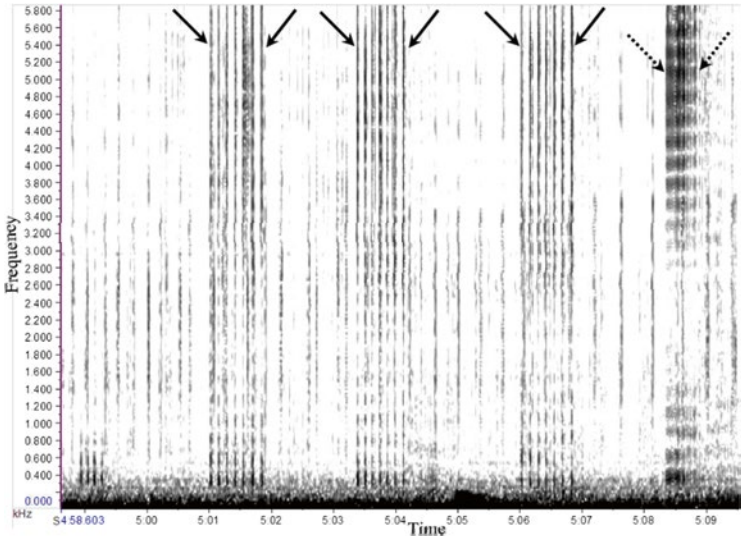


Fig. 6.21 Spectrograph image illustrating three codas (between *solid black arrows*) and a creak (between *dashed arrows*) from the EARS 3 buoy recording file 08652121

Each EARS buoy continuously recorded acoustic signals with frequencies up to 5859 Hz for a period of approximately 36 days (digital sampling rate of 11.7 kHz). Each buoy gathered 72 GB of acoustic data for a three-buoy total of 216 GB. A total of 2592 h of audio data were recorded and then inspected visually and acoustically using Raven 1.1 (Bioacoustics Research Program 2003).

6.10.2 Classification and Repertoire Identification

Codas are stereotyped sequences of sperm whale clicks lasting from approximately 0.2 to 5 s, which occur in a pattern of about 3–20 clicks (Whitehead 2003). Some of the codas we observed are shown in Fig. 6.21. Codas are sometimes produced at the end of a usual echolocation click train, so in following musical terminology, Watkins and Schevill (1977a) called them “codas.”

Codas are most frequently heard when whales are at or near the surface and are moving slowly in and around one another (Weilgart and Whitehead 1997; Whitehead and Weilgart 1991), but are also heard in small numbers during dives (Madsen et al. 2002). Furthermore, they seem to occur only between whales that are in close physical proximity to one another (Watkins and Schevill 1977b).

Codas appear to be used primarily as intragroup communication, rather than in communication between groups since codas lose their acoustic integrity after approximately 2 km and groups are usually separated by much greater distances (Madsen 2002; Weilgart and Whitehead 1997; Whitehead 2003). In addition, there is regional geographic variation in coda types (Weilgart and Whitehead 1997). Weilgart and Whitehead (1997) suggest that this variation results from the distinctive coda dialects of particular social units, which have preferred geographic ranges. Strong group-specific dialects that persist over a number of years seem to exist (Weilgart and Whitehead 1997). Furthermore, differences in repertoire have been found in different geographical locations (Apple 2002; Moore et al. 1993; Pavan et al. 2000; Weilgart and Whitehead 1993, 1997).

To determine the coda repertoire of the whales recorded in this study, codas were classified based on methodology used in previous studies (Apple 2002; Moore et al. 1993; Weilgart and Whitehead 1993, 1997). Using both the number of clicks in the coda and the structure of the click pattern, a coda type was determined. For example, 5-click codas were labeled as type: 5R (Regular: with equal spaces between clicks), 5V (Variable: unevenly spaced clicks), 5 + 1 (plus-one: contained a double interval between the last two clicks), or 5 1+ (one-plus). The one-plus structure is a deviation of the protocol used in previous studies and was created here due to the frequency of codas with a double interval after the first click of the coda.

A total of 5035 codas were identified from the EARS recordings and were classified into 34 types (Table 6.1). Representing 19.09 % of all codas, the type 6V was the most prevalent, with 4V (13.45 %) and 7R (11.88 %) ranking second and third.

The identification of the coda repertoire from sperm whales in a given area can provide information not only about vocal behavior, but also about group structure and group affiliation. This LADC project recorded a large number of codas over the course of the study period. Because codas from known breeding grounds are often produced by socializing females (Goold 1999; Gordon et al. 1992; Marcoux et al. 2006), and this study area is known to be inhabited by a mixed group of mature females and immatures (Watwood et al. 2006; Würsig et al. 1999), it is likely that there were mature females in or passing through the area for much of the study period.

6.11 Statistical Modeling and Population Estimation

6.11.1 Modeling Acoustic Data

Monitoring deepwater marine mammal abundance based on acoustic recordings has been introduced as a new tool when visual observations are limited or unavailable (Marques et al. 2009; Barlow and Taylor 2005). However, only a few case studies to estimate population densities based on acoustic cues have been published in the literature. In this section, we describe a statistical methodology that was recently developed (Ackleh et al. 2012) which utilizes passive acoustic data collected before and after the 2010 Deepwater Horizon oil spill incident to assess its impact on the population abundance of endangered sperm whales.

We begin discussion of the statistical models for the acoustic data collected from buoys in the northern and southern sites in years 2007 and 2010. The click rate histograms imply a “power law" pattern. Therefore, we adopt a general power law

Table 6.1 Summary of category types, visual description of click patterns, number of codas in each type, and the percentage of the total coda repertoire that each type had

Type	Description	# of Codas	% of Total
3R	/ / /	71	1.41
3V	/ //	193	3.83
2+1	/ / /	15	0.30
1+2	/ / /	156	3.10
4R	/ / / /	408	8.10
4V	// //	677	13.45
3+1	/ / / /	17	0.34
1+3	/ / / /	67	1.33
5R	/ / / / /	180	3.57
5V	// // /	274	5.44
4+1	/ / / / /	50	0.99
1+4	/ / / / /	116	2.30
6R	/ / / / / /	402	7.98
6V	// // / /	961	19.09
1+5	/ / / / / /	28	0.56
7R	/ / / / / / /	598	11.88
7V	// / // / /	171	3.40
6+1	/ / / / / / /	87	1.73
1+6	/ / / / / / /	58	1.15
8R	/ / / / / / / /	75	1.49
8V	/ /// / / //	132	2.62
7+1	/ / / / / / / /	23	0.46
1+7	/ / / / / / / /	10	0.20
9R	/ / / / / / / / /	24	0.48
9V	// / / /// / /	124	2.46
8+1	/ / / / / / / / /	5	0.10
1+8	/ / / / / / / / /	13	0.26
10R	/ / / / / / / / / /	36	0.71
10V	/ / //// / / / /	9	0.18
11R	/ / / / / / / / / / /	13	0.26
11V	// / / / / // / / /	14	0.28
1+10	/ / / / / / / / / / /	4	0.08
12R	/ / / / / / / / / / / /	8	0.16
12V	/// / / / // / / //	16	0.32
Total		5035	100.00

Note: The visual description for each variable (V) type is only one example of several forms the variable coda might take

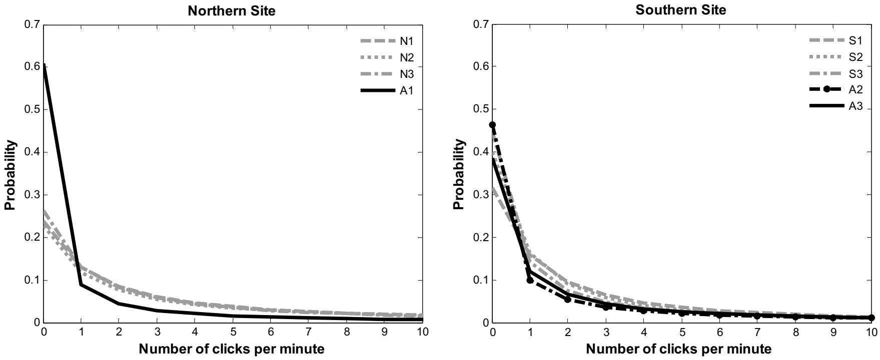


Fig. 6.22 Comparison of the power law fittings for the northern (*Left*) and southern (*Right*) sites. N1–N3 and S1–S3 correspond to data collected in 2007, A1–A3 correspond to data collected in 2010. (Extracted from earlier work (Ackleh et al. 2012))

model (Johnson et al. 1992) for probability density functions P, to fit the histograms formed for selected datasets for a specific experiment and location.

$$P\left(X=x\mid\theta,b\right)=\frac{k\left(\theta,b\right)}{\left(b+x\right)^{\theta}},\quad x=0,1,2,\cdots,$$

where $k(\theta,b)$ is a normalizing constant, and $k\left(\theta,b\right)=\left(\sum_{x=0}^{\infty}\left(b+x\right)^{-\theta}\right)^{-1}$.

The log-likelihood function L for a given dataset with random observations, $x_1,x_2,\ldots,x_n$, of the number of clicks recorded at n consecutive minutes is given by $L\left(\theta,b\mid x_1,x_2,\cdots,x_n\right)=\ln\left({}_{i=1}^{n}k\left(\theta,b\right)/\left(b+x_i\right)^{\theta}\right)$.

Estimates of the parameters b and θ (denoted by $\hat{b}$ and $\hat{\theta}$) are obtained by maximizing the above log-likelihood function over a parameter space $\Omega=\left\{\left(\theta,b\right)\mid\theta>1,b>0\right\}$. However, maximization of L with respect to θ and b simultaneously runs into the “saddle point” type problem, where L is monotonically increasing with respect to θ and b. Thus, to resolve this problem, a different approach is used in Ackleh et al. (2012). In particular, for a fixed b, L is maximized with respect to θ and the optimal value θ, which depends on b, is obtained and denoted $\theta(b)$.

All power law fitting curves for buoys in the northern and southern sites are overlaid in Fig. 6.22. The power law functions indicate a sharp difference between years 2007 and 2010 in the northern area but similar fittings in the southern area. Acoustic activity of sperm whales at the closest northern site (9 miles away from the incident site) shows a decrease between 2007 and 2010, but no obvious differences are observed at the southern site (23 miles away).

6.11.2 Estimating Population Density

The objective of this section is twofold: (1) to formulate a statistical methodology for the point and interval population abundance estimation based on passive acoustics, and (2) to apply this model to data collected before and after the oil spill in the Gulf of Mexico (GoM) and to assess its impact on the sperm whales population.

Following Marques et al. (2009), a point estimate of population density $\hat{D}$ based on the number of detected cues n_c over a time period T can be given by

$$\hat{D} = \frac{n_\mathrm{c}\left(1-\hat{c}\right)}{K\pi w^2 \hat{P}\left(T\hat{r}\right)}.$$

Here, $\hat{c}$ is the estimated proportion of false positive detections and K is the number of replicate sensors used in the experiment ($K = 1$ in our experiment). A target region is considered to be a circular area centered at the buoy location with w representing the maximum detection radius. The expected number of cues per unit time by a single mammal is denoted by r. The estimated average probability of detecting a cue is given by $\hat{P}$.

Different approaches have been applied to obtain a suitable value of $\hat{P}$. In the first procedure (Marques et al. 2009), parameters p_y and $h(y)$ can be evaluated by relating sensor detection events to the sounds produced by tagged animals. This requires tagging a considerable number of animals in a survey area (which was not conducted during LADC deployments). The second approach (Tiemann et al. 2006) is computationally and operator-time costly since it involves a localization of an animal producing each detected cue. The third approach (Zimmer et al. 2005; Küsel et al. 2011) is based on modeling utilizing environmental data and the animal's beam pattern that are absent for GoM. We adopt a different approach and assumptions to obtain $\hat{P}$ (Ackleh et al. 2012). In particular, let $h(y)$ be the probability of the whale being y units away from the buoy location, and p_y be the probability a cue is detected provided that the cue is generated at a distance y. Then

$$\hat{P} = \int_0^w p_\mathrm{y} h\left(y\right) \mathrm{d}y \cdot$$

We further assume that p_y is one of two general types:

$$p_\mathrm{y} = \left(\exp\left(-y/\beta\right) - \exp\left(-w/\beta\right)\right) / \left(1-\exp\left(-w/\beta\right)\right) \text{ for } \beta > 0 \tag{6.1}$$

$$p_y = 1 - \left(y/w\right) \tag{6.2}$$

We generalize $h(y)$ used in Marques et al. (2009) to $h\left(y\right) = \left(d+1\right) y^d / w^{d+1}$.

The most appropriate values of parameters β and d are unknown and probably hard to obtain. For various combinations of β and d this methodology is applied to data collected before and after the 2010 spill, as the acoustic detection techniques used are the same, to see if there is a significant difference between 2007 and 2010 models.

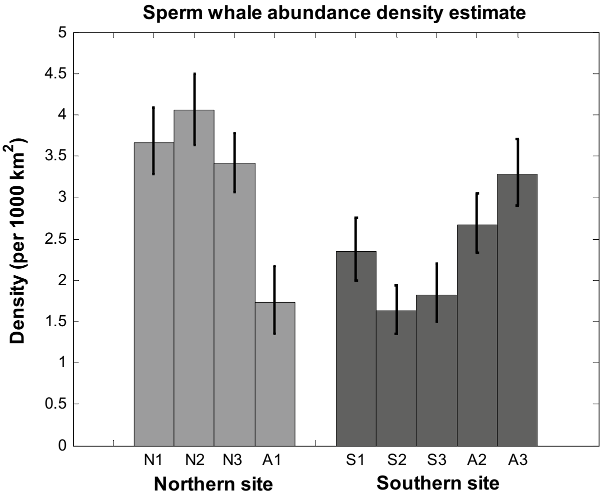


Fig. 6.23 The 95 % confidence interval of the average hourly density for all survey sites in northern and southern locations. *Light gray* denotes northern sites and *dark gray* denotes southern sites. (Extracted from our earlier work (Ackleh et al. 2012))

Due to difficulties encountered in estimating the variance of $\hat{D}$ directly, we apply the following nonparametric bootstrap method for the interval estimates of population density.

1. Specify the location and survey of interest, obtain the *k* consecutive hourly point estimates of *D* for the given survey, and denote them by $\hat{D}_1,\cdots,\hat{D}_k$.
2. Draw with replacement a bootstrap sample of size *k* from $\{\hat{D}_1,,\cdots,,\hat{D}_k\}$, denote this sample by $\hat{D}_1^*,\cdots,\hat{D}_k^*$, and then calculate the sample average $\bar{D}^* = \sum_{i=1}^{k} \frac{\bar{D}_i^*}{k}$.
3. Repeat step (2) *M* times, where *M* is a large number, and obtain *M* bootstrap replicates $\bar{D}^*$.
4. Sort the bootstrap replicates $\bar{D}^*$ from the smallest to the largest as $\bar{D}_{(1)}^* \le \bar{D}_{(2)}^* \le \cdots \le \bar{D}_{(M)}^*$.
5. Calculate the lower and upper tail $\frac{\alpha}{2}$-probability (empirical) cut-off points of $\bar{D}_{(1)}^*,\bar{D}_{(2)}^*,\cdots,\bar{D}_{(M)}^*$ and denote them by $\bar{D}_{((\alpha/2)M)}^*$ and $\bar{D}_{((1-\alpha/2)M)}^*$, respectively. Then the approximation of $(1-\alpha)$ level confidence interval for the hourly point estimates of *D* is $\left(\bar{D}_{((\alpha/2)M)}^*,\bar{D}_{((1-\alpha/2)M)}^*\right)$.

By a comparison of manual and automatic detections we obtain $\hat{c} = 0.059$. From the literature on sperm whales (Watwood et al. 2006: Whitehead and Weilgart 1990) we take the cue production rate to be 1.22 clicks per second per whale and the maximum detection radius as $w = 20$ km. The values $\beta = 2.5$, $d = 1$ are chosen so that the estimated sperm whales density before the spill matches the NOAA reported population of 1665 in the Northern GoM (Waring et al. 2009). The confidence level is set to be $1-\alpha = 0.95$, and the number of replications is $M = 5000$. Based on the values and assumptions chosen above, we obtain estimates of population density as presented in Fig. 6.23. These results show that there is a considerable decrease of the population abundance from 2007 to 2010 at the northern site closest to the DWH incident site and an apparent increase at the southern site. One can further observe that the decrease in the population density at the northern site nearest to the DWH site exceeds statistical uncertainties and can be accepted as an existing trend.

6.12 Summary

This chapter presents the work of the Littoral Acoustic Demonstration Center (LADC), a consortium comprising University, private industry, and U.S. Navy scientists, formed in early 2001. The Universities currently represented are the University of Louisiana at Lafayette (UL Lafayette), the University of Southern Mississippi (USM), the University of New Orleans (UNO), and Oregon State University (OSU). LADC was formed to utilize technology developed by the Naval Oceanographic Office (NAVOCEANO) to make environmental underwater acoustic measurements. Specifically, the technology consists of buoys containing electronics and power and having an external hydrophone(s), which are moored to the ocean bottom to make acoustic measurements over extended periods of time. The buoys are named Environmental Acoustic Recording System (EARS). LADC is using EARS to make measurements which are not part of NAVOCEANO's mission. NAVOCEANO provides technical guidance and support to LADC.

A list of LADC scientists and their affiliations is in Sect. 6.1. This section also elucidates the developments which led LADC into recording marine mammals.

Initially the EARS technology used by LADC recorded to about 6000 Hz. Then buoys which measured to 25,000 Hz were developed. Now our Generation 2 EARS can measure to 25 kHz on four channels or to 96 kHz on one channel. The latter configuration makes possible the measurement of beaked whale clicks and much of the spectral band of offshore dolphin clicks and whistles. A description of the features of EARS buoys which are important for LADC applications is given in Sect. 6.2.

After recording sperm whales in 2001 and 2002, and a seismic airgun array on one mooring in 2003 (Tashmukhambetov et al. 2008), LADC made the first recordings of beaked whales in the Gulf of Mexico (GoM) in 2007. These measurements were at sites which are located 9 and 23 miles from the Macondo well. Then in September 2007, LADC conducted a large exercise to produce detailed measurements of the acoustic field of a seismic airgun array. In 2010, after the oil spill at Macondo, LADC went back to the 2007 sites close to Macondo and to a 2001–2002 site, 50 miles from Macondo. This enabled before and after comparisons to be made. An article comparing before and after abundances for sperm whales has been published (Ackleh et al. 2012). Important details of all LADC marine mammal experiments and experimental collaborations are given in Sect. 6.3.

Since the early 1970s, significant progress has been made in understanding the bioacoustics of sperm and beaked whales. Much of the research is reported in the references given in this chapter and in references cited therein. Various facets of click generation and the properties of the clicks themselves are becoming well characterized. Those aspects of the bioacoustics of these whales which are not yet well understood are mainly related to identification of and communication among the whales and the relation of these to their behavior and the environment. Although these topics are difficult to study because there are not animals in captivity, the clarity and volume of the recordings available have permitted advances to be made, even though the science is still in its early stages. Sections 6.4 through 6.10 describe LADC research in these areas. Section 6.8 on Passive Acoustic Localization also stands on its own, since it can be applied to understanding other areas of whale science.

Section 6.4, Click Structure Analysis and Sperm Whale Identification, discusses the structure of the clicks of an individual sperm whale and how this structure can differ from whale to whale. These differences are used to separate the clicks from different whales and associate them over time into click trains, one for each whale. These identified click trains allow several very important analyses to be made, such as determining interclick intervals for each animal. These are found to differ from animal to animal. They also facilitate identifying the click structure for each animal. It is important that they allow the determination of how that click structure can change as the whale changes its aspect with respect to the receiver. While manual click train identification is too laborious to perform on large sets of data, the analysis that has been done has greatly facilitated the development of related methods to study interclick intervals and identify individual whales from the properties of their clicks.

The idea of an interclick interval or an individual click frequency for echolocation clicks, referred to as a cadence frequency, is explored in great detail in Sect. 6.5, Cadence Frequency Analysis and Identification of Individual Clicking Whales. A robust method is developed and applied to identify all different cadence frequencies present among the group of phonating whales. The method allows the association of clicks with individuals in a group of whales. It has been compared to passive acoustic localization in Sect. 6.8 and cluster identification in Sect. 6.6. The cadence frequency analysis algorithm is based on an approach developed for human motion analysis and is a significant improvement on other methods which have been developed to identify cadences. The important advantages of this approach are given in the section. The details of application of the algorithm are discussed. It has been used for sperm whales, beaked whales, pilot whales, and dolphins. It is found that simultaneously diving whales adopt somewhat different cadences from each other, presumably to keep from interfering with each other as they echolocate. The method shows good agreement with the other approaches mentioned.

In the analysis of the coda clicks of sperm whales, it became obvious that all the clicks in a coda were similar to each other in their time and spectral properties. In comparing codas, it was seen that some codas had the same click properties as some others, while other codas had different click properties. This led to the idea that clustering of coda clicks could be used to identify individual whales. Each cluster or class identified by the clustering method would be associated with an individual. Although several different clustering methods were tried, the one that led to the greatest success is a neural nets-based technique called self-organizing maps. After achieving separation into clusters that were differentiated from each other and could identify sperm whales based on these codas, the method was extended to sperm whale echolocation clicks and beaked whale echolocation clicks. Good agreement was obtained when the clustering of sperm whale echolocation clicks was compared with click train identifications when two whales were present.

In order to deal with the change of received click properties from a turning sperm whale which is changing its aspect with respect to the receiver, a click change detection method was developed. This method is used to determine whether the clicks are from the same or a different whale. It is based on taking successive normalized cross-correlation maximum values and comparing these to a threshold. For the work with sperm whale echolocation clicks reported here, the threshold for the normalized cross-correlation is 0.4. Tiemann has analyzed 550 successive echolocation clicks into click trains. From his analysis it is known for each successive click whether the same whale is clicking or a different whale. The same thing can be determined using click change detection. When the results of manual click train analysis are compared to click change detection, the agreement is 98.5 %, which is very strong supporting evidence for the click change detection method. A sequence of clicks from a turning sperm whale was isolated over a 20 s interval in these data. Click change detection showed a correlation with a minimum of 0.5, indicating that all clicks came from the same whale. In the future click change detection can possibly be used to deal with changing clicks due to changing pressure for a diving whale or the simply natural click to click variation for a single whale.

As stated previously, Sect. 6.8, Passive Acoustic Localization, is important for many applications in studying whale identification, communication, and behavior. Its special importance in this chapter is that it has given a way to check the results of cadence frequency analysis. In the future it can help verify the identifications given by clustering. It is one of the most important ground truth methods available for LADC analysis.

In Sect. 6.9, Identification Cues and Their Integration, an investigation of the combination of the methods of Sects. 6.4 through 6.8 is given. Questions of verification, robustness, and efficiency are considered, as well as how the results of this section can further the science of understanding how whales identify each other. In the absence of sufficient visual identifications, the main bases for verifying the methods have been click train analysis and click localization. It is suggested that whales use elements of all the methods described in Sects. 6.4 through 6.8 to identify and locate each other. Consideration is also given as to whether whales can identify each other from individual clicks. An analogy with human hearing is given to illuminate the possibilities for identification from a single click.

Section 6.10, Sperm Whale Coda Classification and Repertoire Analysis, presents a detailed study of 5035 codas selected from the data of LADC01. It was found that there are 34 different rhythms identified, all given with their frequency of occurrence in the table in the section. Three coda rhythms accounted for almost 45 % of all the codas. These results can be used to give information about group structure and group affiliation among the sperm whales in the region, which are most likely to be mature females and immatures.

Section 6.11, Statistical Modeling and Population Estimation, concerns estimating the population density for sperm whales at the northern and southern sites for LADC07 and LADC10. The estimation is based on using a formula given in the literature in 2009. Because some of the parameters needed for the formula were not measured in the LADC experiments, new techniques have been developed to deduce these quantities. Standard approaches were used to fit probability density functions to the histograms of the data, although different functional forms were needed than those used previously. One of the difficulties is knowing the estimated average probability of detecting a cue. None of the methods for estimating this probability used by others was available for the LADC data so a novel technique was developed. Estimating the variance of the density is also difficult, and a nonparametric bootstrap method was developed to get interval estimates of the population density. Based on the assumptions given in the section, results show a considerable decrease in the abundance of sperm whales from 2007 to 2010 (before and after the Macondo well oil spill) at the northern site, 9 miles away from the spill, and an apparent increase at the southern site, 23 miles away.

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Chapter 7
Listening to Echolocation Clicks with PODs

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Abstract Monitoring echolocation using SAMs—static acoustic monitors—such as T-PODs or, more recently, C-PODs—has provided a wealth of information on the fine-scale distribution and activity of dolphins, porpoises and other toothed whales. Effects of marine construction noise on these animals have been identified at much longer ranges than expected. Strong diel, tidal and seasonal patterning of the animals' habitat use has been found including coastal sites that are regularly used only at night. Arrays of SAMs are now being used for longer term monitoring to assess smaller population trends of lower density populations than could previously be assessed within the limits of economic feasibility. PODs have given insights into the significance of seabed ultrasonic noise from sediment in suspension and diel patterns of activity of benthic organisms, and have also revealed unknown sources of very fast trains of tonal clicks.

7.1 Introduction

7.1.1 Filling a Gap: Origin and Design of PODs

In 1990, following a mass stranding of common dolphins, *Delphinus delphis*, in the southwest of Britain, the local gill netting fleets took observers to sea. They found a large by-catch of porpoises, *Phocoena phocoena*, that was estimated (Tregenza et al. 1997) at over 2000 per year in the Celtic Sea, where a large decline in small cetaceans was already known (Tregenza 1992). This level of by-catch was a shock and made us aware that a tool was needed to reveal the movement of porpoises around nets.

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Porpoises are rarely silent—they make an almost continuous stream of distinctive echolocation clicks that enable them to find prey and orient within their environment. The clicks are ultrasonic, at around 130 kHz, narrowband, i.e. an almost pure tone, and loud, with a source level of up to 191 dB re 1 μPa pp at 1 m (Villadsgaard et al. 2007). An effective system for detecting porpoise clicks from a moving yacht had already been developed by Oliver Chappell, Russell Leaper and Jonathan Gordon (Chappell et al. 1996). To distinguish porpoise clicks from the huge numbers of marine broadband clicks this system compared each click's energy at porpoise frequencies with that at lower frequencies.

Using their pioneering work in a modified form, a prototype porpoise detector, or POD, was built with funding from The Body Shop and the European Commission. This proto-POD continuously measured and compared four bands of ultrasound and counted periods when the energy in the band covering porpoise frequencies exceeded each other band by user-defined ratios. It did not embody any concept of a click as a spike in intensity but was, in effect, a simple analogue spectrum analyzer that counted events in each second that met the spectral criteria. In shape it resembled a bomb, it ran for 10 days and it had 1 MB of memory. Fishermen from Newlyn, Cornwall, put 'the bombs' on their nets in the Celtic Sea (Tregenza et al. 2001), with results that surprised us and are covered later.

7.1.2 Towing a POD

Jefferson et al. (2002) surveyed the very busy waters of Hong Kong by deploying this first version of the POD several meters below a small surf board that was towed by a ferry. Finless porpoises (*Neophocaena phocaenoides*) are very hard to spot at sea, but the team found that nearly all the groups of animals they saw within 300 m were also heard by the POD.

Results were very different along the west coast of Britain, where Goodwin (2007) also towed a POD, but this was behind a small boat sailing or motoring through these much quieter waters. She found much lower detection rates for harbor porpoises. Visual observers here saw that the porpoises were actually avoiding this small towing vessel, unlike the finless porpoises which did not flee from much larger vessels in the noisier waters of Hong Kong. The simplest interpretation is that in quiet places porpoises are not habituated to boat noise and turn away from it at much greater distances than in noisy places. Their narrow forward-facing sonar beam (Au 1993) can then no longer be heard. This is a major factor limiting the accuracy of boat surveys of echolocation clicks, unless they can be heard well beyond the range of responsive movement. Unfortunately this effect is very difficult to quantify, and nothing is known of how quickly animals develop habituation or how fast it fades as they move through different noise regimes.

7.1.3 Static Acoustic Monitors: SAMs

For static acoustic detectors, responsive movement is not a problem, except that the animals may be interested in the instrument—more on that later. Static PODs were at first used to study porpoise behaviour around nets, and to study the pingers that are used to reduce fishery by-catch of cetaceans. Subsequently they have been used to show levels and patterns of habitat use by porpoises and dolphins; to monitor the impact of marine engineering projects on small cetaceans, especially wind, wave, and tidal power generation sites and to estimate populations and population trends.

These studies have shown that passive acoustic monitoring can reveal patterns of animal presence that are very hard to detect visually, such as at sites that are used only at night, or cetacean use of sites far from shore, or those with very low densities of cetaceans. In very high tidal current sites, PODs have been floated through on the current, suspended below a buoy and delivered good data (Wilson et al. 2013).

The relatively lower cost of getting large volumes of data by using SAMs means that proportionately lower densities can be measured, and smaller trends in numbers identified. This potential has been exploited in large projects on two greatly depleted and critically endangered porpoise populations—the Vaquita, *Phocoena sinus*, in the Upper Gulf of California and the SAMBAH project to assess the population of harbour porpoises, *Phocoena phocoena*, in the Baltic Sea. Both started in 2011.

7.1.4 Echolocation Click Train Detection: T-PODs

In good broadband records of marine ultrasound, porpoise clicks are quite distinctive but there is no set of criteria based on click features alone that can deliver very low rates of false detection without being rather insensitive. This is because weaker clicks are more degraded by ambient noise and because there are non-porpoise sources of porpoise-like clicks. These limitations can be reduced if the target for detection is a coherent train of similar clicks instead of a single click. A train is a more or less regular spatial or temporal sequence of similar elements. Cetacean clicks are nearly all produced in trains and the coherence of a train is the similarity between successive spacings (inter-click intervals) and click characteristics.

To gain access to the power of trains the timing-POD or T-POD was developed. Figure 7.1 shows the filtering effect of the train detection process. T-PODs log the time and duration of each click at a resolution of 10 µs—in engineering terms the output is a 1 bit measurement at 100 k samples per second. Such data can easily be compressed.

The T-POD allows users to vary both the target frequency and the 'reference or 'guard band' frequencies used for comparison. To save power the number of filter bands was reduced. The filter Q values (the narrowness of the frequency range passed by the filter), the integration period, and an optional noise-determined loading of the detection ratio between target and reference bands were optimized in multiple sea trials.

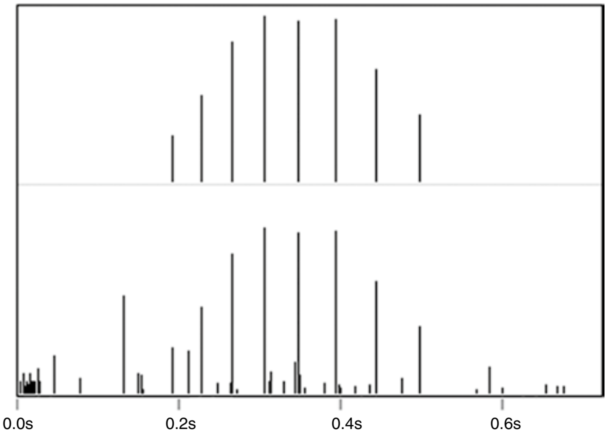


Fig. 7.1 Train detection: Each *vertical line* represents the duration of a click. All clicks in the raw data are shown in the *lower panel*. Only those clicks identified as belonging to a train are shown in the *upper panel*

The switch to train detection meant that the volumes of data were now far greater than simple counts of clicks per second Visual analysis of a year's data without an automated classifier could easily take more than a year. The clicks logged were analyzed in post-processing on a PC to detect any trains and try to identify the nature of the source.

7.1.5 Covering the Frequency Range: C-PODs

T-PODs require users to set target frequency bands for each of six 10 s periods (or scans) each minute, and this requires prior knowledge of the frequency of click that the animals will produce. If that was unknown then the T-POD can step through six different frequency configurations each minute.

The C-POD was developed to overcome the problem of prior knowledge of the target sound being needed to configure the T-POD's detection process. By collecting more information on each click it creates the potential to find whatever coherent trains of tonal events that exist in the data. This aim drove the design towards a digital system that measures the times and amplitudes of waveform inflections and zero-crossings and stores a summary of the characteristics of each click as input data for the train detection and classification. A prototype detected dolphins surprisingly well and became the C(etacean)-POD, which records, for every click, the dominant frequency, the final zero-crossing interval, the maximum peak-to-peak amplitude of the click, and an index of the click bandwidth, along with the time of occurrence and duration.

To select clicks for storage, this digital instrument looks for tonal segments of ultrasound in time windows of variable length that move along the data stream. The C-POD has shown that weakly tonal segments are generally detectable within or following most dolphin clicks. These sequences of tones provide less information than a continuous high sampling rate record of dolphin clicks but they do provide a rich input to a train detection process, and the identified trains give more information on cetacean behaviour than clicks do.

Dolphin detection is very much harder than porpoise detection because their clicks are broadband transients and not unlike many other such brief sounds in the sea. The most distinctive feature of dolphin clicks is that they are very loud, but this is only evident when they are recorded at short range. Dolphins, unlike porpoises, can change the frequency content of successive outgoing clicks (Au 1993). When the dolphin's sound beam is directed towards the instrument it will generally receive more high frequencies than if it is further off the acoustic axis of the click. Figure 7.2 shows clicks received from a bottlenose dolphin, *Tursiops truncatus*. In this example the direct path shows higher frequencies than those received via surface reflections of off-axis components of the click beam. At other times the on-axis components are the reflected echo of the click.

The complexity of the beam structure and echoes makes it impossible to achieve a low false-positive rate from a classifier that identifies individual dolphin clicks. To overcome this it is necessary to use some higher level of information, such as the temporal or spatial (if a source direction is available) clustering of specific click characteristics.

Train detection is such a method and Figs. 7.3 and 7.4 show typical data. The earlier clicks are part of a slow train, with inter-click intervals (ICIs) of 70–90 ms, that overlaps a much faster subsequent train with ICIs rising slowly from 8 to 11 ms.

C-PODs have detected all the 26 species of odontocetes on which they have been tested, but it is unlikely that they will detect the mighty sperm whale-the only very large odontocete, as the dominant click frequency of this species falls below the C-POD frequency range (20–160 kHz). Cryptic echolocation (Barrett-Lennard et al. 1996) from killer whales, *Orcinus orca*, must also be problematic.

Seasonal, diel and tidal patterns of detectability are commonly seen, with many coastal sites showing primarily nocturnal detections. Figure 7.5 shows such a pattern in bottlenose dolphin activity on the east coast of the USA.

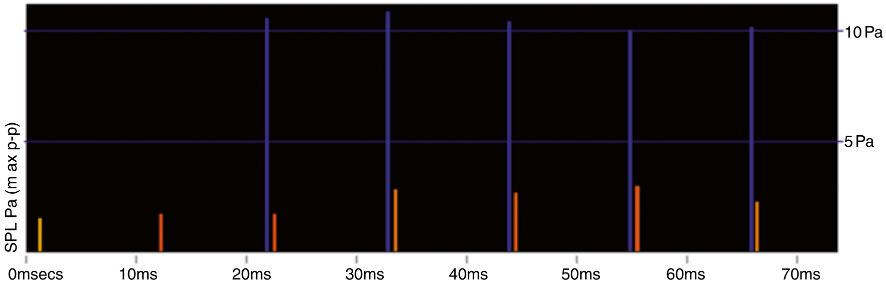


Fig. 7.2 Direct path and reflected echoes of dolphin clicks: The frequency of tones is shown by colour (*red* = 20 kHz, *violet* = 140 kHz) and their maximum peak-to-peak sound pressure in Pascals by the length of each *line*

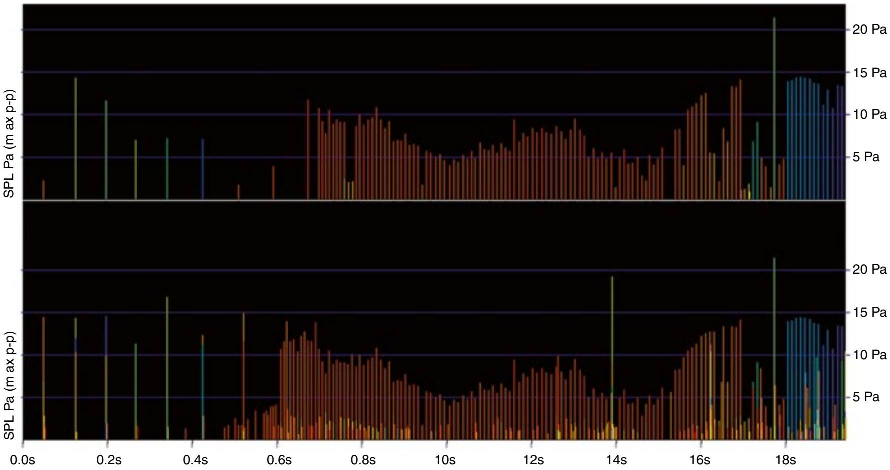


Fig. 7.3 Click trains from bottlenose dolphins: The frequency of tones is shown by colour (*red*=20 kHz, *violet*=140 kHz) and their maximum peak-to-peak sound pressure in Pascals by the length of each *line*

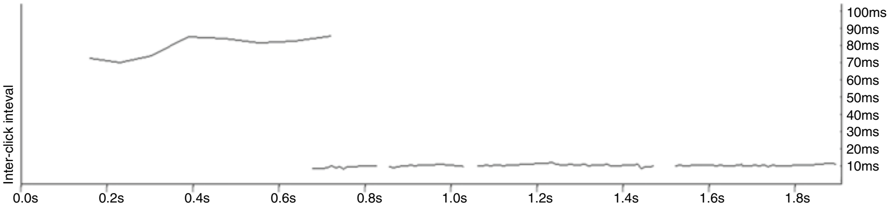


Fig. 7.4 Inter-click intervals extracted from the data shown in Fig. 7.3

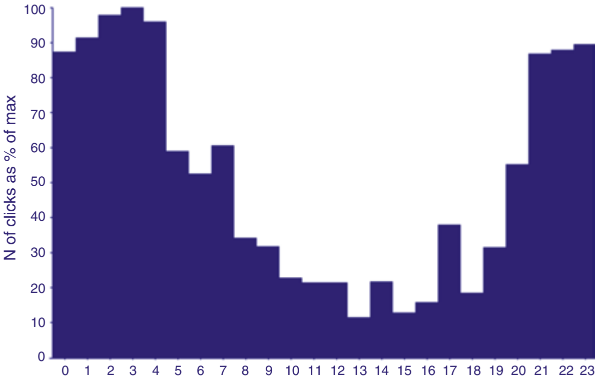


Fig. 7.5 Number of bottlenose dolphin clicks logged by hour of day at a coastal site. *N*=1,892,93

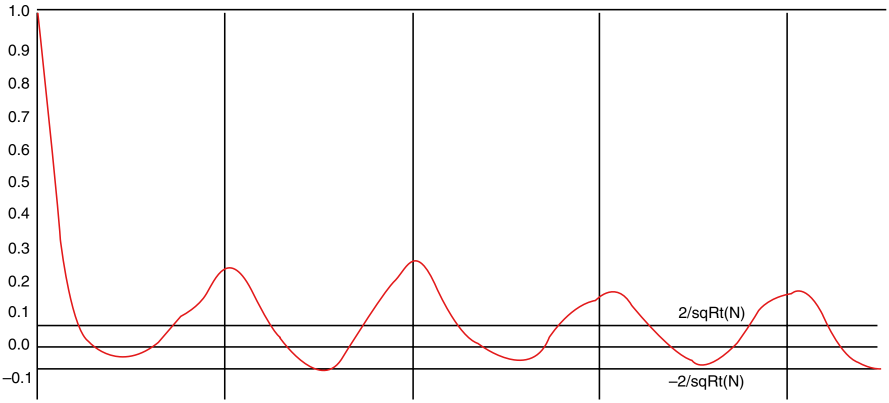


Fig. 7.6 Auto-correlation function of dolphin detections. *X*-Axis *grid lines* at 24-h intervals

The autocorrelation (Fig. 7.6) shows 24-h peaks that are significant across more than one lunar cycle. At other sites, patterns of use have been seen in which 24-h and tidal cycle patterns alternate.

7.1.6 Black Boxes

Train detection and classification, in common with all but the simplest pattern recognition systems, are sufficiently complex that it is not possible to predict its performance from examination of the algorithm (Theodoridis and Koutroumbas 2009). By virtue of their complexity alone such processes are 'black boxes' that require external validation of their transfer function—the relationship between the input and the output. In practice even much simpler electronic instruments, from hydrophones to oscilloscopes, are also generally used as black boxes validated by empirical transfer functions that are both more accurate and more credible than any transfer function that might have been derived from knowledge of the component dimensions, materials, circuits, and any internal logic. Detectors that were black boxes on account of lack of knowledge of how they worked, such as the litmus test, have always played a huge role in scientific research. In the computer age we see a huge increase in the use of models and pattern recognition methods that are inevitably to some extent 'black by virtue of complexity' and must depend on empirical validation.

For the C-POD an adaptive polythetic classifier, called the KERNO classifier, has been developed. It seeks coherent trains, gives each a confidence class representing the confidence that the source is an actual train source, and ascribes each train to one of four possible source types or 'species': 'NBHF' (narrowband high-frequency click producing species such as porpoises), 'other cetaceans', 'boat sonar' and 'unclassified'. For specific locations 'encounter classifiers' have been developed that look at a wider time span of data and all the KERNO-classified trains within it to give a better classification of the 'species', e.g. the 'Hel1' classifier was developed as an outcome of an international workshop at the Hel Marine Station in Poland in 2010 to give very low false-positive rates in the detection or porpoises in data from the Polish waters of the Baltic Sea.

For the T-POD and C-POD, with their automated classifiers, our knowledge of their transfer functions is based on laboratory studies and various published studies in the sea. Tank tests have been made of detection thresholds, amplitude and frequency values by Dähne et al. (2013a) and others, and have been used to relate tank acoustic measures to performance at sea by Kyhn et al. (2008) and by Verfuss et al. (2007, 2013).

Deployments both in cetacean free environments and visually monitored deployments in locations with cetaceans have provided essential validation for performance in respect of different species groups: porpoises—narrowband high-frequency species—Carlström et al. (2009), Culik et al. (2001), Koschinski et al. (2003, 2006), Rayment et al. (2009a), Thomsen et al. (2005), and Tougaard et al. (2006a, b); Bottlenose dolphins, *Tursiops truncatus*—broadband transients—Philpott et al. (2007a, b), Bailey et al. (2010), Nuuttila et al. (2013a, b), and white whales, *Delphinapterus leucas* by Castellote et al. (2013).

7.1.7 The Needle and the Haystack

How to reduce huge volumes of continuous ultrasound data to something easy to manage without losing the sounds of interest is a major challenge. To record brief cetacean clicks with reasonable fidelity requires a sampling rate of at least three times this frequency and preferably more. A reasonable dynamic range requires 16-bit amplitude measurements. The SAMBAH project, that is near to publishing its results at this time, has collected 390 years of data on porpoises from 200 C-PODs deployed during 2 years in the Baltic Sea. The data amounted to 300GB. Using continuous recording of ultrasound up to 150 kHz would have produced approximately 11,000 TB of data. This level of selection and compression—a factor of over 30,000—inevitably decreases as animal density rises. The next step is to selectively record high-sampling rate data to give full detail of samples of clicks and of noise without storing huge data volumes.

7.1.8 Pattern Recognition

This selective approach to data logging does make large projects manageable by reducing the size of the haystack, but the needle to be found is still very small, and finding it in post-processing is a tougher challenge than controlling the data volume.

The first version of the train detection aimed to find trains that resembled porpoise trains within T-POD data. When applied to dolphin trains it showed a marked reluctance to recognise trains of clicks from dusky dolphins logged in New Zealand. So the detection process was reversed to work primarily by rejecting 'chance trains'—false positives arising by chance in noise while accepting actual train sources irrespective of source. This produced a much higher level of detection of dusky dolphin trains, which was valuable, but it also revealed the existence of previously unknown train sources, described later.

This is a general problem: seeking a tightly defined pattern entails a risk of excluding variants of the pattern that were not known when the system was devised—you only see what you look for. Even worse is 'the elephant outside the room'—if the detector is fitted too tightly to the target pattern you may not discover that there are other sources in the sea that produce many sounds some way off the target with only a few that fit the detector criteria. The simplest solution is widening the selection criteria to bring enough data home to see what is going on in such cases. Logging sediment transport noise is a good example of this. However, weak selection criteria can massively increase the data volume and a balance is required.

In the SAMBAH project, a quantitative study of porpoise density in the Baltic Sea, C-PODs selected less than 1 TB of raw data from 10,000 TB of continuous data and, using the Hel1 encounter classifier, gave a false-positive rate of less than 1 detection positive second per year at high sensitivity in some 390 years' worth of continuous data. The same performance could not be achieved in soundscapes with high levels of sediment transport, with high levels of non-cetacean train sources, or if the target was dolphins.

Such locations with many boat sonar or many weak unknown train sources are much more difficult, especially for monitoring species producing broadband transients. The successor to the C-POD (the C-POD-F) employs a train detection algorithm running on board to select clicks and captures waveforms of these. It also saves an expanded set of compressed data on each click to provide the input for a more powerful train detection process that can reduce the susceptibility of dolphin detection to false positives arising from ambient noise sources.

7.2 Working with Cetacean Echolocation

7.2.1 Detection Thresholds and Functions

Since the early development of radar, 'receiver operating characteristic' (ROC) curves of the true detection rate plotted against the false detection rates have been widely used to assess the performance of signal detectors, and to help decide where to put the detection threshold. In their original use the number of signals was known and detections were made against a constant background of noise from the electronics. In most marine acoustic tasks the relevant noise levels are ambient noise and are highly variable across times and locations, so each soundscape requires its own particular ROC curve and these are rarely available. To accommodate this variability the train classification developed for PODs gives four possible detection thresholds called CetHi, CetLo, 'doubtful' and 'very doubtful' for T-PODs and High, Mod, Low and 'doubtful' for C-PODs.

Because cetaceans are highly mobile, their movement through the detection zone of a SAM usually provides distinct temporal clusters of true detections and this allows huge volumes of data collected from diverse locations, without any visual supervision, to be used to develop and improve classification methods. It also provides a means of selecting an appropriate classification class as poor classes will show outlying detections that do not cluster with more reliable classes.

Research and monitoring projects divide into two groups—those that can achieve their aims using relative levels of activity or presence, and those that need to estimate absolute densities of animals, which is much harder to do.

Logger detection thresholds can be measured, and Dähne et al. (2013a, b) reports porpoise detection thresholds for C-PODs as 114.5 ± 1.2 dB re 1 μPa peak-peak at 130 kHz. But the detection threshold does not, on its own, predict the detection performance, because echolocation clicks are produced in a narrow beam which may not sweep across the logger hydrophone while the animal is within detection range. Kyhn et al. (2008), using visual theodolite tracking of porpoises, estimated the distance detection functions for T-PODs and showed that the detection performance varied with the laboratory measurements of the detection threshold in accordance with a simple model of sound propagation.

The SAMBAH project, acoustically assessing the population of porpoises in the Baltic Sea, includes a new method in which long-baseline acoustic ranging is used to track animals moving through an array of C-PODs and other detectors. SAMBAH has also included local measurements of propagation conditions.

T-PODs have been used to evaluate the efficacy of management actions aimed at conservation of Hector's dolphin in New Zealand. Rayment et al. (2009a) used concurrent T-POD and theodolite surveys with Hector's dolphins (*Cephalorhynchus hectori*) at Banks Peninsula, New Zealand, to address the questions: Over what range can the T-POD detect the species, and what proportion of groups that approach within that range are detected? They recorded a maximum detection range of 431m and combined the distance and detection data, Fig. 7.7, to estimate an effective detection radius (EDR), analogous to the effective strip width in line-transect surveys (Buckland et al. 2001).

In the case of species with broadband clicks, theoretical modelling of detection is uncertain because of the uncertainties arising from the complicated broadband beam structure and from reverberation and propagation effects over long pathways, which are often much longer than the depth of water. Reverberation, in particular, affects the performance of train detection. These factors make empirical estimation of detection ranges more credible and these have been undertaken by Philpott et al. (2007a, b), using a T-POD in the Shannon Estuary, Ireland, and land-based theodolite tracking. They recorded a maximum detection range of 1246 m for bottlenose

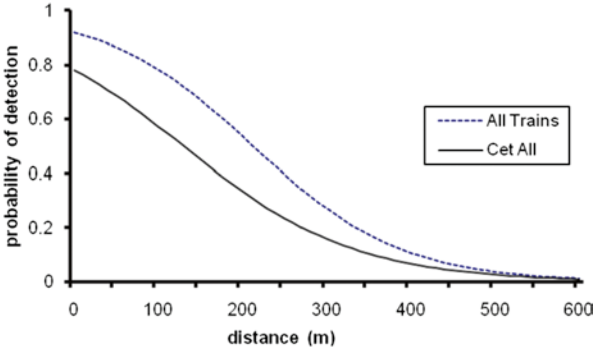


Fig. 7.7 Detection functions for a v3 T-POD from theodolite distance measurements of Hector's dolphins at Banks Peninsula, New Zealand. The two curves show the detection functions for all train categories and the more conservative 'Cet all' categories which includes only trains classified as 'Cet Hi' and 'Cet Lo'. Curves were fitted using a logistic regression model

dolphins and reported that 82 % of dolphin pods which approached within 500 m of the T-POD were detected acoustically. They found no effect of dolphin school size on detectability.

Nuuttila et al. (2013a, b) studying bottlenose dolphins in Wales reported a detection function and found a maximum detection distance ranging from 1343 to 1779 m. They found that minutes with feeding activity had higher acoustic detection rates and longer average effective detection radius (EDR) than minutes of travelling. Surprisingly they found that the detection probability for single dolphins was significantly higher than for groups.

A detection function for bottlenose dolphins was also estimated for T-PODs by Bailey et al. (2010) in three areas off the east coast of Scotland. Land-based surveys recorded 89 groups of dolphins within 900 m of the T-POD. All groups spending >30 min in the area were detected on the T-POD, and the probability of detection declined in relation to distance from the recording site. The number of dolphin clicks recorded on the independent hydrophone system was significantly related to the number detected by a T-POD. Year-round deployments of paired T-PODs detected significant geographical variation in detections for both bottlenose dolphins and harbour porpoises. This pattern reflected published data from visual surveys.

Obtaining absolute densities from static acoustic monitoring of echolocation is an evolving field. For harbour porpoise and Hector's dolphin, another species with narrowband high-frequency clicks, estimates of distance detection functions for T-PODs have been made by Kyhn et al. (2008) and Rayment et al. (2009a).

Static acoustic monitoring changes the nature of the problem of measuring densities of animals in that individuals are not counted, and usually not tracked, but their presence is evident for a period of time which is the duration of the logged click train.

In distance sampling theory a method—cue-counting—has been developed to avoid the need to distinguish individuals. In the case of cetaceans the cue might be whale blows or surfacings, and the density estimate depends on an estimate of the average rate of cue production by an individual animal. In static acoustic monitoring a simple thought experiment is informative: porpoises at some low density in a sea area with a sparse array of loggers will give some number of logger days with detections. These detections will typically consist of a number of fragments of trains, each lasting a fraction of a second as the porpoise's sonar beam sweeps across the hydrophone. If the porpoises now swim around faster, with no change in the density of animals, the number of logger days with detections will rise, but the sum of durations of trains will stay the same because animals will be spending less time within the detection range of a logger on each 'visit', but that will be balanced by the increase in the number of visits.

When an animal is within range of a logger, only a very small proportion of time shows detection of click trains because the animal's sonar beam is narrow (Au et al. 1999) and is swept around the underwater scene ahead of the animal. As a result, when two animals are within range there will be relatively few overlapping trains logged, and 'sum of train durations' does not easily saturate, i.e. become so high that another animal arriving has a much reduced chance of affecting the measurement. As a rough guide, it is best to avoid any detection rate metric (e.g. detection positive days DPD, detection positive hours DPH, detection positive minutes DPM, sum of train durations) that goes over 30 % positive in order to keep the effect of saturation of the measurement small. Brookes et al. (2013) give an interesting discussion of other aspects of the choice of metric, and show that a large C-POD data set gave a useful fit to a distribution model based on multiple visual surveys and physical features. The challenge now is to find the most practical and accurate methods of relating the detection metrics on any static detection system to the local density of animals. Social species commonly generate overlapping train detections and will be particularly challenging.

7.2.2 Inferring Behaviour from POD Data

Nuuttila et al. (2013a, b) made extensive visual observation of bottlenose dolphins and porpoises in the vicinity of C-PODs. They found that both bottlenose dolphin and harbour porpoise click train characteristics matched those reported in the literature for frequency range and for average and minimum ICI. The recorded click trains from both species had different characteristics for two observed behavioural categories: travelling and foraging, as has been proven on porpoises in a semi-natural environment (Verfuss et al. 2005, 2009). For both species, trains with minimum ICIs less than 10 ms were more frequent by a factor of 3 or 4 during foraging and the click trains were of shorter duration and had shorter mean inter-click intervals. The distinction in the click trains between the two behaviours was stronger for harbour porpoises. For both species, the C-PODs showed potential in detecting foraging behaviour and in identifying potential feeding sites and trends in foraging activity.

A detailed analysis using generalized additive models (GAMs) by Pirotta et al. (2013) of ICIs from dolphin click trains logged at four sites in Scotland showed that SAMs (T-PODs and C-PODs in this study) can provide important insights into the distribution of foraging activity in relation to site and tidal phase with foraging occurring at different tidal phases at different sites, and that GAMs can provide a less arbitrary measure of type of activity than a single ICI threshold.

7.2.3 Landmark Sequences

Access to large sets of train data has given new evidence of how porpoises use their sonar. 'Landmark sequences' are a striking example. Where a large acoustic target is present on a rather featureless background, such as a buoy in deep water or a group of PODs on a level seabed, sequences of train fragments lasting for 30–140 s are sometimes detected. Such trains have a progressive fall in the inter-click interval (ICI) from a maximum that may be over 300 ms down to around 40 ms, although occasional short ICIs may occur at some points. The linear fall in ICI is in line with the studies by Verfuss et al. (2005) of landmark use during small-scale navigation by captive porpoises in which the ICI falls in line with the two-way travel time of the click from the animal to a landmark and back, plus a fixed 'processing time' of 14–36 ms. The same pattern has been observed on T-PODs in many locations. The example in Fig. 7.8 comes from a T-POD hanging below a navigational buoy in Falmouth Bay on the SW coast of England. These patterns are also recorded frequently in the German Baltic Sea (Meding et al. 2005; Verfuss et al. 2009), in data from groups of T-PODs on the seabed in the southern North Sea (Ansgar Diederichs, pers. comm.), in data from C-PODs attached to gillnets in the northern North Sea (Alice Mackay, pers. comm.) and from many locations in the Baltic Sea (SAMBAH project). The term 'approach sequence' was previously used for these patterns, but risks confusion with the 'approach phase' of a prey capture sequence described by Verfuss et al. (2009).

Using the two-way travel time when the ICI is 300 ms gives a maximum detection distance of approx. 210 m, substantially greater than anything previously reported for porpoises. The swimming speed of the porpoise can also be calculated from the ICI slope and in Falmouth Bay, UK, 13 such sequences showed a mean speed of 2.1 m/s (standard deviation 0.8).

A landmark sequence detection algorithm was added to the T-POD software to speed up the process of finding such click patterns. The detector was symmetrical, so that it would detect sequences of trains with rising, as well as falling, ICIs with the same sensitivity. Use of this detector showed that the inverse of an approaching sequence is very rarely seen. That rules out the possibility that these are actually sequences of unrelated train fragments, and, given that, it is hardly surprising that there are no 'retreating sequences' as cetaceans do not swim very far backwards.

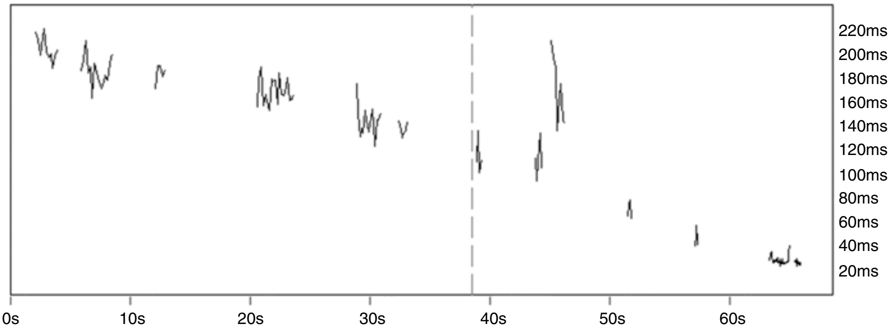


Fig. 7.8 Inter-click intervals in a landmark sequence from a porpoise

However, more surprisingly, landmark sequences are very rarely seen from dolphins. This could arise because the targets have been detected at much greater distance by dolphins with their louder sonar. At such distances dolphin clicks arrive with so many multipath replicates that landmark sequences involving very long inter-click intervals could easily be missed. Alternatively dolphins may be processing echoes from distant objects that actually arrive after the next click has been made.

C-PODs are standardized to give a uniform sound pressure scale at 130 kHz, with good radial uniformity, so landmark sequences can be used to estimate both source levels and a maximum level for the echo that the porpoise is receiving, but with a limitation that the target strength is not known apart from being unlikely to exceed a reflection from a perfect flat reflector.

7.2.4 Multipath Clusters

Cetacean clicks are most often received with replicates of the click following it. These replicates could be created in several ways: reflections within the animal or from reflective structures such as the sea surface or bottom, by refraction as the acoustic wavefront passes through water with varying speeds of sound conduction, or by secondary radiation from resonant structures such as bubbles or the swim bladders of fish. This multipath propagation, Fig. 7.9, typically produces a cluster of progressively weaker, and very brief, tones following the sound arriving by the most direct path. Often the amplitude envelope of this sequence of tones is concave, resembling exponential decay. The pattern of these multipath replicates conveys information about the pathway between the animal and the logger, and the occurrence of similar patterns in successive clusters is useful evidence of a common source for the clicks, although it does vary rapidly as features of the pathway change, such as the shape of the sea surface.

The C-POD finds tonal segments of sound and identifies a single dominant frequency within each. This approach does not give the spectral detail that is available from a Fourier analysis of the sound stream, when sampled at a sufficiently high rate, but the range of frequencies seen in the multipath cluster approximately represents the spectrum of the original click and the representation shown in Fig. 7.9 proves to be a very useful format.

Porpoise clicks, when produced, have a narrow spectrum around 130 kHz, with very little energy at frequencies more than 20 kHz away from the peak of the spectrum. Porpoise clicks are also often followed by a cluster of tones, and these also represent the spectrum of the source, being close in frequency to the original click. Figure 7.10 shows the waveform of a porpoise click and the subsequent multipath replicates, which are likely to be echoes. These echoes may sometimes be louder than the direct path, e.g. when the latter is off the centre of the click axis while the echoes are from sound paths nearer the centre of the beam. Echoes from curved wave surfaces may also be louder than the direct path due to focusing, and multipath replicates from varied directions may interfere destructively to produce a locally

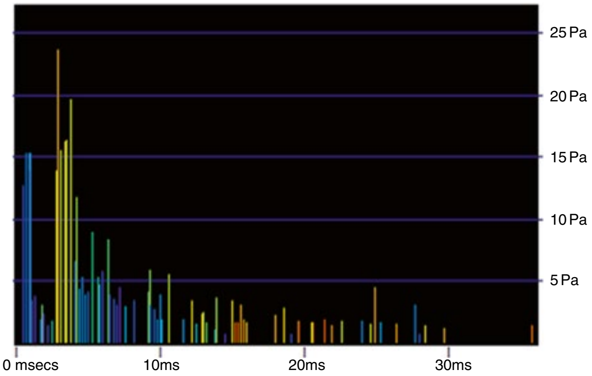


Fig. 7.9 Multipath cluster following a bottlenose dolphin click. Maximum peak-to-peak sound pressure in Pascals. The frequency of tones is shown by colour (*red* = 20 kHz, *violet* = 140 kHz)

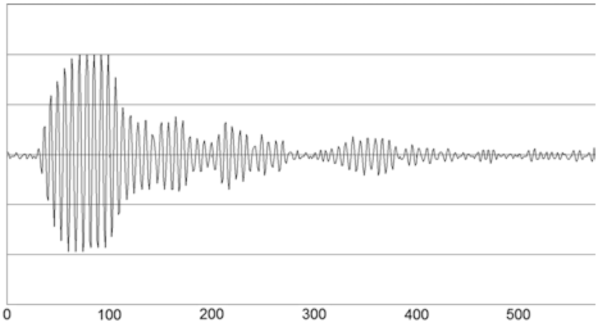


Fig. 7.10 Waveform of a single porpoise click with subsequent multipath replicates. *Horizontal axis* units are µs

weaker and apparently shorter click, or interfere constructively to produce a locally louder click. They may also concatenate to produce a much longer click.

7.3 Noise and Worse: Shrimps, Sand, Storms, Sonars and WUTS

The concept of ‘noise’ was developed in the early days of signal detection systems and developed by the pioneers of radar. It properly refers to Gaussian noise—the product of a random process like thermal acoustic noise in the sea or thermal electrical noise in electronic systems. Signal detection in the sea is often more seriously affected by other types of sounds that have particular resemblance to the signal and are better described as ‘interference’. Each of these sources poses different problems for each type of signal that may be sought.

PODs were at first moored close to the seabed, because the classic descriptions of marine noise had shown strong correlations between the wind and the state of the sea surface and ambient ultrasound (Wenz 1962), but we found that the seabed was the source of much louder and more problematic tonal ultrasonic interference. Classifiers had to be tougher to work well over sandy and rocky substrates, and the news that the seabed was muddy was a cause for joy—it would probably be quiet and relaxing!

The soundscape is often dominated over periods of hours or seasons by shrimp clicks, tidal sediment transport, boat sonars and other man-made sources, storms, chorusing of marine animals, ‘packet noise’ or cetaceans. Cetaceans are so noisy that they are the main source of ultrasound in many locations. Packet noise is a working term for repeated bursts of noise that last up to a few seconds and are of unknown origin. Most difficult of all are weak unknown train sources or ‘WUTS’.

7.3.1 Shrimps

Snapping shrimps, of the family *Alpheidae*, are very loud sources of transient ultrasounds (Au and Banks 1998) and are found widely in both tropical and temperate waters. You can hear snapping shrimps by ear when snorkeling, or if you listen intently you can hear them from inside the hull of thin-skinned ships as a sound like fine rain falling on aluminium cooking foil. Their clicks are too broadband to be logged by PODs, but occasionally, when received by a logger, they are sufficiently tonal to be logged, perhaps as a result of the original click exciting some resonant structure in the pathway.

Shrimp clicks typically show a distinct diurnal pattern (Radford et al. 2008) and in some locations they are sufficiently numerous to impair the detection of dolphin click trains. This species specificity of the interference arises because shrimp clicks are much more similar to dolphin clicks than to NBHF (porpoise) clicks and consequently interfere more strongly with the detection of trains of similar clicks.

7.3.2 Sediment Transport

Sandy seabeds are never static—they must be disturbed and brought, at least superficially, into suspension at times or they would become gradually covered with mud. In shallow water they are often brought into suspension by local currents arising from tides, storms or waves, or by currents driven by differences in temperature or salinity as in the thermo-haline currents seen in the Upper Gulf of California. The sound made by seabed sediments in suspension has been investigated by Thorne (1986, 1990) who showed that it corresponds closely to rigid body radiation that arises when particles collide with each other, and that it can be a dominant source of ultrasound in shallow waters. The centroid frequency, fc, of the sound is determined by the particle diameter (D) and is given by

$$fc = 209 / D^{0.88}\ \text{Hz} \tag{7.1}$$

This predicts that a particle diameter of 0.65 mm will generate tones at porpoise frequencies. These sounds are sufficiently tonal that they are readily logged by C-PODs, and where fine sand is lifted off the seabed by currents a C-POD will often log huge numbers of tones of similar pitch with a collective amplitude envelope that undulates smoothly over periods of several to many seconds giving a typical appearance of blue/violet grass on the graphical display of click amplitudes. This form of display (amplitude of tonals colour coded by frequency) of acoustic data often gives better visual differentiation of the nature of marine soundscapes than the conventional display of frequency spectra with power displayed as colour or grayscale coding (Fig. 7.11).

A strikingly accurate replicate of this pattern of tonal ultrasounds can easily be generated in the laboratory using a ‘sand fountain’ technique in which a flow of water upwards into a funnel containing sieved sand of the predicted diameter causes a small plume (e.g. 20 mm high) of sand to be held in suspension. This test bed shows that logging these self-generated noises does not depend on any collision between the sand particles and the rubber hydrophone housing. That view has persisted since the early descriptions of marine ultrasound (Willis and Dietz 1965), when the role of turbulence as a noise source was also over-rated, but such collisions actually create very little sound compared to the rigid-body noise created by the collisions between the sand particles. Some very approximate estimates of the size of particles in suspension can be made from C-POD data, and Wilson et al. (2013) found that C-PODs provided useful data on local noise profiles logged when drifting through a high-current tidal power site.

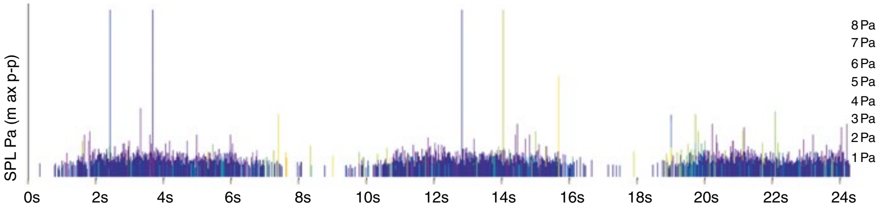


Fig. 7.11 Wave-induced bursts of 130 kHz noise due to fine sand in suspension at the beginning of a storm at the mouth of the River Vistula, Poland. Data from Hel Marine Station

7.3.3 *Masking Cetacean Sonar*

Episodes of sediment suspension typically start with bursts of tonal noise lasting for a few seconds, and the bursts gradually become longer and closer together until this noise background is continuous, with peak-to-peak sound pressures commonly reaching 7 Pa (137 dB re 1 μPa) at 2 m above the seabed. This sediment noise is much louder than the echoes that a porpoise needs to hear and could substantially reduce the effective range of the animal's sonar. Porpoise clicks are logged in the early stages of increasing sediment noise but largely disappear when this noise becomes continuous, even though they are loud enough to be clearly logged against this background.

This interesting observation suggests that sediment noise can effectively jam the porpoise's sonar and that they respond either by stopping echolocation or perhaps more likely by moving to quieter areas, which might be deeper with lower bottom-current speeds, but this speculation has yet to be confirmed.

The resemblance of fine sand noise to porpoise clicks means that it is a more potent type of interference in the detection of NBHF species.

All sandy seabeds must experience fairly frequent suspension of surface sediments and Fig. 7.12 shows a typical strong tidal pattern of sediment transport noise which disappears completely during the neap phase of the lunar cycle. It also shows striking ebb-flow asymmetry that arises because the spatial pattern of flow varies between the two. Patterns of apparent sediment noise were encountered in the shallow waters of the Upper Gulf of California during feasibility studies for acoustic monitoring of the Vaquita marina (*Phocoena sinus*) and corresponded to combined patterns of both tidal and thermo-haline sediment transport that had been previously identified by Alvarez (pers. comm.).

Listening to the sea though a heterodyne detector, or a C-POD, within or just outside the zone of breaking surf usually reveals loud ultrasound bursts as each wave passes and briefly brings sand into suspension above the seabed, creating another distinctive underwater soundscape. C-PODs have been deployed in many shallow waters and sediment noise is often seen as the major source of loud natural ultrasound. Surprisingly, current textbooks describe surface noise from wind and rain but most, if not all, overlook sediment noise despite Thorne's clear analysis and field observations. The ability to detect these noise events in acoustic monitoring data is useful and may lead to further insight into how cetaceans respond to this

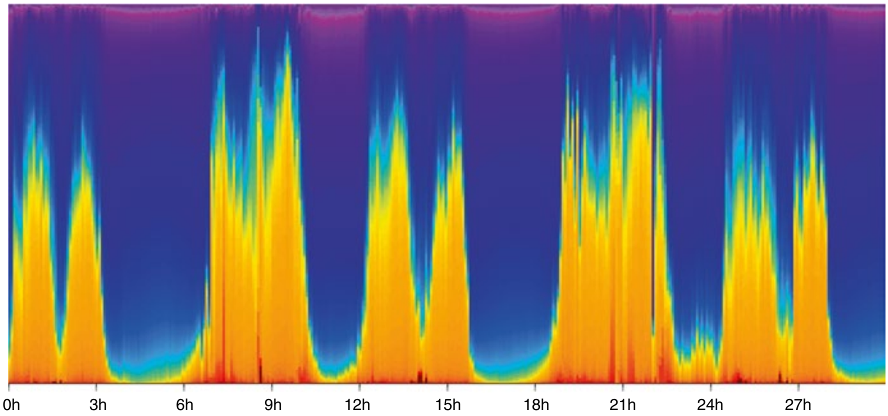


Fig. 7.12 Distribution of frequency of tones logged in south west Britain, over 2.5 tidal cycles (30 h), showing ebb-flow asymmetry. The frequency of tones is shown by *stacked bars*. Colour *red* = 20 kHz, *violet* = 140 kHz

noise source, and it may be that some benthic species have evolved behaviour that exploits the possibilities created by periods of protection from cetaceans created by natural, and in some places predictable, jamming of their sonar.

7.3.4 Storms

Storms in shallow water generate high levels of ultrasound and interfere strongly with detection processes but little investigation has been made of the relative contributions of bottom currents and surface noise from rain, spray, breaking waves and breaking bubbles. Storms are recognized in the data as long irregular periods of noise spread across a wide range of frequencies. They inevitably interfere with cetacean detection, but in a T-POD study by Todd et al. (2009) of the activity of porpoises around an active gas extraction platform in the North Sea, severe storms were followed by unusually high levels of activity of porpoises and in these episodes the inter-click intervals were often very short, which is known to be associated with feeding. It may be that the storm caused scouring of sediments around the legs of the rig and exposed benthic animals, attracting fish that were themselves the prey of porpoises.

7.3.5 Chorusing

Diel patterns of activity of fish that chorus in the range of human hearing are well known, but ultrasonic choruses also occur and surprisingly complex diel patterns of ultrasound repeat regularly over many weeks in some locations (Fig. 7.13).

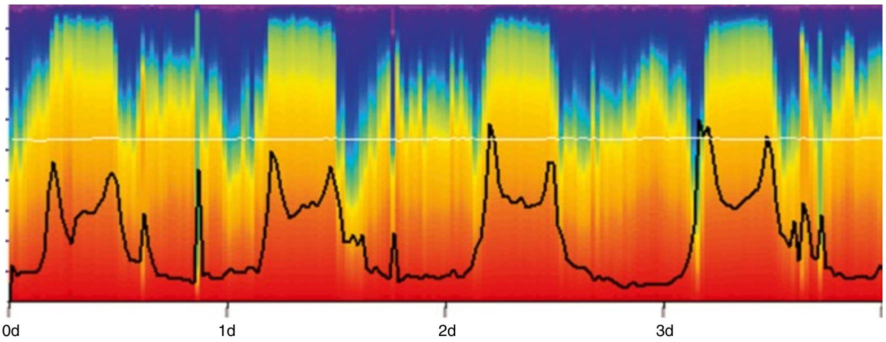


Fig. 7.13 Diel chorusing in a coastal site, France. The *line* shows the number of tones and the distribution of their frequencies is shown by colour (*red* = 20 kHz, *violet* = 140 kHz). An 80 kHz sonar (*green*) appears twice

Knowledge of the sources of such patterns is very limited at present. Radford et al. (2008) and others have identified shrimps and sea urchins as possible sources.

7.3.6 *Chinks and Chunks*

In air we perceive a distant loud sound as both distant and loud even though it is no louder than a sound that is close and weak, and these distinctions can be made with one ear only. In graphical representations of marine sound these subtle distinctions are easily overlooked; however, the characteristic 'decay profile' of the multipath cluster of tones that follows a dolphin click is easier to see in the graphical representation of the sound pressures of clicks (with frequency shown by colours) logged by C-PODs. These exponential decay profiles actually appear quite commonly in the absence of cetaceans and in most locations their source is unidentified, but mooring chains do seem to be one of them.

Another ubiquitous but enigmatic feature of marine soundscapes is 'packet noise' in which ultrasonic tones appear in brief temporal packets of higher incidence and amplitude. Sometimes small surface wave breaks seem to be a likely source, but often it is hard to find a plausible explanation of their source. Packet noise provides a challenging example of interference. In the early development of the T-POD train detection, the process utilized the presence of quiet periods around a train as a positive feature—it showed that the prevailing rate of arrival of clicks was so low that the risk of a train arising by a chance concurrence of evenly spaced clicks was extremely low, and a useful likelihood estimator was constructed around that idea and was based on a rolling estimate of the prevailing rate of arrival of clicks. That approach does not perform well in packet noise because it often has a time profile that is far too similar to the packets of clicks and their multipath replicates created by cetaceans.

7.3.7 Interference

These natural soundscapes provide specific kinds of interference. Their differing characteristics greatly reduce the value of any simple measure of background noise or signal-to-noise ratio as useful predictors of the impact of ambient noise on the performance of classifiers. Simple signal-to-noise ratio measures exaggerate the significance of loud transients which may briefly totally prevent detection of the signal while having no effect on the detection process for most of the time.

However, alternative noise metrics will be more complicated, narrower in their relevance and difficult to validate.

7.3.8 Unsupervised Assessment

A computationally cheap and useful tool that has been developed for assessment of POD detection processes is the time-interval-clustering, or TIC index, value of the detector output. Each train has a time to the last train and the next train, or perhaps to some superior class of train that already commands more confidence. If the shorter and longer of each pair are separately summed across a large test set, then the ratio of longer over shorter totals provides a simple measure of clustering. The ratio will be 2 if the times are all random but more than 2 if they are not.

Because cetaceans are typically moving over much larger distances than the range of a logger, but are within range for long enough to score multiple hits on the logger, this works quite well, and it can be improved in various ways including limiting the longer times and/or relating them to the overall mean interval or to the estimated encounter rate. The response of the TIC index to varying soundscapes can be a useful way of quantifying interference in the absence of visual verification.

7.3.9 Acoustic Doppler Current Profilers and Fish Tags

PODs have often been deployed on instrument arrays that include acoustic doppler current profilers. Although the specification of the ADCP may give the operational frequency as 1 MHz—way above POD hearing—its activity pattern may be clearly seen in the POD record at much lower frequencies that are emitted at lower intensities. These may be in trains of pulses with some resemblance to cetacean sonar, especially narrowband high-frequency clicks. Apart from any effect on the detection process they have the potential, like a fishery pinger, to affect the distribution of cetaceans locally.

More rarely fish tag emissions are logged, and where these are used as an acoustic marker beacon attached to an instrument rig they can create serious local acoustic pollution. As their emissions are in the hearing range of cetaceans they must also advertise the position of any marked fish to cetaceans!

7.3.10 Boat Sonars

Random sources can produce trains by chance coincidence but can be powerfully rejected on the basis of measurements of the coherence of the train. However boat sonars produce real, highly coherent, trains that must also be identified and rejected, and this is inherently more difficult.

In most locations the prevalent source of non-cetacean trains is boat sonars that are used as depth finders or fish finders. 50, 100, and 200 kHz sonars are very common and sonars are heard operating at many other frequencies. Static loggers reveal the massive levels of ultrasound pollution from boats. A strong diurnal pattern is evident at many coastal and estuarine sites with recreational and other boat traffic as shown in Fig. 7.14.

Boat sonars most often appear as clusters of tones that are very close to the frequency of the source, but sometimes quite strong harmonics are detected especially at the end of the multipath cluster. Because of their high source level and long duration, large clusters of tones, Fig. 7.15, are commonly received from each sonar pulse. Embling (pers comm) has found that in 60 m of water a C-POD could detect the sonar of a marine research vessel whenever it was within 1 km.

Cetacean click trains are sometimes logged at the same time as the pulses of boat sonars, Fig. 7.15, which are typically operated at lower pulse rates, so several clicks from the cetacean are logged between pulses from the boat sonar.

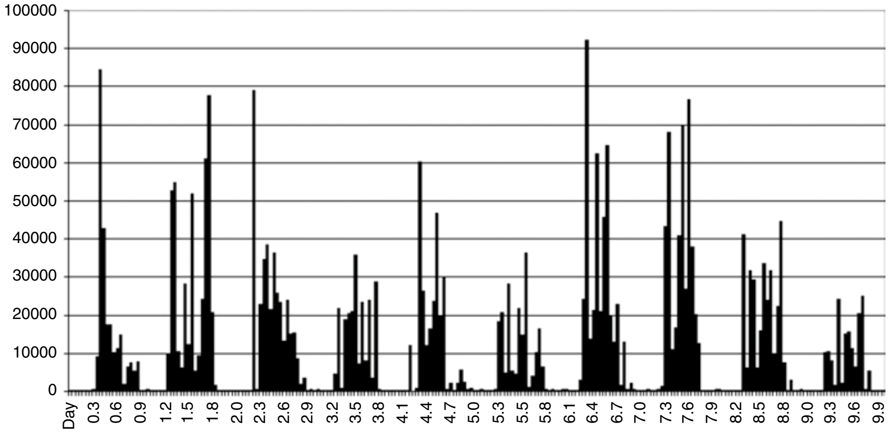


Fig. 7.14 Hourly numbers of ultrasonic (20–160 kHz) tones logged by a C-POD over 10 days in the Fal Estuary, south west Britain

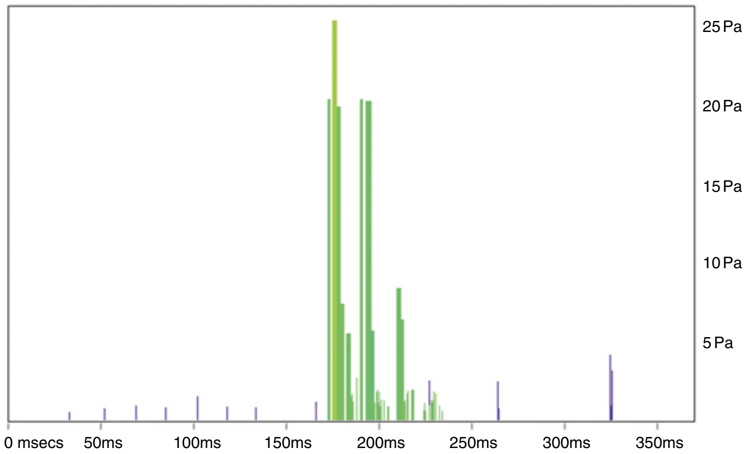


Fig. 7.15 Duration and amplitude of 80 kHz tones logged from a single boat sonar pulse, and 132 kHz tones from a porpoise

7.3.11 *Weak Unknown Train Sources: WUTS*

PODs have occasionally shown remarkable trains of weak tones at around 130 kHz. In the first examples identified these trains showed a characteristic pattern of falling click rate as in Fig. 7.16. The tones are generally weaker, shorter and more broadband than porpoise clicks. They show little or no multipath replication, and also do not show the initial rise and terminal fall in amplitude of successive clicks that is seen as the porpoise's sonar beam sweeps across the POD transducer but instead the trains peter out into scattered very weak clicks. Initial pulse rates were as high as 2500 s^{-1} and the fall may go down to 10^{-1}.

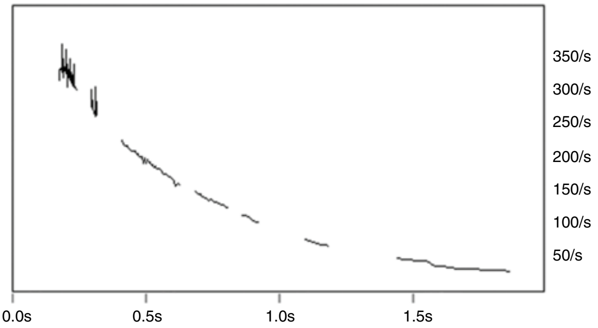
Since those first discoveries in rias in the south west of Britain, other patterns of weak and not-so-weak unknown train sources have been found. Figure 7.17 shows a WUTS from the Gulf of Alaska (data from K. Stafford, University of Washington).

Various sources, physical and biological, have been proposed. Some small crustacean that settles on the transducer housing from the plankton is the most popular at present, but the nature of the source is still entirely unknown. They must have been captured in many broadband recordings but have not been identified, probably because their contribution to the sound spectrum is so small.

WUTS were first detected on T-PODs in rias in the south west of Britain (Tregenza and Loveridge, 2006), and were subsequently seen in C-POD data from mangrove areas in eastern Australia, in the Gulf of Maine, the Upper Gulf of California, the Baltic Sea and the Gulf of Alaska. The sites with most recordings are sites with high nutrient levels.

A classification of WUTS would be very premature, but their features do appear to vary with location.

Fig. 7.16 Trend in click rates from a weak unknown train source



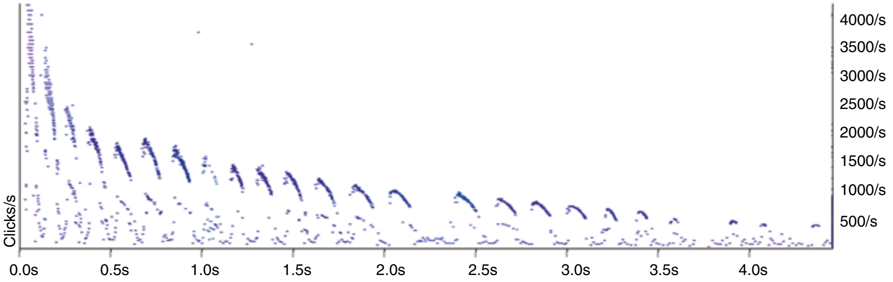


Fig. 7.17 Click rate in a train sequence from a weak unknown train source (WUTS)

7.4 Research Using PODs

7.4.1 By-Catch and Pinger Studies

Gill netters in the Celtic Sea shoot their nets with the boat moving fast so that adding any heavy object to the gear is challenging. However, fishermen from Newlyn, Cornwall, put ‘the bombs’, as they called the early PODs, on their nets in the Celtic Sea (Tregenza et al. 2001) and the results were surprising. Porpoises were detected much more often than expected. The loggers were estimated to monitor an effective area of not more than 500 m diameter. A net length of 500 m in this study caught, on average, one porpoise in 83 days, but during that time the logger on the net detected porpoise clicks, on average, in 10,500 periods (4 %) of 30-s duration, most of which were within encounters lasting a few minutes. Theoretical estimates of the distance at which a porpoise might detect a net by Au (1994) and later experimental study by Kastelein et al. (2000) had shown that the net could be detected at sufficient distance to be avoided by the porpoise, but it was not known how often they would avoid the net even when they had detected it. This study showed that, contrary to the general assumption at the time, entanglement is a rare outcome of a porpoise encountering a net in the wild.

One boat in that study had by far the largest by-catch of porpoises in a single trip. We expected the PODs to show a lot of porpoise activity, but surprisingly few porpoises were heard. That fishing trip also had a large by-catch of mackerel, a fish that has no swim bladder. This suggested a possibility: perhaps mackerel return such a weak echo of the porpoise's click that porpoises choose to 'run silent' and simply listen to the noise of the fish swimming, and in that silent state they have no means of detecting the net.

Pingers, making a ping every 4 s at 10 kHz (in the upper part of our audible range) had previously been shown by Kraus et al. (1997) to reduce porpoise by-catch if placed every 100 m along a net. These pingers worked although they were very much quieter than the porpoises themselves—their intensity was 130 dB re 1 μPa at 1 m. The earliest POD gave a means of studying this. Cox et al. (2001) showed that pingers, when active, reduced the number of porpoise clicks detected by a POD placed next to the pinger, but this effect faded to some extent over the next 2 weeks. This study and others by Carlström et al. (2009), Culik et al. (2001) and Koschinski et al. (2003, 2006) resolved an existing question (Dawson 1994) on how pingers might work by showing that they affected porpoises as aversive devices and not as alerting devices that stimulated echolocation. Cox also found, from visual observation of the experimental site, that occasionally porpoises were silent—they were seen approaching the POD directly and were well inside the detection range but no clicks were logged.

Reducing deaths of cetaceans is the definitive measure of the effect of a pinger, but is far from easy to quantify. In many fisheries it requires the participation of many vessels and a lot of time at sea to see a sufficient number of lethal by-catches, and then the number seen may be a significant underestimate if a significant proportion of by-caught animals drop out of the net before they are hauled over the side of the boat (Tregenza et al. 1997).

The work of Carlström et al. (2009) established a 'cycling pinger' assessment method for pingers that is simpler and is validated by the fact that those pingers that have been shown to reduce actual by-catch and have been studied with T-PODs or C-PODs have also been found to reduce the rate of detection of porpoises. Hardy et al. (2012) used C-PODs to provide this form of acoustic proxy for by-catch risk in a study of Aquamark pingers that were modified to operate for 7 h and then remain silent for 7 h to provide control periods at the same site as test periods. This study showed a reduction in detected porpoise clicks to a little less than half the expected number when the pinger was active, and also showed a lower effect at a site that was relatively noisy due to sand transport on strong tidal currents. It also gave some indication that a 7-h period was too short to allow a full return to normal levels of porpoise use at the quieter site.

Brandt et al. (2013) used C-PODs to study the range of the effect on porpoises of a loud seal scarer designed for use on fish farms and were able to show an effect out to 7 km. Dolphins also suffer incidental and lethal capture in fisheries. The T-POD was used to study the response of dolphins to pingers by Leeney et al. (2007) who found evidence of an aversive effect on bottlenose dolphins. The response of dolphins to pingers is harder to test for three reasons: firstly, their sonar is generally louder than the pinger and is detectable from dolphins that are too far away to hear the pinger; secondly, some pingers can be confused with dolphins and thirdly and most significantly, it seems that porpoises are generally neophobic, unlike dolphins which may be inquisitive. The first of these can be estimated and the second avoided by using a POD, as a means of dolphin monitoring, that is far enough from the pinger not to record it. The last is more difficult as it makes the link between changes in acoustic detections and by-catch rates uncertain and requires more studies in which actual by-catch is monitored.

7.4.2 Estimating Trends in the Vaquita Population

The Vaquita marina (*Phocoena sinus*) is the most endangered species of marine mammal in the world. It occurs only in the northern Gulf of California, Mexico. The species is endangered due to by-catch in fisheries. The abundance of this species has declined from approximately 567 in 1997 (Jaramillo-Legorreta et al. 1999) to approximately 245 in 2008 (Gerrodette et al. 2011). Following feasibility trials of different methods of monitoring trends in the population, an array of 44 C-PODs, deployed across the area of maximum density, was designed as being capable of detecting a 4 % per annum trend in population within 5 years. Analysis of the data from the first 3 years is presented in the Report of the Fifth Meeting of the 'Comité Internacional Para La Recuperación De La Vaquita' (Cirva-5 2014). They show, Fig. 7.18, a rapid acceleration of the annual rate of change in population size to −18.5 % p.a. and attribute the recent increase in the rate of decline primarily to increased illegal gillnet fishing for totoaba—a large fish that is also endemic to the Upper Gulf of California.

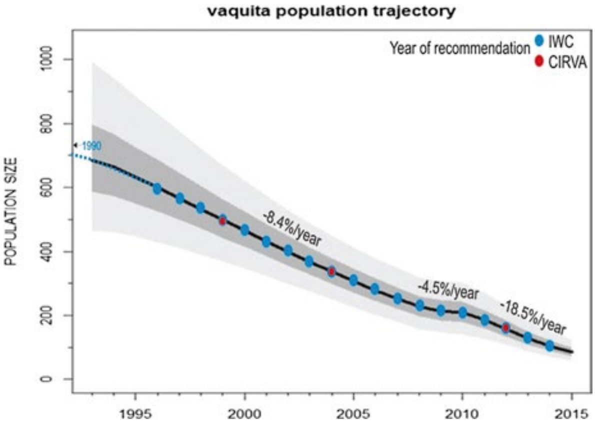


Fig. 7.18 This figure depicts the population trajectory of the vaquita. *Blue dots* represent recommendations from the International Whaling Commission (IWC) and *red dots* represent recommendations from the International Committee for the Recovery of the Vaquita (CIRVA); both the IWC and CIRVA have recommended repeatedly that gillnets be eliminated from the range of the species (see Section 7.3.1). Rates of decline originate from Gerrodette et al. (2011) prior to 2010 and from the Expert Panel results (Annex 8) using the passive acoustic data from 2011 onwards (from report of CIRVA-5)

7.4.3 Porpoises in the German Baltic

A massive decline in porpoises is known to have occurred in the inner Baltic Sea since the middle of the twentieth century. The German Oceanographic Museum (Verfuss et al. 2007, 2009) set up a static acoustic monitoring programme in 2002 using T-PODs across the German Baltic Sea. Up to 42 sites were monitored, including sites in the Bay of Pomerania in the east where densities of porpoises were too low to give useful results from any other method. This extensive study showed, Fig. 7.19, for the first time, that porpoises are still regularly using the whole of the German Baltic, and that there are strong seasonal patterns. The percentage of days with registrations was interpolated between monitoring stations with a generalized additive model (GAM).

The seasonal pattern fits an eastward migration of porpoises in spring from the Belt Seas into the German Baltic, through the Kadet Channel and across the Darss Sill and their return in autumn. Especially in cold winters, after the departure of the summer immigrants from the west, the Pomeranian Bay, which partly freezes in most winters, shows its highest density of animals (Gallus et al. 2012; Benke et al. 2014). These animals may represent a part of the extremely depleted Inner Baltic porpoise stock and their westward movement may be determined by water temperatures or ice cover. Gallus et al. (2012), and Benke et al. (2014), reviewing the acoustic monitoring series find evidence of the Pomeranian Bay as an area of spatial but not temporal overlap between two populations of harbour porpoise apparently moving in synchrony.

The discovery of clear evidence that migration patterns known in the past still exist, and that there is still extensive, albeit low density, use of the German Baltic has given a valuable basis for conservation efforts of the only cetacean species resident in those waters. Working with very low densities makes any assessment vulnerable to even low levels of false-positive detections, and the German Oceanographic Museum projects have developed methods (Verfuss et al. 2007) for visual verification of the automated detections, with the aim of both removing false positives and ‘upgrading’ true detected trains that were classified as ‘doubtful’ by the software. This process could not be applied to the whole of the raw data as it would be too large a task, so it was limited to trains detected by the T-POD software, but including trains placed in the two lowest confidence categories that are normally excluded from analysis.

Anja Gallus (formerly Meding), analysing the T-POD data from the German Baltic study, also found a previously unknown link between water depth and porpoise click rates. The modal value of ICIs tended to correspond to the two-way travel time for a click from a porpoise close to the surface directing its sonar beam downwards and receiving an echo from the sea floor (Meding et al. 2005).

The wide distribution of loggers in this study also gives insight into how spatially coherent detection rates are, and how many loggers may be required to monitor an area. Although the maps above of the year 2006 give a rough idea of this, precise evaluation of data retrieved in this project before 2005 has been hampered by the

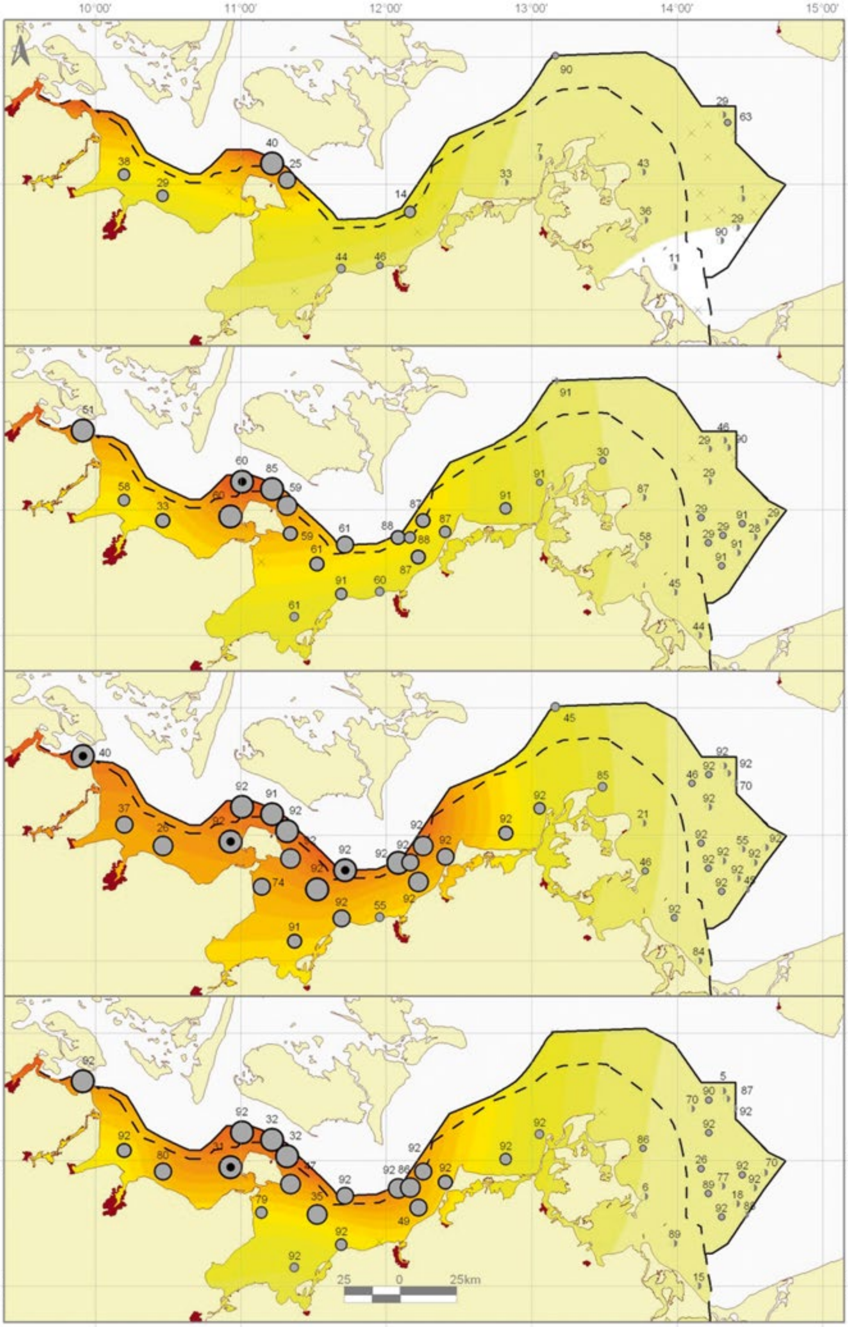


Fig. 7.19 German Baltic Sea: Detection rates of the first (*top*), second, third and fourth (*bottom*) quarter of the year 2006. *Circles* give the monitoring positions, with the number of monitoring days beside each position. Adapted from Verfuss et al. (2009)

fact that the earlier instruments used did not have a standardised sensitivity. To address this, the German Oceanographic Museum team undertook tank calibrations of all PODs (Verfuss et al. 2013) and deployed them set to a standard sensitivity.

7.4.4 Porpoises in the Wider Baltic

The SAMBAH project (Static Acoustic Monitoring of the Baltic Sea Harbour Porpoise) aims to map the distribution and density of harbour porpoises in the Baltic Sea where the cost per detection from visual line transect surveys is too high for such methods to be economically feasible. The project has used C-PODs at 300 sites in a randomly positioned regular grid within all waters less than 80 m deep, Fig. 7.20. This depth limit is based on previous studies of porpoise distribution in higher density areas of the Baltic.

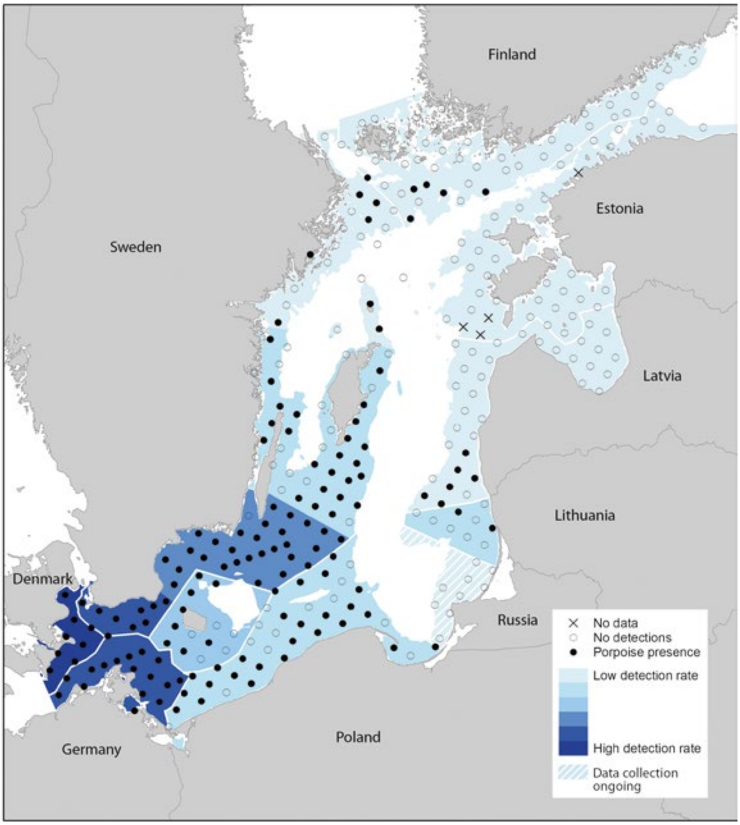


Fig. 7.20 SAMBAH project: Locations for static acoustic monitoring of Baltic harbour porpoises (www.sambah.org)

SAM in the Baltic is challenging because porpoise densities are low or zero in large areas in which any false-positive rate will provide all the (false) detections. For specific locations ‘encounter classifiers’ have been developed that look at wider time spans of data and use all the trains found within them to give a better classification. The ‘Hel1’ classifier was developed from an international workshop at the Hel Marine Station in Poland in 2010 to give very low false-positive rates in the detection of porpoises in data from Polish waters, and has been used in the SAMBAH project.

7.4.5 *Hector’s Dolphin, New Zealand*

Hector’s dolphin (*Cephalorhynchus hectori* van Beneden 1881), Fig. 7.21, is a coastal delphinid endemic to New Zealand (Slooten and Dawson 1994), with a very simple vocal repertoire, consisting almost exclusively of ultrasonic clicks (Dawson 1991) that are remarkably similar to those made by harbour porpoise (Au et al. 1999). Hector’s dolphins were classified as ‘Endangered’ by the IUCN in 2009, principally due to by-catch in bottom set gillnets (Dawson and Slooten 2005). Data on habitat use are not only essential for understanding the ecology of a species, but are also necessary for evaluating the efficacy of management actions aimed at conservation of threatened populations, particularly when those actions are area based (e.g. time and area closures, MPAs).

In 1988, an MPA was established at Banks Peninsula on the east coast of New Zealand’s South Island, within which commercial gillnetting was effectively banned and recreational gillnetting was permitted in winter only. In this context, T-PODs have been used to study habitat use at two different scales. Using T-PODs, three locations around the Banks Peninsula were acoustically monitored in summer and winter over a period of 2 years (Rayment et al. 2009b), Fig. 7.22. Although there was a large seasonal effect, with more than three times as many minutes per day

Fig. 7.21 Hector’s dolphin

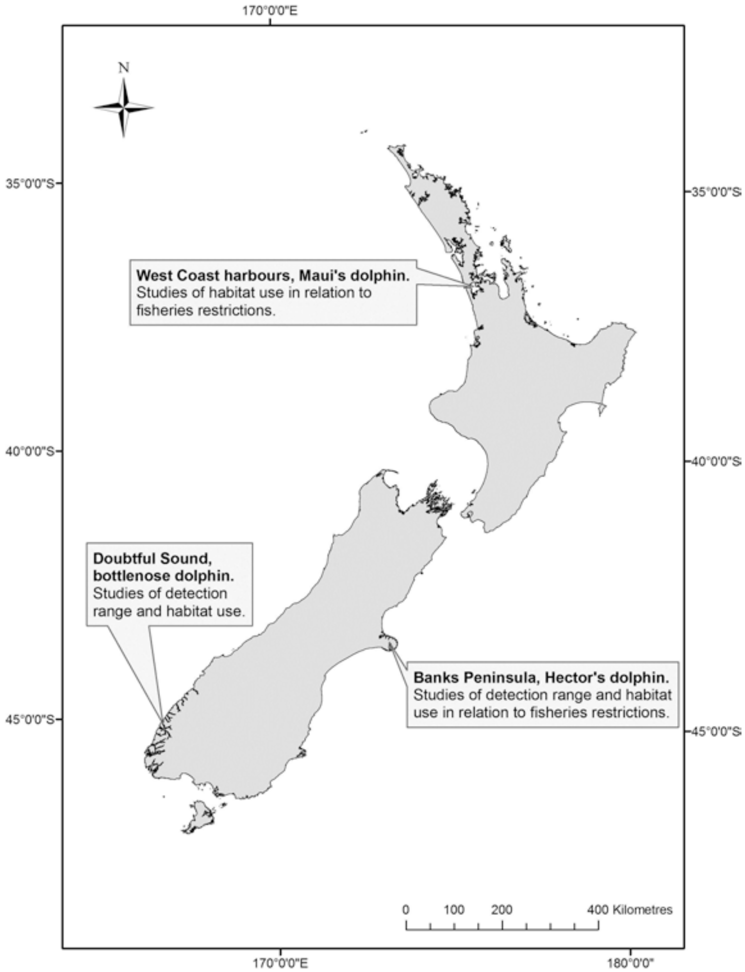


Fig. 7.22 New Zealand: Location of static acoustic monitoring sites

with dolphin detections in summer compared to winter, dolphins were still detected on 88 % of winter days. These data suggest that there was a greater overlap between Hector's dolphins and gillnetting than had previously been suspected and provides good evidence to support the recently imposed year-round ban on all gillnets. Prior to this study, simultaneous cliff top observation, T-POD deployment and wideband acoustic recording (300–150 kHz) were used to confirm that detected clicks were made by Hector's dolphins, and to quantify detection range (Rayment et al. 2009a).

At a much finer scale, T-PODs have also been used to evaluate a specific compromise in the regulations of the Banks Peninsula Marine Mammal Sanctuary. The innermost third of Akaroa harbour is one of three zones in the sanctuary where amateur fishers are permitted to set unattended gillnets for flounder. Dolphins are routinely seen in this area in summer (Dawson 1991), but only rarely so in non-summer months. Hence fishers are permitted to set flounder gillnets in this zone between 1 March and 1 November.

To evaluate dolphin usage of different parts of the harbour, T-PODs were moored in representative sites in the inner, mid and outer harbour, and maintained over 12 months in 2007/2008. The inner harbour site was well within the flounder fishing zone described above. The instruments were set so that five of the six scans were optimised to detect Hector's dolphin sonar clicks, which are narrowband pulses centred on 120–130 kHz (Dawson and Thorpe 1990). The remaining scan was set to detect the broadband echolocation clicks characteristic of bottlenose, dusky and common dolphins, which are the only other small cetaceans likely to use this zone. The fact that the sonar sounds of Hector's dolphin are so different to those of the other inshore dolphins allows reliable discrimination of them from acoustic records.

Acoustic detections show that Hector's dolphin use of the upper harbour is strongly seasonal, while little seasonal pattern is evident at the outer harbour site. Despite this, dolphin use of the upper harbour site was unexpectedly frequent outside the summer months. Hector's dolphins were detected on 41 % of the days during which gillnetting is legal. Especially considering that the detection radius of Hector's dolphins by T-PODs is relatively small, and therefore that the acoustic detections are a highly conservative measure of habitat use, these data strongly indicate that the inner harbour compromise for flounder netting is unlikely to be safe. These findings have been confirmed and extended by a modelling approach analysing T-POD data by Dawson et al. (2013).

Like Vaquita and Baltic Harbour Porpoises, the North Island subspecies of Hector's dolphin, called Maui's dolphin (*Cephalorhynchus hectori maui*), poses the problem of detecting animals at extremely low densities (Rayment et al. 2011). The most recent abundance estimate of this critically endangered subspecies is 55 individuals (older than 1 year; Hamner et al. 2012). Clearly, continuing by-catch presents a substantial risk of extinction, so getting the boundaries of any protected area right is of crucial importance. The offshore boundaries of the current protected area have been set largely on the basis of sightings made in aerial surveys. T-POD data, however, provided the basis for extending the protected area into the Manukau harbour. In his keynote address at the 2013 Biennial conference on the Biology of Marine Mammals, Pete Hodgson, the Minister of Fisheries at that time, described his response:

> An Italian PhD student … set out acoustic detectors tuned to the sonar clicks of Maui's. Her data showed that the dolphins ventured further into the harbours than was thought. This is research at its most basic and most important and it caused me to regulate a somewhat greater area of coastline than I had proposed in my first attempt.

7.4.6 White Whales

Castellote et al. (2009, 2013) used T-PODs and subsequently C-PODs to monitor white whales, *Delphinapterus leucas*, in various Arctic sites. Their validation testing included both extensive visual observation and comparison of the frequency spectrum of clicks recorded from this species both in the Arctic and in captivity with the C-POD data. They found good correspondence in both measures and obtained useful results even in challenging acoustic environments. Diel and tidal behaviour patterns were identified.

They also found that white whale echolocation behaviour was variable between habitats and this might be related to habitat differences or to the impact of differing risks of predation on acoustic behaviour. The presence of sympatric orcas, *Orcinus orca*, in Svalbard has been suggested as a possible explanation for the acoustic behaviour seen there, perhaps resulting in echolocation by belugas being restricted to good feeding opportunities inshore to reduce the risk of predation. There is an Inuit term for the behaviour of beluga that follow the coastline that translates as 'travelling in fear or orcas'. Consequently the effectiveness of passive acoustic monitoring will likely also vary by location.

7.4.7 *Heaviside's Dolphin,* Cephalorhynchus heavisidii

Leeney et al. (2011) used T-PODs to monitor Heaviside's dolphins in Walvis Bay, Namibia, and found clicks in the 120–140 kHz frequency range, typical of NBHF (narrowband high frequency) species.

Diel patterns in detections and inter-click intervals are found in most species and locations studied. In this case a diel pattern in click activity was observed, with many more detection-positive minutes per hour recorded between dusk and dawn, and vocalisation activity dropping to low levels in the middle of the day. This corresponded with visual observations made on abundance of dolphins in the study area. A distinct diel pattern to the hourly mean inter-click interval was observed, with higher values during daylight hours than at night, suggesting that click trains are produced at faster rates at nighttime, suggesting that Heaviside's dolphins use this site for foraging at night.

7.4.8 *Deep Divers: Deep C-PODs*

Monitoring at depth with deep C-PODs that can be deployed down to 2000 m has been interesting. A few locations have been studied and all have shown very quiet ultrasound backgrounds. Distant ultrasound sources are inaudible due to absorption, so the record can be amazingly free of tones with very little being logged other than cetacean clicks. The records in Fig. 7.23 were obtained at 900–1000 m in the Mediterranean Sea. The most likely deep-diving species in this area is Cuvier's beaked whale, *Ziphius cavirostris*.

A period of greatly reduced detectability occurs during the day and is associated with a marked increase in inter-click intervals and louder clicks.

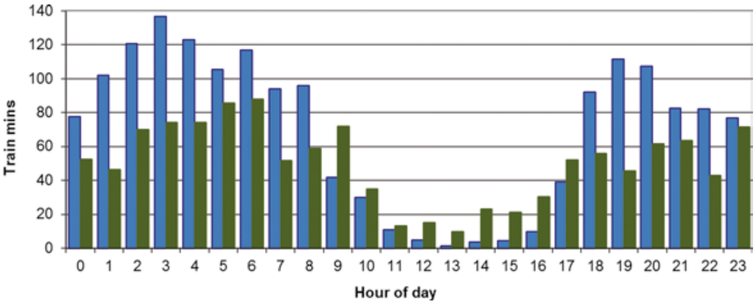


Fig. 7.23 Mediterranean DeepC-POD: Hourly sum of duration of trains detected at two sites over 42 days

Johnston et al. (2008) also found many more clicks, similar to those produced by ziphiid and mesoplodont beaked whales, at night using wideband recordings from a SAM at 395 m depth over the Cross Seamount, Hawaii, while Baird et al. (2008) found different patterns again using loggers on the whales. SAMs for periods of a year or more at different sites are needed to elucidate these different patterns.

7.4.9 Marine Offshore Industries

The Danish National Environmental Research Institute pioneered the use of SAMs to monitor environmental impacts on porpoises using the first T-PODs to monitor the construction of marine wind farms which involves driving massive cylindrical steel piles into the seabed. Tougaard et al. (2009) showed an increase in the median 'waiting time'—the time to the first porpoise detection after the end of this very noisy operation. The gap between detections had increased from 1 to 4 h, but was subsequently followed by an apparently normal pattern of detections.

This effect extended out to 15 km and could be due to porpoises remaining silent or moving away from the source. Visual observations on days with pile driving showed predominantly directional swimming, away from the noise, in contrast to the non-directional swimming that was dominant on days without pile driving. The effect extended to the 10 km limit of the study, and a review by Tougaard et al. (2009) finds evidence from T-POD studies that porpoises respond to pile driving beyond 20 km distant. SAM studies at a wind farm site off the German coast by Dähne et al. (2013a, b) produced similar findings and concluded that a behavioural reaction could be detected using SAM at a much larger distance than a pure avoidance radius would suggest.

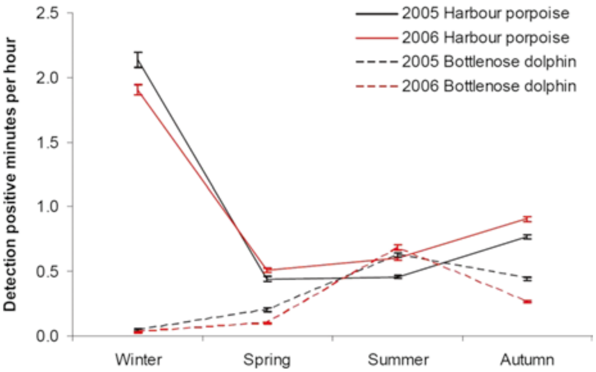
Longer term acoustic studies have also been carried out. At Nysted wind farm in Denmark much greater durations of immediate effect were found (Carstensen et al. 2006) and levels of activity were still low 2 years into operation. The picture is quite different at other sites. Scheidat et al. (2011) report findings of a year's pre-construction baseline study, 2003–2004, of the Dutch offshore wind farm, Egmond aan Zee, followed by monitoring in 2007–2009 when the wind farm was in normal operation. Control sites north and south of the impact site were also monitored. Control and impact sites showed an overall increase in porpoise activity in line with that seen more widely in Dutch waters, but the wind farm site showed a substantially greater increase than the control sites. The authors consider two explanations: (1) an increase in food (reef effect) and/or (2) porpoises avoiding disturbance. T-POD studies of the Horns Reef site in Denmark have also shown increased use by porpoises once in operation.

7.4.10 Harbour Porpoises and Bottlenose Dolphins

A conservation area has been designated in Cardigan Bay, Wales, partly for the conservation of a local population of inshore bottlenose dolphins. It also contains a high density of harbour porpoises. This was the first site to use static acoustic monitoring of dolphins to identify seasonal patterns of use of the conservation area. The seasonal patterns, Fig. 7.24, seen over the first 2 years (Baulch 2008) were strong and apparently stable, with separation of the species in winter but not in summer.

The very different pattern of detection of the two species was also seen in relation to the tidal cycle, Fig. 7.25, and was some of the first evidence of habitat partitioning between these two species, which has particular interest as lethal injuries inflicted by bottlenose dolphin are a major cause of death here among beachcast porpoises (Jepson and Baker 1998). Simon et al. (2010) also found that the T-POD site with the strongest overlap of the two species was close to the location of the peak of strandings of porpoises injured by bottlenose dolphins.

Fig. 7.24 Seasonal detection rates by T-PODs in Cardigan Bay, Wales, for harbor porpoises and bottlenose dolphins



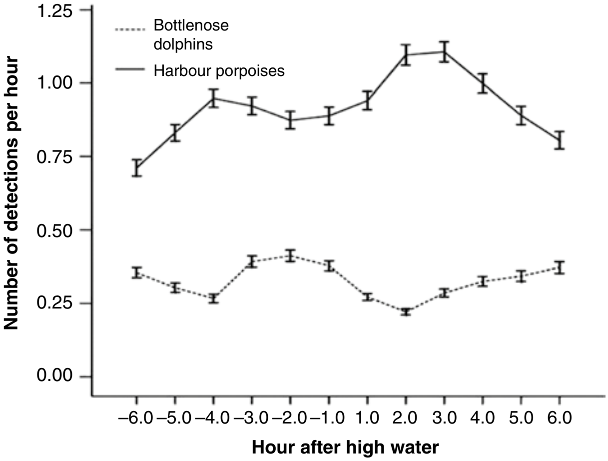


Fig. 7.25 Detection rates by T-PODs of harbour porpoises and bottlenose dolphins through the tidal cycle

7.4.11 Seismic Survey Impacts

The fine spatial resolution of static acoustic loggers has been used to map porpoise distribution changes in response to seismic exploration in the Moray Firth, Scotland, by Thompson et al. (2013). The study period included 10 days of seismic survey in the area, which used a 470 cu in. array, and found evidence of group responses to airgun noise over ranges of 5–10 km, at received peak-to-peak sound pressure levels of 165–172 dB re 1 μPa and sound exposure levels (SELs) of 145–151 dB re 1 $\mu Pa^2 s^{-1}$. However, porpoises were typically detected again at affected sites within a few hours. Acoustic detections decreased significantly during the survey period in the impact area compared with a control area, but the authors conclude that this ‘effect was small in relation to natural variation and that these results demonstrate that prolonged seismic survey noise did not lead to broader-scale displacement into suboptimal or higher-risk habitats, and suggest that impact assessments should focus on sublethal effects resulting from changes in foraging performance of animals within affected sites’. The volume of pre-exposure data that can be obtained through static acoustic monitoring provides valuable quantitative evidence of the level of natural variability against which possible impact effects should be judged.

Pirotta et al. (2014) demonstrated a distance-related decline in the incidence of feeding buzzes recorded on a C-POD array in response to seismic survey activity.

7.4.12 Acoustic Behaviour Around Fishing Gear

Static monitoring has been used to study acoustic behaviour of cetaceans around fishing gear. Lauriano and Bruno (2007) deployed T-PODs opportunistically on different types of fishing gear in Asinara National Island Park, Sardinia, and found that click trains from bottlenose dolphins around striped red mullet trammel nets had click rates that were concentrated around 210–280 clicks per second, with very few below 140 clicks per second, while around other lobster nets and fish traps, click rates were mostly less than 40 clicks per second.

Typical feeding buzzes are often seen in POD data, Fig. 7.26, but where cetaceans are pursuing pelagic prey many more buzzes are seen than when the prey is on or in the seabed and the buzz is 'lost' in the seabed.

This suggests that the dolphins were actively foraging on fish in or near the nets, but the deployment regime did not allow for a control study of the same locations without the fishing gear.

Hernandez-Milian et al. (2008) studied predation by odontocetes on longline fisheries in waters off the Azores and Brazil. Acoustic detection rates, using T-PODs, were low when depredation by false killer whales, *Pseudorca crassidens*, occurred, although high rates of clicks were detected when delphinids were sighted and when false killer whales were by-caught. This suggests that false killer whales were actually not echolocating when feeding on fish hooked on a longline.

7.4.13 Acoustic Behaviour in River Dolphins

Differences in click train characteristics, Fig. 7.27, have also emerged from cetaceans that are not feeding. The two dolphin species found within the Amazon river system have strikingly different behaviour and morphology. The Boto (*Inia geoffrensis*) readily enters the flooded forest to forage, or swims beneath floating

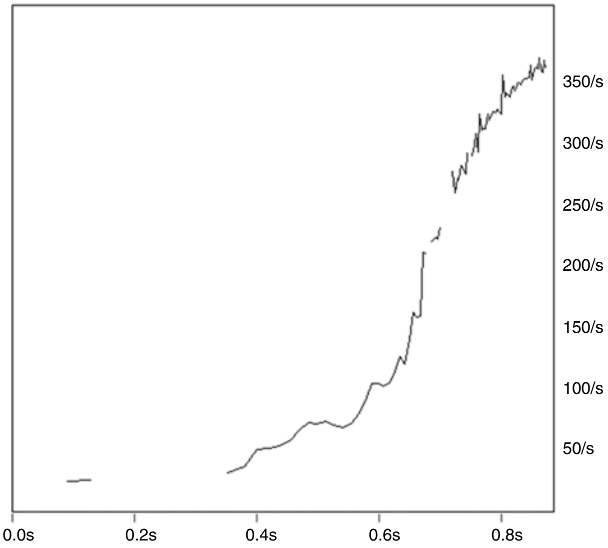


Fig. 7.26 Click rates recorded by a T-POD during a porpoise feeding buzz

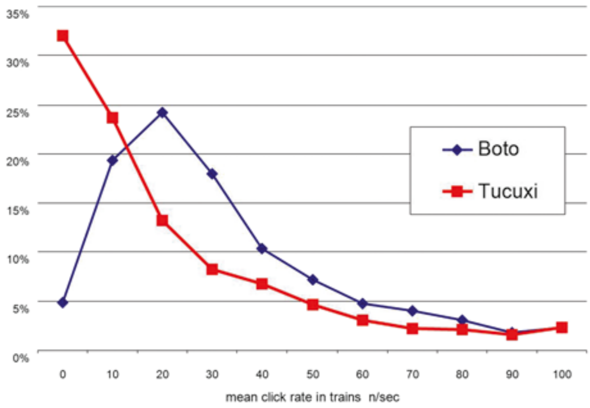


Fig. 7.27 Distribution of click rates in trains produced by Boto and Tucuxi

meadows. It has a long beak, no dorsal fin, large pectoral fins and a very flexible spine and is able to move backwards out of tangles of roots, branches or vegetation.

The smaller Tucuxi (*Sotalia fluviatilis*), by contrast, is very similar to oceanic dolphins and has a dorsal fin. T-POD data, from open water, has shown that slow click-rate trains are used much more often by the Tucuxi than the Boto (Tregenza 2007).

A possible explanation for the use of long inter-click intervals by the Tucuxi is that it must ensure that it does not enter areas where it may become entangled or lost, Fig. 7.28. It therefore needs to maintain a more extensive longer range acoustic picture of the waterways, thus requiring it to click more slowly to allow time for echoes to return from distant features.

In the oceans, the pattern appears to be mostly the other way round, with smaller species, such as porpoises, using low click rates less often than larger species, such as bottlenose dolphins. Those differences fit with the weaker clicks and smaller prey of the porpoise.

7.4.14 Porpoise Communication

Porpoises, like other species producing narrowband high-frequency clicks, do not use whistles to communicate, and there have been relatively few studies of how acoustic social communication is achieved by these species. Amundin (1991), reported in Au and Hastings (2008), described six different patterns of clicking associated with fear, pain, threat, signaling of dominance, sexual display and agonistic behaviour, and Clausen et al. (2011) have provided strong evidence of social communication via click patterns in porpoises. A manual search for these communication patterns, and for feeding buzzes and landmark sequences, was made by Koschinski et al. (2008) in T-POD data from two sources: a long deployment of a T-POD moored near the seabed, and a short data segment from a T-POD that was

Fig. 7.28 High water levels persist for months in parts of the Amazon basin. This fig tree shows the level and the potential for entanglement

about 20 m from a chance entanglement of a wild porpoise calf that happened to be observed. The mother was also entangled in the net but freed herself, while the calf was released by the observers. This study showed clearly that click trains with short inter-click intervals, less than 10 ms, had a social role in wild porpoises but failed to find all of the described patterns, perhaps because static loggers only capture fragments of trains when the animal's sonar beam is pointing in their direction. The development of automated classifiers for social communication would be of great interest, particularly in the context of the very large volumes of suitable data currently being collected.

7.5 Future Directions

Studies using PODs have shown that large numbers of detections are obtained at a low cost per detection, and show good correspondence both with high-resolution acoustic data and with visual survey methods. The rapid expansion in SAM studies throws up a shopping list of information and equipment that would be very desirable.

Species discrimination is limited at present. To maximize the capacity for species identification in long SAM deployments the successor to the C-POD (the C-POD-F, currently under test) employs a train detection algorithm running in real time to select clicks and capture full waveforms of these while saving an expanded summary of each click as the input for a more powerful train detection process.

More information is needed, perhaps from loggers on the animals, on the echolocation activity of those species that do not produce narrowband high-frequency clicks. Ease of deployment and recovery is a key cost issue in SAM studies and developments in integral acoustic releases would be useful to make very light moorings possible. Finally a fuller understanding of how to translate SAM data into local densities, and how to design optimal spatial sampling regimes, would be immensely valuable. The SAMBAH project in the Baltic aims to measure the size of a small thinly spread population, and the results will be of great interest!

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Chapter 8
PALAOA: The Perennial Acoustic Observatory in the Antarctic Ocean—Real-Time Eavesdropping on the Antarctic Underwater Soundscape

Holger Klinck, Lars Kindermann, and Olaf Boebel

Abstract The Perennial Acoustic Observatory in the Antarctic Ocean (PALAOA) was developed to study the underwater vocal behavior of cetaceans and pinnipeds and to monitor ambient noise levels in the Southern Ocean. Establishing an autonomous long-term observatory in Antarctica is challenging mainly because of the harsh weather conditions and logistic constraints. The project goal was to build an autonomously operating, passive-acoustic observatory which allows scientists (1) to reliably and continuously record the Antarctic underwater soundscape year-round, (2) to record all vocalizations produced by marine mammals in the study area (frequency range of the recordings: 10 Hz to 96 kHz), (3) to locate vocalizing marine mammals and other underwater sound sources, (4) to obtain information on ambient noise levels in the area, and (5) to access and analyze the incoming acoustic data stream in real time at the Alfred Wegener Institute for Polar and Marine Research (AWI) located in Bremerhaven, Germany.

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8.1 Introduction and Motivation

The Southern Ocean[1] provides a nearly pristine habitat to a great variety of marine mammals, birds, fishes, invertebrates, microorganisms, and plants, of which many are endemic to this region. For most, only rudimentary information is available, as research is seriously hindered by the region's remoteness and extreme environmental conditions such as the formation of sea ice, low temperatures, and lack of daylight during polar winter. The sea ice around Antarctica covers, at its maximum extension during austral winter, approximately 20 million km^2 (Fig. 8.1).

During austral summer, when the solar radiation reaches maximum intensity, the ice-covered area shrinks to four million km^2 (Kaiser et al. 2005). Light conditions alternate between continuous daylight during summer and complete darkness for up to 5 months (depending on latitude) during winter (El-Sayed 1971).

The Southern Ocean is presumably the last refuge for the marine megafauna from anthropogenic influences (Smetacek and Nicol 2005). Yet, there are extraordinarily large gaps in our knowledge of many Antarctic marine mammal species as exemplified by our current and quite limited understanding of the distribution of Arnoux's beaked whales (*Berardius arnuxii*), which is based on sparse visual sightings (Fig. 8.2).

While even limited information is an important piece in the investigation of the impacts of environmental changes—such as those induced by global warming—in the Southern Ocean, it is not at all sufficient for any accurate assessment on the abundance and distribution of marine mammals in the region. Collecting additional data on marine mammals is essential because as top-level predators their movement patterns, abundance, and distribution are an effective reflection on the health of the larger Southern Ocean ecosystem. How can reliable data be collected in this hostile and difficult-to-access environment?

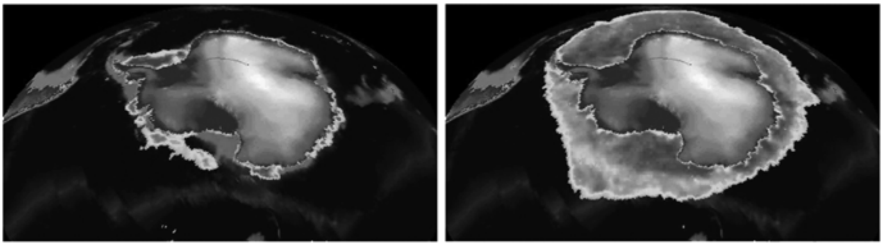

Fig. 8.1 Sea ice concentration around Antarctica in austral summer (end of February—*left side*) and winter (end of September—*right side*)—derived by satellite imagery. Image source: http://earth.rice.edu/mtpe/cryo/cryosphere/topics/sea_ice/antarctic_sea_ice.html

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[1] *Definition*: *The Southern Ocean, also known as the Antarctic Ocean or the South Polar Ocean, is, by definition of the International Hydrographic Organization, the oceanic division encircling Antarctica. It comprises the southern-most waters of the world's oceans south of 60° S latitude.*

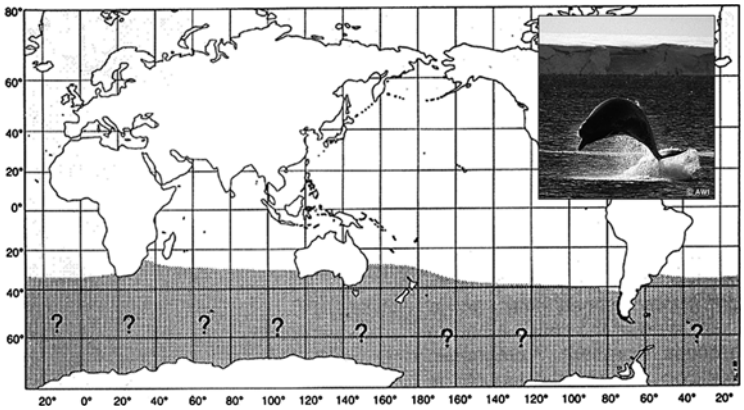

Fig. 8.2 Supposed distribution of the Arnoux's beaked whale (*Berardius arnuxii*). Map source: Jefferson et al. (1993). Image source: Dr. Joachim Ploetz, Alfred Wegener Institute

One particular research method has emerged that effectively overcomes these challenges: passive acoustic monitoring (PAM) (Tyack 1998; Richardson et al. 1995). Many marine mammals regularly use sound underwater for communication, navigation, and prey detection. Thus, PAM has the potential to provide year-round information on the presence/absence of (vocalizing) animals, independent of weather conditions and without direct visual observations (Mellinger et al. 2007). Depending on the frequency and intensity of the vocalization, the vocal behavior of marine mammals can be investigated, under favorable sound propagation conditions, within a range of up to a few kilometers (for ultrasonic vocalizations) to a few hundred kilometers (for infrasonic vocalizations) around a hydrophone (Sirovic et al. 2007). Furthermore, the use of PAM in the Southern Ocean in particular allows scientists to investigate the acoustic behavior of marine mammals and ambient noise levels in an environment almost undisturbed by humans.

In December 2005, the Alfred Wegener Institute for Polar and Marine Research (AWI), Germany, established an autonomous listening station named PALAOA[2] (*P*erenni*AL* *A*coustic *O*bservatory in the *A*ntarctic Ocean) in the eastern Weddell Sea close to the German Antarctic research base Neumayer Station. The project goal was to develop an autonomously operating observatory which records the Antarctic underwater soundscape year-round and continuously covers a frequency range between 10 Hz and 96 kHz, and allows real-time access to the acoustic data. The collected data are used to study the acoustic ecology of marine mammals as well as the ambient noise levels in this pristine environment. Additional sensors such as an AIS receiver also allow scientists to study potential impacts of human activities on the Antarctic marine environment.

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[2] *PALAOA = Hawaiian; means (sperm) whale, whale tooth*

8.2 Environmental Conditions

Meteorological observations have been carried out at Neumayer Station since 1993. These are regularly contributed to the World Meteorological Organization (WMO) network Global Atmospheric Watch and provide basic weather forecast information for the DROMLAN[3] flight network. At Neumayer Station, monthly mean wind speeds at 10 m height range between 6.7 m s^{-1} in January and 10.1 m s^{-1} in August. In general, wind speeds are significantly higher during the austral winter months. However, occasional wind speeds exceeding 40 m s^{-1} (144 km h^{-1}) can occur year-round. Meteorological observations show that during the austral winter months (June to September) the mean monthly temperatures drop below −22 °C with mean monthly minimum temperatures ranging between −39.6 and −41.8 °C. The Antarctic continent is covered by an ice sheet (i.e., glacier) which reaches a thickness of more than 4000 m in central Antarctica. The ice sheet slowly floats (caused by gravity) towards the coast and into the ocean, predominantly along so-called ice streams. At the grounding line, the ice sheet detaches from the seafloor and starts to float on the ocean. This floating part of the glacier—which features a thickness between 500 and 1000 m at the grounding line (in the Dronning Maud Land Area) and several tenths of meters at its oceanic edge (Steinhage et al. 1999)—is called the ice shelf. Parts of this floating ice shelf regularly break off, a process termed calving. Thus, both small chunks of ice and icebergs measuring many hundreds of square kilometers are formed. The icebergs continue drifting with the predominant current into warmer regions where they melt. The ocean area directly adjacent to the ice shelf edge is most important for the formation of sea ice. Cold offshore winds from the high continental plateaus (so-called katabatic winds) push the sea ice offshore. Within the resulting area of open water, or polynya, intense air-sea exchange of heat leads to cooling of surface waters and formation of new sea ice. As a result, water of high density (low temperature and high salinity) is formed which contributes to the formation of Antarctic bottom water (Fahrbach and Rohardt, 2008). Figure 8.3 depicts the predominant glaciological and oceanographic processes of the Antarctic coastal ocean and ice shelf.

8.3 Challenges and Design

To get an overview of the seasonal variation of the vocal activity of marine mammals, continuous, long-term recordings covering all seasons are essential. This requires both year-round energy supply and access to the ocean. For the power supply of PALAOA a battery bank charged by a combination of solar panels, a wind generator, and a methanol fuel cell ensures year-round operation. Because of the lack of sunlight during austral winter, PALAOA cannot be

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[3] http://dromlan.org

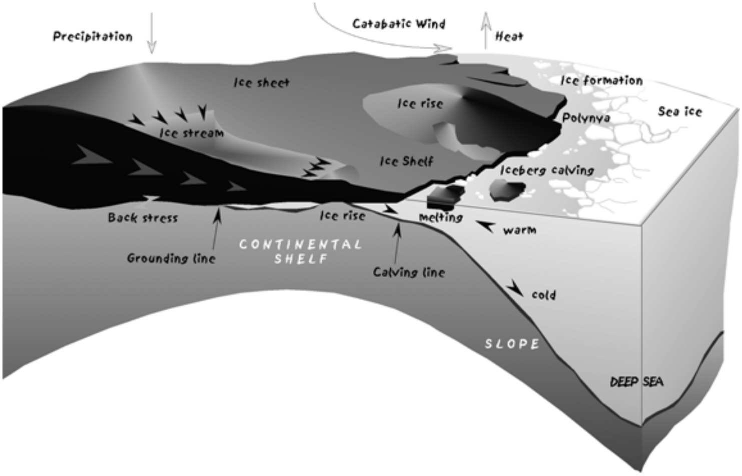

Fig. 8.3 Sketch of the Antarctic coast with glaciological and oceanographic processes. Terms are described in the main text. Image source: Dr. Hannes Grobe, Department of Geosciences, Alfred Wegener Institute

exclusively powered by solar panels. Wind generators can close this energy gap during austral winter, as meteorological conditions with high wind speeds occur more frequently during this season. Occasional gaps of low winds during wintertime darkness are bridged by the use of a methanol fuel cell. During austral winter, all electronic equipment and installations have to endure low temperatures of up to −50 °C on a regular basis. The most severe impact of these low temperatures is their influence on the battery capacity: below −30 °C the usable capacity of lead batteries will typically be less than 10 %.

Placing PALAOA close to the ice shelf edge maximized the reception probability of vocalizations because of the short distance between the hydrophones and marine mammals migrating within the coastal polynya (Figs. 8.3 and 9.4).

However, long-term hydrophone deployments over the ice shelf edge are not feasible due to the high potential of damage by calving of the ice shelf or passing icebergs. Furthermore, fast or sea ice deployments would not sustain year-round observations due to summer melting and autonomous recording units moored at the seafloor do not provide real-time access and are threatened by grounding icebergs. Therefore, we decided to place the infrastructure of PALAOA inside a container on top of the ice shelf, and drill holes through the ice to install hydrophones in the water below. To reduce the risk of losing the station due to break-off—the steady advance of the Ekstrom Ice Shelf results in break-offs of ~150 m per year on average—data from previous airborne radio-echo sounding surveys were consulted. These indicated an ice thickness between 80 and 200 m on the ice shelf north of Neumayer Station (Fig. 8.4). Satellite interferometric imagery indicated that the northernmost protrusion of the ice shelf exhibited little shear—a favorable condition for long-term stability without putting stress on the cables inside the ice.

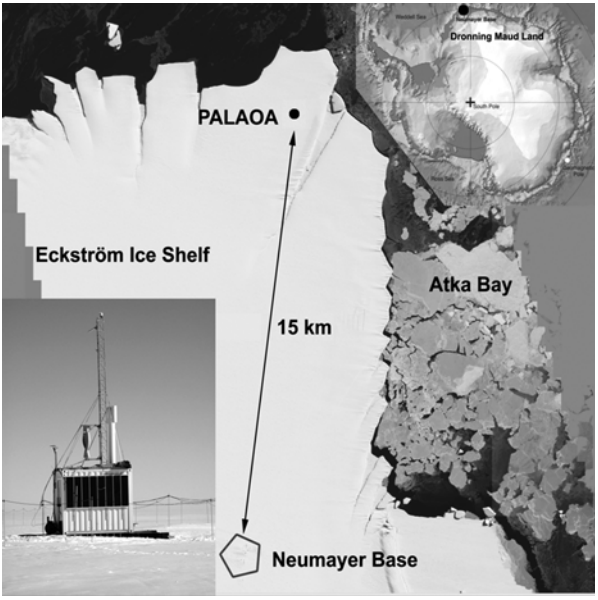

Fig. 8.4 Location and picture of PALAOA. Source of satellite image: Google Earth. The satellite image was taken 14 March 2006

Anticipating the need of regular maintenance of the observatory, particularly during its first few years of operation, feasible access from Neumayer Station at 70°40′S and 8°16′W using a snow crawler, was considered a necessary constraint on PALAOA's possible location.

To transmit the data in real time from the ice shelf edge to Neumayer Station (distance ~15 km), a radio link was established. The topography of this area is flat and the stations are within sight. This allows for a point-to-point connection without the need of a relay station. Real-time access allows the analysis of acoustic data (quasi) instantaneously and year-round without the need of retrieving physical data storage units. Most importantly, the real-time connection permits continuous monitoring of the station, alerting service personal at Neumayer Station to malfunctions.

To deploy the hydrophones in the water body below the ice shelf, a hot water drilling operation was conducted to penetrate the 100 m thick ice shelf. The hot water drilling system was designed by the AWI and first used in 1993 (Nixdorf et al. 1994). Drilling a single hole took around 12 h of continuous operation.

In the original setup, the PALAOA array consisted of four hydrophones arranged in a flattened tetrahedron configuration with a 500 m baseline. However, during the first 6 months of operation, two hydrophones failed for unknown reasons. The remaining two hydrophones (type Reson TC4032 and Reson TC4033; each connected to a Reson VP2000 amplifier/filter) are spaced 300 m apart. A 3D sketch of the PALAOA hydrophone array is presented in Fig. 8.5. In addition a CTD sensor measuring conductivity, temperature, and depth was deployed to obtain information on ocean currents and sound propagation conditions.

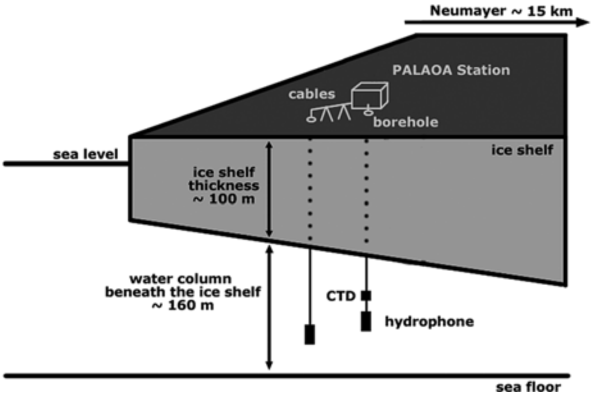

Fig. 8.5 3D sketch of the PALAOA hydrophone array

To be able to control the station remotely from Germany, a microcontroller (type BARIX Barionet 100), equipped with relays and I/O modules, was installed. This device is freely programmable (in BASIC) and allows an operator to turn on/off all devices in the observatory remotely from Germany. This is very useful as the station's energy consumption can be adjusted according to the available supply. For real-time data access a WLAN point-to-point connection between PALAOA and Neumayer Station was established. Maximum bandwidth of the WLAN radio link is around 2.5 Mbit/s.

The design goal for the acoustic module was to acquire continuous, long-term, and broadband (frequency range usually 10 Hz to 15 kHz, up to 96 kHz on demand) recordings of the Antarctic underwater soundscape. However, because of the energy shortage during austral winter and the limited bandwidth of the WLAN radio link, two acoustic systems are operated in parallel.

The high-quality digitizing system consists of an industrial PC with an external FireWire studio-grade soundcard (MOTU Traveler). This enables sampling of the two hydrophone signals at rates of up to 192 kHz at 24 bit. In parallel a 1 pps signal provided by a GPS receiver is recorded on a third channel for accurate time stamping of the audio files. The MOTU data are recorded on a PC with software specifically developed for the PALAOA project. This program (called AsioRecorder) is a stable recording software supporting audio stream input/output (ASIO) multichannel drivers. The recorded, high-quality data are stored locally on an exchangeable high-capacity hard disk which is sent to Germany once a year via ship or airplane. Selected files of interest can be accessed via FTP (file transfer protocol) from PALAOA to Neumayer Station receptively the AWI in Germany at any time.

This system (incl. WLAN link etc.) consumes about 53 W in total, which often exceeds the power limitations of the energy module during wintertime. For this reason, a second low-power audio module was installed in parallel. Signals of the two hydrophones are additionally routed into a stream encoder (type BARIX Instreamer 100), which provides a compressed 192 kBit/s MP3 stream of reduced bandwidth (10 Hz–15 kHz). This approach minimizes the power consumption of the entire system to about 15 W. The MP3 data stream is transmitted continuously

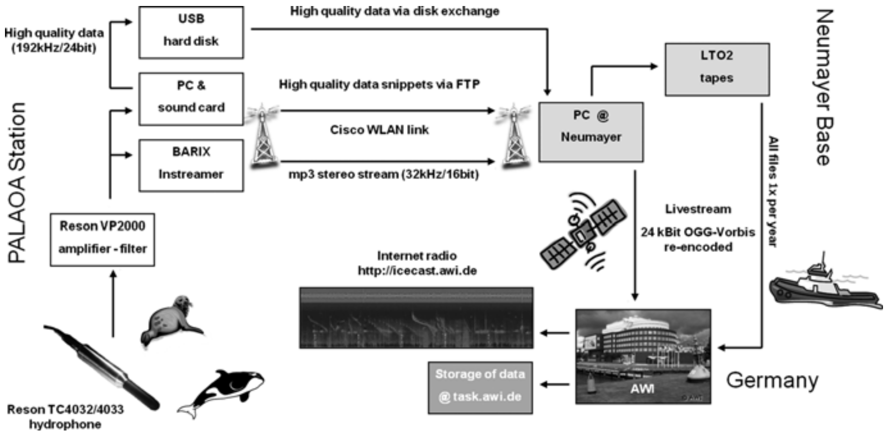

Fig. 8.6 Flowchart PALAOA acoustic data streams

via the established WLAN link to Neumayer Station. At Neumayer Station, these data are saved as time-stamped 1-min files for later shipment to Germany, and additionally re-sampled to an OGG-Vorbis compressed audio stream (24 kBit/s) and transmitted in real time via IntelSat satellite link to the AWI in Germany. This allows scientists to monitor and analyze the data almost instantaneously in the lab. An overview of the PALAOA data streams is given in Fig. 8.6.

8.4 Data Management and Analysis

PALAOA was intended to continuously record the Antarctic underwater soundscape. Consequently, the station is producing large amounts of data. As described, the PALAOA recordings are being sent continuously via IntelSat satellite link to the AWI in Germany. The highly compressed OGG-Vorbis audio stream is segmented and stored as time-stamped, 1-min files on a server located at the AWI. Once a year, this extremely compressed audio data are replaced by the MP3 files, which are stored on hard disks and shipped from Neumayer Station to Germany.

MP3 files of 1-min duration have an approximate file size of about 1.25 MB. Thus, during 1 day (year) of continuous operation 1440 files (525,600 files) and 1.7 GB (620 GB) of data are generated. This estimation is for the MP3 stream data only. Broadband data recorded with the high-quality digitizing system during polar summer (high biotic activity and no power constraints) are not included in this budget. The amount of additional data (webcam pictures, CTD data, GPS data, AIS data, operating data, meteorological data, and network statistics) is about 300 MB (110 GB) per day (year). Additionally, spectrograms covering 1 min, 5 min, 1 h, and 1 day of acoustic data are generated continuously using the Spectrum Lab[4] software

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[4] http://www.qsl.net/dl4yhf/spectra1.html

and stored as jpeg images to allow for fast visual screening of the incoming data. Since start of operation in December 2005 a total of ~10 TB of data were collected and stored in the AWI data silo.

All PALAOA recordings consist of standard multimedia files (.wav, .flac, .mp3, and .ogg). They are kept transparent on a network drive and can easily be accessed/ viewed with standard audio software. However, the sheer amount of files makes it hard to analyze longer periods as no commercially available software can load a million sound files at once. An application called PALAOAdb was developed in Matlab™ to allow users easy access to the dataset from a timeline- or event-oriented view. PALAOAdb periodically updates its database by analyzing the most recent recordings to provide an up-to-date display. The initial view is a plot of several selectable parameters for the entire recording period. Available are sound-specific measures like RMS or peak sound level, and other environmental observations like air and water temperature or tidal current. Also, the results of analyses like pattern recognition algorithms can be selected. Users can zoom in and click on the timelines to open single files, either with a built-in player and spectrogram viewer or via any external program like Ishmael,[5] XBAT,[6] or Triton.[7] PALAOAdb provides displays to visualize parameters and results from the entire data set. It takes about 1 s to load and process a single MP3 file with the basic procedures. Thus an off-line analysis can be done in up to 60 times real-time speed. PALAOAdb is easily extendable as new algorithms can be implemented as Matlab functions. Also, PALAOAdb will create timeline views from the results of the analyses.

To speed up processing of long-term data sets (e.g., several years of recordings), PALAOAdb was extended with a parallel computing system that allows users to distribute the analysis across multiple computers. An executable program called PALAOAdb-worker—which contains, for example, a detection algorithm for a specific marine mammal call—can be compiled in PALAOAdb. PALAOAdb-worker is a stand-alone application which can run on any computer. There is no Matlab installation necessary. PALAOAdb generates a to-do list which contains a list of all files to analyze. The to-do list and the data sets are located on a server (or multiple servers) within a local area network. The principal configuration of the parallel computing system is given in Fig. 8.7.

Any computer in the local area network running PALAOAdb worker is repeatedly connecting to the central server and checking the to-do list for open jobs. Once an open job is detected, the corresponding data set is transferred to the worker which conducts the analysis and sends the results back to the central server. In a final step, PALAOAdb collects all results and compiles them for further analysis.

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[5] http://www.bioacoustics.us/ishmael.html

[6] http://www.birds.cornell.edu/brp

[7] http://cetus.ucsd.edu/technologies_Software.html

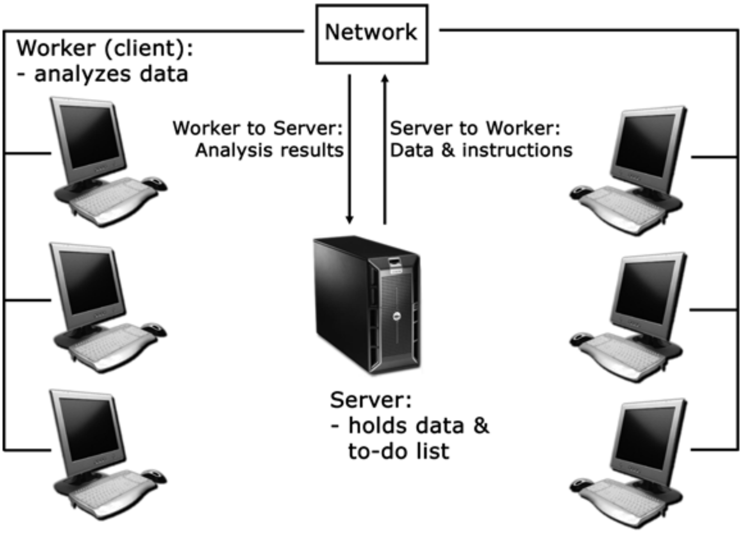


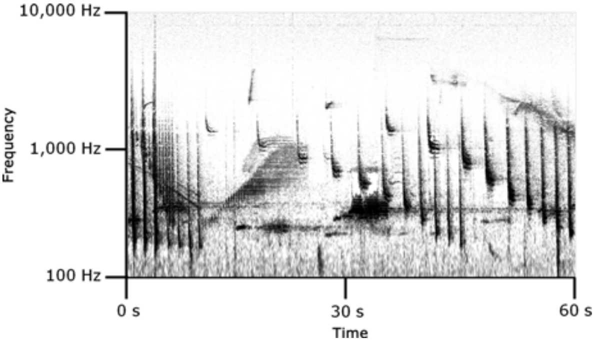
Fig. 8.7 PALAOAdb—a parallel computing system

As there is no inter-process communication between the workers, the speed scales linearly with the number of nodes, as long as the network and the file server are not saturated by fetching the audio files. With a size of 1.25 MB per 1-min MP3 file, a 100 MBit/s network can handle up to ten files per second. Thus, it is possible to scan a year of data with basic detectors in less than a day by running ten clients in parallel. This, of course, scales with the complexity of the conducted analysis.

8.5 Results

As of October 2013 PALAOA has recorded more than 50,000 h of multichannel audio data. The PALAOA recordings have revealed a high degree of biotic and abiotic acoustic activity in the Southern Ocean during all seasons, dominated by the vocalizations of Weddell seals (*Leptonychotes weddellii*), Ross seals (*Ommatophoca rossii*), crabeater seals (*Lobodon carcinophaga*), and leopard seals (*Hydrurga leptonyx*), as well as various cetaceans (blue whales, *Balaenoptera musculus*; fin whales, *Balaenoptera physalus*; humpback whales, *Megaptera novaeangliae*; Antarctic minke whales, *Balaenoptera bonaerensis*; and killer whales, *Orcinus orca*) and ice-generated noise. Figure 8.8 shows a typical spectrogram recorded with the PALAOA observatory in December 2007.

Fig. 8.8 Typical spectrogram of the underwater soundscape recorded with the PALAOA observatory in December 2007. Spectrogram shows various call types produced by Weddell seals and leopard seals



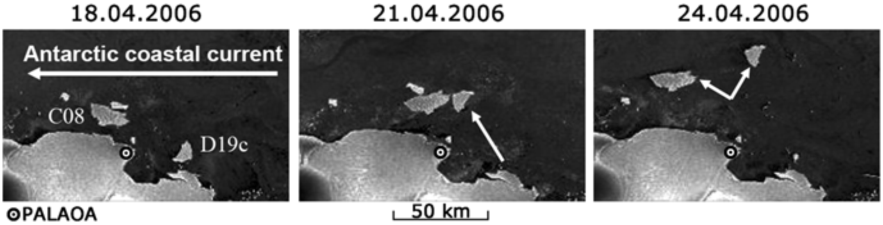


Fig. 8.9 Collision of two icebergs (C08 and D19c) close to the PALAOA observatory, Antarctica. Source of satellite images: European Space Agency, ENVISAT-ASAR

8.5.1 *Selected Research Highlights: Ambient Noise*

In April 2006 PALAOA recorded the collision of a grounded iceberg (C08) and an iceberg drifting (D19c) with the Antarctic coastal current (ACC), concurrent with supporting satellite imagery (Fig. 8.9).

The estimated source level and sound exposure level (at the source) of the acoustic event (10-min duration) were approximately 200 dB re. 1 μPa at 1 m and 228 dB re. 1 $\mu Pa^2 s$, respectively. This observation revealed that iceberg collisions are one of the loudest acoustic events in the Southern Ocean (Boebel et al. 2008).

8.5.2 *Leopard Seals*

Previous studies (on other leopard seal populations around Antarctica) reported that leopard seals predominately reside in the vicinity of penguin colonies during January and February when the inexperienced chicks enter the water for the first time (Lowry et al. 1988; Siniff 1991). However, the results of the acoustic observations made with PALAOA suggest that they migrate towards our study area as early as September, possibly to feed on adult foraging emperor penguins. The period of observed vocalizations is surprisingly well matched with the period when both penguin parents start to undertake regular foraging trips and move between the colony and their oceanic feeding areas to feed their chicks (unpublished data by Dr. J. Ploetz, AWI). The continuous presence of a substantial number of birds in the ocean is likely to provide an attractive feeding spot for leopard seals in the nearby vicinity of PALAOA (Klinck 2008).

8.5.3 Pinniped Vocal Behavior

The timing of vocal activity of the four ice-breeding pinniped species that occur near PALAOA (leopard seals, Weddell seals, Ross seals, and crabeater seals) shows a strong seasonal cycle with little interannual variation (Van Opzeeland et al. 2010). Furthermore the PALAOA continuous long-term recordings revealed quasi-permanent bioacoustic activity during the species-specific periods of peak vocal activity (Van Opzeeland et al. 2010).

8.5.4 Pinniped Vocal Repertoire

The PALAOA recordings made possible the first detailed description of the long-range vocal repertoire and acoustic behavior of the crabeater seal (Klinck et al. 2010) and Ross seal (Seibert 2007).

8.5.5 Cetacean Presence

A recent study by Van Opzeeland et al. (2013) focused on the acoustic presence of humpback whales in the vicinity of PALAOA in 2008 and 2009. Results indicated that calls were recorded during 9 and 11 months of 2008 and 2009, respectively. In 2008, humpback whale vocalizations were present in January through April, June through August, November and December, whereas in 2009, calls were present throughout the year, except in September. The detection radius of the recorded calls was estimated to be in the order of 100 km. The presence of vocalizations during austral winter demonstrates that the year-round ice-free polynyas near the Antarctic continent are likely of greater importance to humpback whales than previously assumed.

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Chapter 9
Listening for Whales at the Station ALOHA Cabled Observatory

Julie N. Oswald, Helen Ou, Whitlow W.L. Au, Bruce M. Howe, and Fred Duennebier

Abstract The Station ALOHA Cabled Observatory (ACO) is an ocean-bottom observatory that allows continuous real-time monitoring of ocean processes including sounds produced by baleen whales. Baleen whales can be challenging to study using traditional visual methods due to their cryptic behavior and offshore ranges. Many baleen whales produce distinctive sounds that propagate well under water and so ocean-bottom hydrophones like the one at the ACO can be used to investigate the occurrence and acoustic behavior of these animals in locations that are difficult to access and study long-term using other methods. We examined 12 months of recordings from the ACO (February 2007–February 2008) and found that sounds produced by blue, sei, and minke whales all occurred seasonally between October and April. Low-frequency pulses produced by fin whales were detected year-round, although much less frequently during the summer months than during the winter months. These seasonal patterns matched those of humpback whales, who migrate to Hawai'ian waters to breed and give birth. Blue, minke, fin, and sei whales are probably using Hawai'ian waters for breeding, but further research is necessary to confirm this. The ACO has provided, and continues to provide, a long-term dataset for investigating seasonal and diurnal trends in the occurrence of baleen whales and other cetaceans at a location that would be difficult to study any other way.

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9.1 Station ALOHA

9.1.1 What Is the Station ALOHA Cabled Observatory?

The University of Hawaii's Station *ALOHA* Cabled Observatory (ACO) is a seafloor oceanographic observatory that is linked to shore by a fiber-optic cable, which allows continuous, real-time monitoring of ocean processes. To quote the ACO website, it is "one of but a handful of seafloor observatories worldwide connecting deep-sea science directly to the researchers who are working to understand the complex processes that occur there" (http://aco-ssds.soest.hawaii.edu/ALOHA/ACO.html). The ACO is located 100 km north of Oahu, Hawaii (22 45′N 158 W) as shown in Fig. 9.1 and is also the site of the long-term Hawaii Ocean Time-series (HOT) open ocean measurement program. As part of the HOT program, research vessels visit Station ALOHA 10–12 times each year to study physical and biogeochemical properties of the North Pacific Ocean (Karl and Lukas 1996). ALOHA stands for "A Long-term

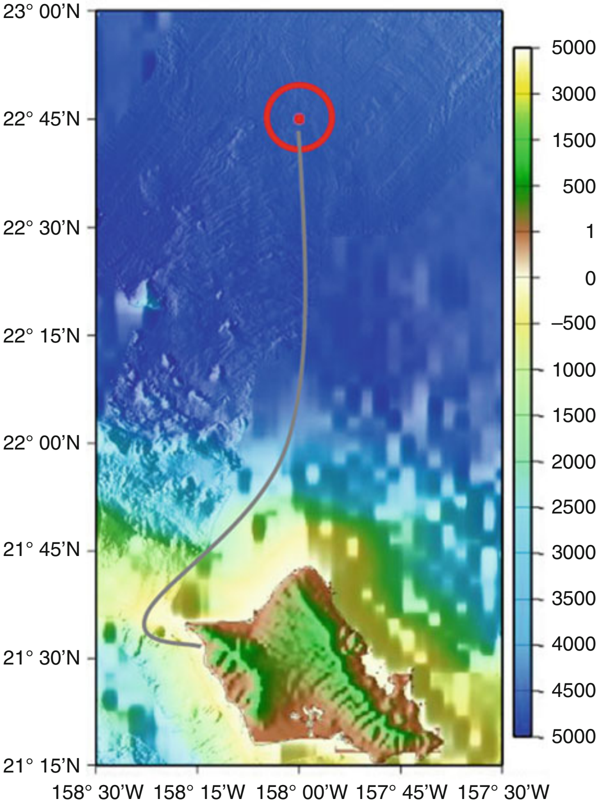

Fig. 9.1 A map showing the location of the Station ALOHA Cabled Observatory and the fiber optic cable connecting the ACO to the AT&T cable station at Makaha, Oahu

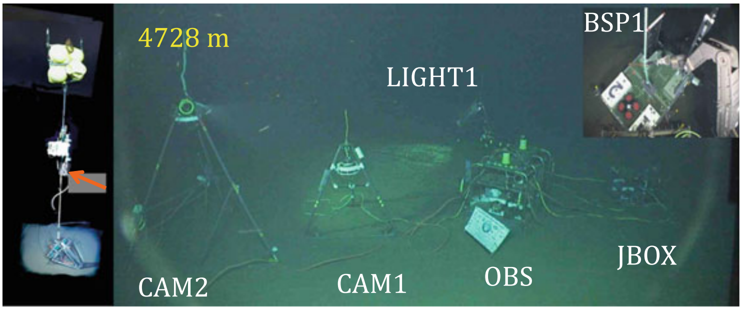

Fig. 9.2 The ACO seafloor system at 4728 m water depth. (*left*) the proof module; the hydrophone is within a PVC vented shroud 10 m above the *bottom*, indicated by the *red arrow*. The *white rectangular* structure just above and to the left is the sea water return electrode, covered with aragonite. Glass ball floats in protective hardhats above keep the mooring line taut. (*right*) the configuration of the seafloor system after the November 2014 service, showing the new camera and lights (CAM2, LIGHT1) and basic sensor package with modem and CTD (BSP1), as well as the JBOX, OBS, and CAM1 deployed in June 2011

Oligotrophic Habitat Assessment"; the ocean here is a "desert" (oligotrophic) and is representative of 70 % of the world's ocean. Because the ACO sits on the seafloor at approximately 4800 m depth, it provides researchers with the opportunity to study deep-sea processes in conjunction with ship-board observations, resulting in the ability to examine this location at all depths (Howe et al. 2015).

The ACO consists of a number of modules (Howe, et al. 2011; Howe 2015), including:

1. Video cameras with lights to record the behavior of deep water animals such as shrimp and sea cucumbers.
2. A thermistor array and acoustic modem to collect temperature profiles of the bottom 200 m of the ocean (deployed 2011–2012).
3. Acoustic Doppler profilers to measure ocean currents.
4. Temperature and conductivity sensors (MicroCat CTD) for continuous observations of temperature, salinity, and dissolved oxygen.
5. Several hydrophones for continuous acoustic monitoring.
6. A pressure sensor (Howe et al. 2011).

Several pictures of the underwater unit of the ACO are shown in Fig. 9.2. The ACO modules are connected to shore via a retired AT&T HAW-4 electro-optical cable (Duennebier et al. 2012), which allows continuous, real-time oceanographic observations. A junction box (JBOX) at the termination point of the cable converts fiber-optic communication signals to Ethernet signals, which are then distributed by the observatory module (OBS) with low voltage power to eight user ports (Howe et al. 2011). The cable comes ashore at the AT&T station at Makaha, Oahu (Fig. 9.1). Real-time displays of temperature, salinity, currents, pressure, acoustic "seismograms," audio and video are available on the Station ALOHA website http://aco-ssds.soest.hawaii.edu/dataDisplay.php.

9.1.2 History of the ACO

In February 2007, scientists from the University of Hawaii's School of Ocean and Earth Science and Technology (SOEST) and the 513 ft Navy cable repair ship, *Zeus*, grappled a retired AT&T HAW electro-optical cable from the seafloor where it had lain for almost 20 years. They cut the cable and moved the Hawaii end to the location of Station ALOHA (Howe et al. 2011). When the cable had been relocated, the Navy ship *Zeus* lowered the "proof module" frame, which contained a hydrophone and pressure sensor. On February 16, 2007, the proof module began to send acoustic signals from the ACO back to the AT&T receiving station on Oahu. The proof module collected data nearly continuously for 20 months until it was removed in October 2008 to install more instruments and add capabilities to the observatory, e.g., user ports with power and Internet connectivity (Duennebier et al. 2012). Unfortunately, a dry-mate fiber-optic connector on this new observatory module failed, so it had to be recovered and returned to land for repair.

Repair and reinstallation of the ACO was delayed due to funding challenges. Finally, in May 2011, a redeployment mission commenced. On June 6, 2011, using the remotely operated vehicle (ROV) *Jason*, SOEST scientists successfully reinstalled the observatory at Station ALOHA. This time, the observatory contained a more extensive collection of instruments that allowed real-time visualization of the seafloor, monitoring of sound in the ocean, and measurements of temperature, salinity, and currents. The ACO has been continuously in operation since that time, and continues to evolve. In November 2014, a cruise was conducted to repair and expand the bottom instrumentation; the resulting bottom configuration is shown in Fig. 9.2. This configuration includes a new camera system with lights and hydrophone, a pumped conductivity, temperature and oxygen sensor, and an acoustic modem. The latter will serve double duty as an inverted echosounder to measure the depth averaged temperature.

9.1.3 ACO Hydrophones

The ACO is equipped with several hydrophones that detect sounds produced by marine animals, environmental processes such as rainfall and water movement, and earthquakes. One of the hydrophones (OAS Model E-2PD) has a frequency response of 0.01 Hz to 8 kHz (Howe et al. 2011). The other, uncalibrated hydrophone was home-built using a 1 cm piezoelectric ceramic element. This hydrophone has a frequency response of 0.1 kHz to 48 kHz (Ethan Roth, 2013, unpublished data). Both hydrophones are mounted 1 m off the seafloor and are spaced 1 m apart (Ethan Roth, 2013, unpublished data). Gain and filter settings for the hydrophones can be changed via an ACO user interface (Howe et al. 2011). Only data from the E-2PD hydrophone was used for the work described in this chapter.

Signals from both of the ACO hydrophones are recorded by a computer located at the AT&T Makaha cable station on Oahu using a 96 kHz sampling rate. These data are buffered at the Makaha cable station on a RAID system and are transferred in near-real time to the University of Hawaii-Manoa for archiving. The 96 kHz sample rate data are also decimated into 24 kHz datasets and are transmitted via TCP/IP to the University of Hawaii-Manoa in real-time (Duennebier et al. 2012). Real-time streaming audio and spectrographic displays are available at the ACO website (http://aco-ssds.soest.hawaii.edu/dataDisplay.php).

9.2 Baleen Whales at the ACO

Many species of baleen whales travel in small groups, exhibit cryptic behavior at the sea surface and spend a large proportion of their time under water. As a result, these animals can be challenging to study using traditional visual methods. In addition, much of the range of baleen whales includes offshore waters that are difficult to access with ships, especially for long periods of time. Fortunately, baleen whales produce low-frequency sounds that propagate well under water. In many cases, these sounds are quite distinctive and it is possible to identify them to species with a high degree of confidence. These distinctive, low-frequency sounds provide an alternative method for investigating the occurrence and behavior of elusive species and the ACO provides an excellent tool for taking advantage of these sounds. Acoustic data from the ACO are recorded continuously, providing a long-term dataset for investigating seasonal and diurnal trends in the occurrence of baleen whales at a location that would be difficult to study any other way. In the following sections, we describe our investigation of the occurrence of sounds produced by baleen whales at the ACO hydrophone.

9.2.1 Characteristics of Baleen Whale Sounds Recorded at the ACO

The baleen whale species that occur near Station ALOHA include blue whales (*Balaenoptera musculus*), fin whales (*B. physalus*), minke whales (*B. acutorostrata*), and sei whales (*B. borealis*). All of these species produce sounds that can be identified to species with a relatively high degree of confidence, although there is some uncertainty about the acoustic repertoire of Pacific sei whale. Humpback whale (*Megaptera novaeangliae*) song can also be heard on the ACO hydrophone; however, we decided to focus our attention on the other four species of baleen whales because there have been over 40 years of research on humpback whales, resulting in a tremendous amount of accumulated knowledge of this species compared with the almost nonexistent knowledge of the other species in Hawai’ian waters.

Blue whales produce sounds that have slightly different characteristics in different oceans of the world. Two characteristics that are common to blue whales in all oceans are the low tonal fundamental frequency between about 15 and 20 Hz and the long duration between 10 and 20 s (Stafford, Chap. 2; Cummings and Thompson

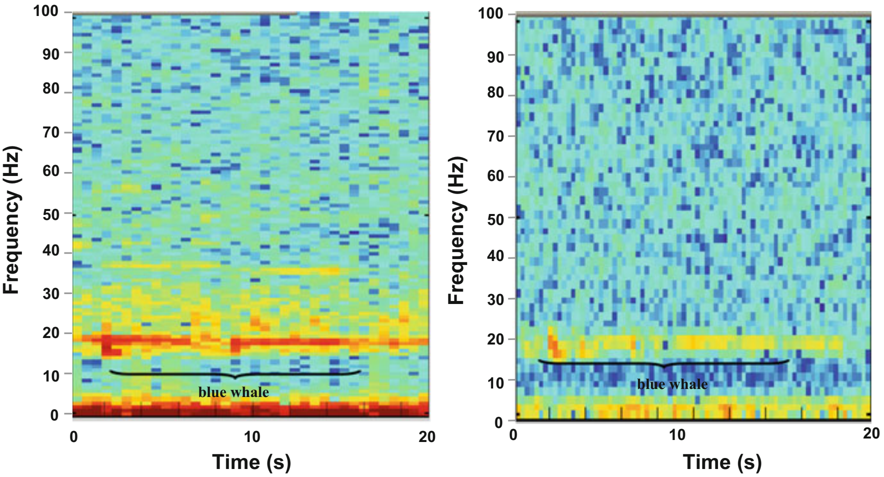

Fig. 9.3 Spectrograms of two blue whale calls recorded at the Station ALOHA hydrophone. The fundamental at 18 Hz and the 2nd harmonic at 36 Hz can be seen on the left spectrogram. The spectrogram on the right only contains the fundamental

1971, 1994; Oleson et al. 2007a, b). In addition to long duration tonal sounds, blue whales also produce stereotyped calls in two-part "AB" phrases where "A" is a series of pulses and "B" is a long, low-frequency tonal sound (see Fig. 2.2 of Stafford, Chap. 2). Spectrograms of two blue whale calls recorded at the ACO are shown in Fig. 9.3. The low-frequency (around 20 Hz and lower), tonal nature of the calls and the long duration (about 14 s) of the calls can be seen in these two examples.

Fin whales produce slowly varying, frequency modulated (FM) pulses of sound that start at approximately 25 Hz and decrease to approximately 17 Hz over a duration of 0.6–0.7 ms (Fig. 9.4). These sounds are known as "20 Hz" pulses. Fin whales produce 20 Hz pulses singly, in irregular series and as stereotyped bouts of repetitive sequences (Watkins et al. 1987). Fin whales also produce steeper FM downsweep pulses that start between 30 and 40 Hz and sweep down to slightly below 20 Hz over a duration of approximately 1 s (Cummings and Thompson 1994).

Very few recordings of sei whales exist. Thompson et al. (1979) reported that sei whales produced a sonic burst of 7–10 metallic-like sounding pulses with energy at peak frequency of 3 kHz. The train of pulses lasted 0.7 s with each pulse being about 4 ms in duration. Knowlton et al. (1991) reported sei whale sounds that consisted of two phrases of 0.5–0.8 s duration spaced about 0.4–1 s apart. Each phrase was composed of a series of 10–20 FM sweeps in the range of 1.5–3.5 kHz and lasting about 30–40 ms/sweep. However, later studies indicated that one of the predominant calls produced by sei whales is a downswept FM signal starting around 100 Hz and decreasing almost linearly to about 38 Hz (Rankin and Barlow 2007; Baumgartner et al. 2008). Spectrograms of two calls assumed to be produced by sei whales detected with the ACO hydrophone are shown in Fig. 9.5. The sei whale downsweep FM signals in the figure start at approximately 100 Hz and sweep down

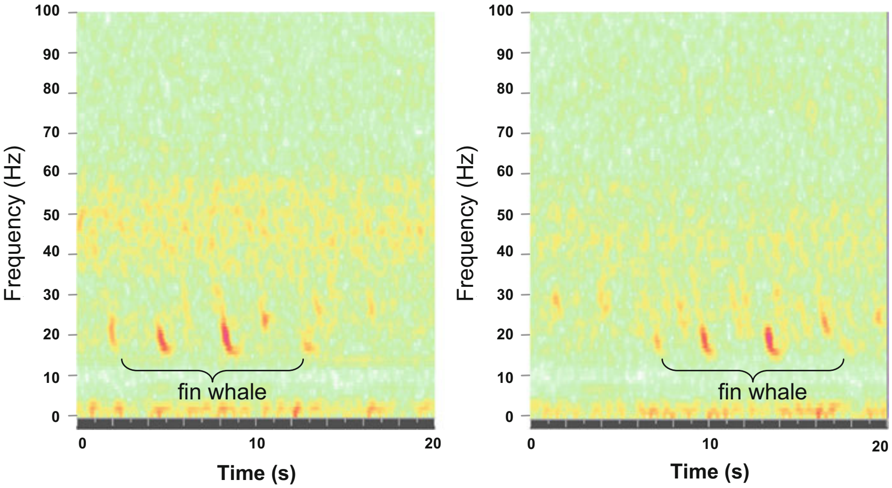

Fig. 9.4 Spectrograms of fin whale FM downsweeps recorded with the Station ALOHA hydrophone

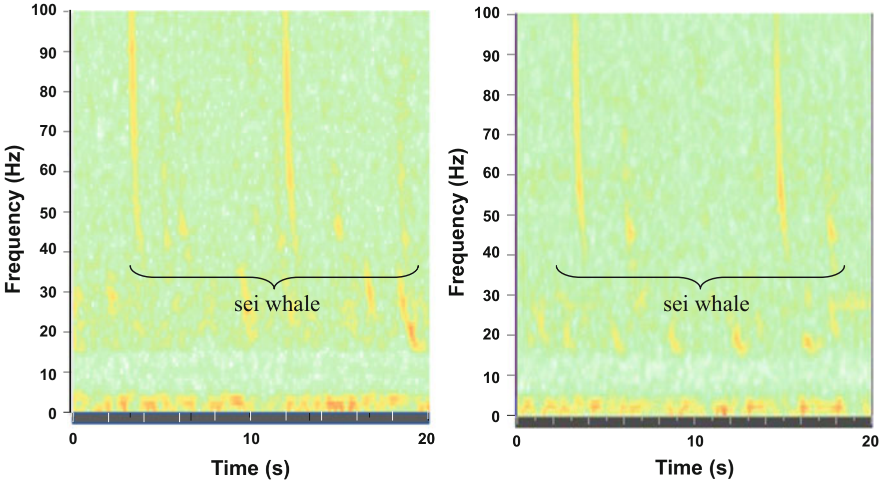

Fig. 9.5 Spectrograms of calls assumed to be produced by sei whales (based on Rankin and Barlow 2007; Baumgartner et al. 2008) detected at the Station ALOHA hydrophone. Fin whale calls can also be seen at lower frequencies

to 38–45 Hz in approximately 1 s. Sei whale downsweep FM signals can also be seen in the spectrograms in Fig. 9.5.

Minke whales in the north Pacific Ocean produce a sound known as the "boing." Boings are relatively stereotyped sounds that usually begin with a brief pulse followed by a longer, frequency and amplitude modulated component centered at approximately 1.4 kHz (Fig. 9.6). Based on the pulse repetition rate in the amplitude modulated component, Rankin and Barlow (2005) reported two types of boings. The "eastern

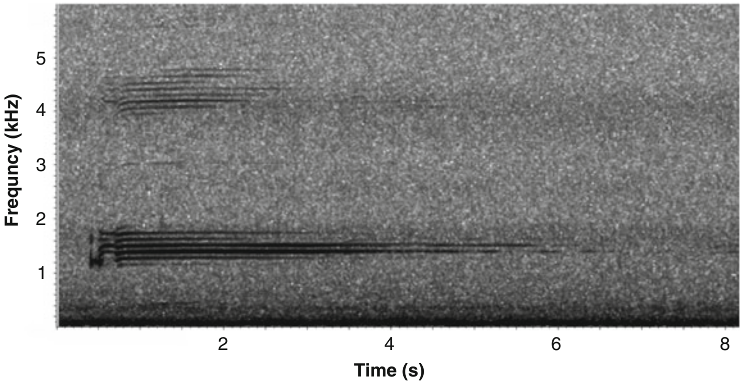

Fig. 9.6 Spectrogram of a minke whale boing detected at the Station ALOHA hydrophone

boing," which has a pulse repetition rate of 91–93 pulses/s and a mean duration of 3.6 s, was recorded east of 138° west latitude. The "central" boing has a pulse repetition rate of 114–118 pulses/s and was recorded west of 135° west latitude.

9.2.2 Automatic Detection of Sounds Produced by Baleen Whales

Matlab scripts were used in the acoustic analysis of the ACO data. The hydrophone data were digitized at a sample rate of 24 kHz, which is much higher than necessary for working with low-frequency baleen whale calls. For a standard spectrogram determination, the frequency bin size is equal to the sample rate divided by the number of points in the Fourier transform window, so for a given window size, the higher the sampling rate, the larger the frequency bins. For low-frequency baleen whale calls, bin sizes should be on the order of several Hz. The automated detectors for low-frequency blue, fin, and sei whale signals decimated the hydrophone data by a factor of 24, making the effective sampling rate equal to 1 kHz. The automated detectors for higher frequency minke whale signals decimated the hydrophone data by a factor of 6 making the effective sampling rate equal to 4 kHz.

The acoustic data were first analyzed using a bandpass filter to obtain signals in the appropriate frequency range of the species of interest. An envelope detector was applied to each file being analyzed and the average value of the ambient noise was determined. The threshold was adaptively determined by choosing a value that represented an intensity that was 3-dB higher than the averaged ambient noise intensity. The blue whale detector examined potential blue whale calls by calculating the spectra of consecutive ½ second windows using a fast Fourier transform algorithm in Matlab. If a signal was in the appropriate blue whale frequency range and had a continuous duration between 11 and 18 s, the signal would be designated as a blue whale signal. If at least three signals had the appropriate frequency range and duration in the 5-min .wav file being examined, that file would be designated as a blue whale file. Extra caution was taken when including potential blue whale signals due to non-blue whale low-frequency long-duration tones that have been recorded in the area, probably from distant shipping.

Calls produced by fin and sei whales were detected by first processing the data in each file with a bandpass filter followed by an envelope detector and establishing a threshold in a similar manner as was done for the blue whale detector. A spectrogram similar to those shown in Figs. 9.4 and 9.5 was calculated for each file and the beginning and ending frequencies along with slope of each supra-threshold signal were determined. Signals that had beginning frequencies between 80 and 100 Hz and ending frequencies between 40 and 50 Hz and had durations between 0.5 and 1 s were designated as sei whale signals. Signals that had beginning frequencies between 40 and 60 kHz and ending frequencies between 18 and 30 Hz and had duration between 0.5 and 1 s were designated as fin whale signals. At least 5 signals with the appropriate characteristics had to occur in a single 5-min .wav file before that file was designated as a fin or sei whale file.

Matlab blue, fin, and sei whale detector scripts were developed specifically for the ACO data. An interactive procedure was used in which a test data set containing about 20 5-min files with manually confirmed calls from the three species was created. A detector for a specific baleen whale species was initially created and used to analyze the files in this test set to determine how well the algorithm performed. Each detector algorithm was fined-tuned until it worked almost perfectly with the data in the test set. In addition, an informal ground-truth or validation process was conducted after all the ACO data from the time period of 17 February 2007 until 18 February 2008 were analyzed using the blue, fin, and sei whale detectors. For each species, one hundred randomly chosen files that were labeled by the detector as containing that species were examined. The spectrogram for each file was visually examined and if at least five signals that exhibited characteristics associated with fin and sei whale calls were found, then the label was considered to be correct. The correct classification rate was very high, greater than 97 % for fin whales and 98 % for sei whales. Because the detector performed so well for fin and sei whales, a validation test for blue whales was not conducted.

Two different types of minke whale detectors were used to analyze the ACO data. The first used a data template detector (Oswald et al. 2011) created with XBAT (Extensible Bioacoustic Tool) software. XBAT's data template detector is a spectrogram correlation detector that examines the time cross-correlation sequence between an example sound [in this case, both a high signal-to-noise ratio (SNR) boing and a medium SNR boing were used as example sounds] and the sound file being analyzed. Events are detected when the correlation exceeds a user-defined threshold. The XBAT detector was ground-truthed using 8 h of data recorded on 5th March, 2007. An experienced acoustician visually and aurally identified boings in a spectrogram, and ranked each boing as one of five quality categories ranging from one (audible, but barely recognizable as a boing on the spectrogram) to five (very loud and clear boing). The results of the manual examination were then compared to automated detections made using XBAT on the same section of dataset. A total of

783 boings were manually identified in the 8-h recording that was used for groundtruthing the detector. The automated detector identified 100 % of category 5 boings ($n = 49$), 99 % of category 4 boings ($n = 78$), 91 % of category 3 boings ($n = 150$), 59 % of category 2 boings ($n = 259$), and 22 % of category 1 boings ($n = 247$). Only 5 % of detections made by the XBAT detector were false detections and most of these were caused by sounds produced by humpback whales.

The second minke whale boing detector utilized the same process as was used for fin, sei, and blue whales. The signals detected by the envelope detector were subsequently analyzed in the frequency domain by creating 250 ms segments, with each segment analyzed using fast Fourier transform (FFT). The peak frequency and sideband frequencies (the localized maxima if there are any) were calculated for each Fourier spectrum. The signal was classified as a boing sound if its peak frequency remained within the range of 1375–1430 Hz with less than 10 Hz fluctuation from one step to the next, and if the separation between main band and side bands was in the range of 116 ± 6.75 kHz. If a signal contained an outstanding side-frequency component (not necessarily a side band of the peak frequency), it would not be classified as a “boing” if (1) this side-frequency portion did not have time duration comparable to the peak frequency band or (2) its separation from the peak frequency did not fall into the required range. If a signal satisfied the condition on the peak frequency range and it did not contain any side frequency components in the 1–2 kHz range, it would also be classified as boing (Ou et al. 2012).

This boing detection algorithm was tested on the same data set used by Oswald et al. (2011) to test the XBAT algorithm. Out of 1447 boing sounds that were manually detected by visual inspection of the spectrograms, both of the detectors recognized more than 90 % of them, with XBAT giving slightly better results. However, the non-spectrogram method produced a lower number of false alarms, with a 0.3 % false alarm rate compared to 5 % for XBAT, indicating that the XBAT detector was more sensitive to noise caused by humpback background chorusing sounds that were also detected by the ACO hydrophone. Because of this, all analyses presented in the following sections are a result of the non-spectrogram analysis method.

9.2.3 Baleen Whales at the ACO

The detection of baleen whales in the ACO recordings is reported in terms of the number of 5-min files per day in which whales of a given species were detected. The overall results are shown in Fig. 9.7 as a function of month. One of the obvious but very important results is that whales were generally only detected during the winter and spring months. The only exception to this occurrence pattern was fin whales. Throughout the months of June–September, when there were no detections of minke, blue or sei whales, there were days in which one or two files contained fin whale downsweeps, except for September 10 and 11 in which 8 and 9 files, respectively, contained fin whale downsweeps. The actual number of files per day for a given species was not considered to be an important metric in this study because detection depends on the distance between the whale and the hydrophone, as well

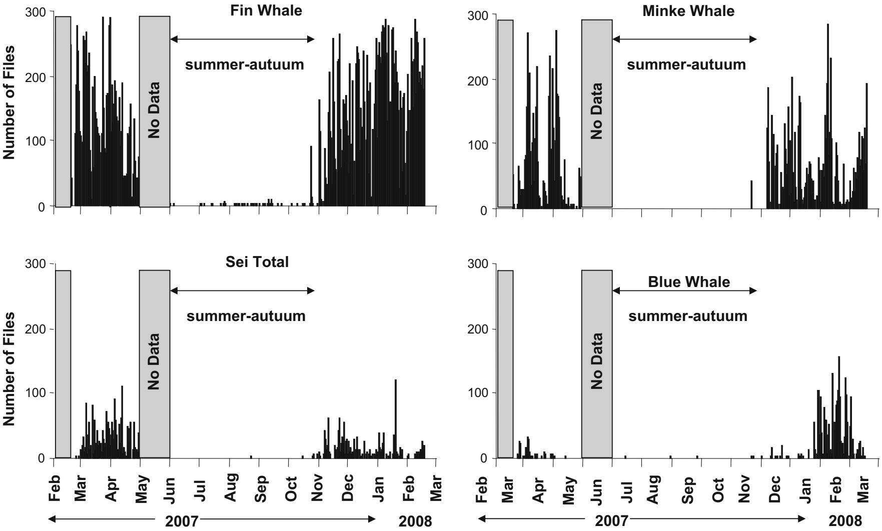

Fig. 9.7 The number of 5-min .wav files recorded at the Station ALOHA ACO that contained sounds produced by baleen whales during the period of February 17, 2007–February 18, 2008. *Grey boxes* represent time periods in which recordings were not made

as the ambient noise level for any given time and day. High winds, rain, and high sea states are some of the environmental variables that would affect the ambient noise for any given period. Fin whales were the most frequently detected species, followed by minke whales. Blue and sei whales were detected the least frequently. On several days, fin whale calls were detected in over 96 % of the files.

Based on the results in Fig. 9.7, whales do not suddenly appear but arrive in Hawai'ian waters in a gradual but somewhat sporadic manner. This can also be seen in Fig. 9.8, which is an expanded view of Fig. 9.7 to show in greater detail the beginning of the 2007–2008 baleen whale season. A small number of sounds produced by sei whales were detected as early as October 2, while a small number of sounds produced by fin whales were detected on the next day, October 3. A number of fin whale calls were detected sporadically during the October 4–28 period, after which they were detected regularly. Minke whale boing sounds were regularly detected starting on November 7. Even though sei whale calls were the first to be detected in October, calls produced by this species did not occur regularly until after October 31. The blue whale calls in the beginning of the 2007–2008 baleen whale season were fairly sporadic, making it difficult to ascribe a pattern to the occurrence of these calls. The important features in Figs. 9.7 and 9.8 can be summarized as: (1) the calls from the different species were not detected at the same time but were spaced out by days and weeks, (2) in the beginning, there were days during which a small number of calls were detected followed by days during which no calls were detected, (3) the pattern of calls on a day-to-day basis varied considerably. For example, fewer than 30 files contained fin whale calls on November 15 but the next day, the number of files with fin whale calls shot up to 258, an increase of nearly nine times over 2 consecutive days.

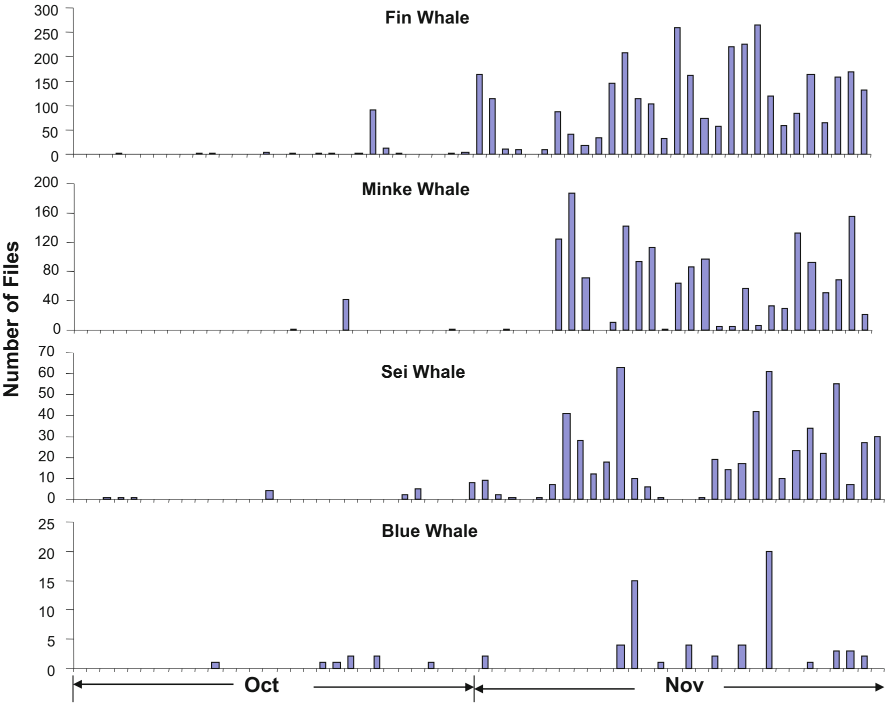

Fig. 9.8 An expanded view of the number of 5-min .wav files recorded at the Station ALOHA ACO that contained sounds produced by baleen whales at the Station ALOHA hydrophone at the beginning of the 2007–2008 baleen whale season in Hawai'i. Note that the vertical axes have different scales

An expanded view of the acoustic detection of these four species of whales at end of the 2006–2007 season is shown in Fig. 9.9. Unfortunately, the ACO hydrophone stopped functioning on April 30, 2007 for about a month so that data for the month of May, 2007 were not available. As with beginning of the baleen whale season in Hawai'i, the ending portion of the season was spaced out over about a month as the number of calls from the blue, fin, and sei whales gradually became less frequent. Blue whale calls over consecutive days dropped out on April 4, and were only detected during 2 other days in April (April 13 and 26). Consecutive days in which minke whale boings were detected ended on April 21, and boings were detected during 3 other days that month (April 25, 27 and 28). More boing sounds may have been detected if the ACO hydrophone had continued operating into May, but the pattern in April does suggest the end of the minke whale season in Hawai'i. Sei whale calls dropped off fairly steadily after April 5 with short increases on April 11, 18, and 25. Fin whale calls were detected regularly throughout April and we surmise they probably persisted into May.

The diurnal variation in baleen whale call detections over the entire baleen whale season in Hawai'i is shown in Fig. 9.10. The shaded areas on each plot approximate the twilight, night, and dawn periods. The vertical axis is the total number of files in which baleen whale calls were detected. The results indicate that the number of fin

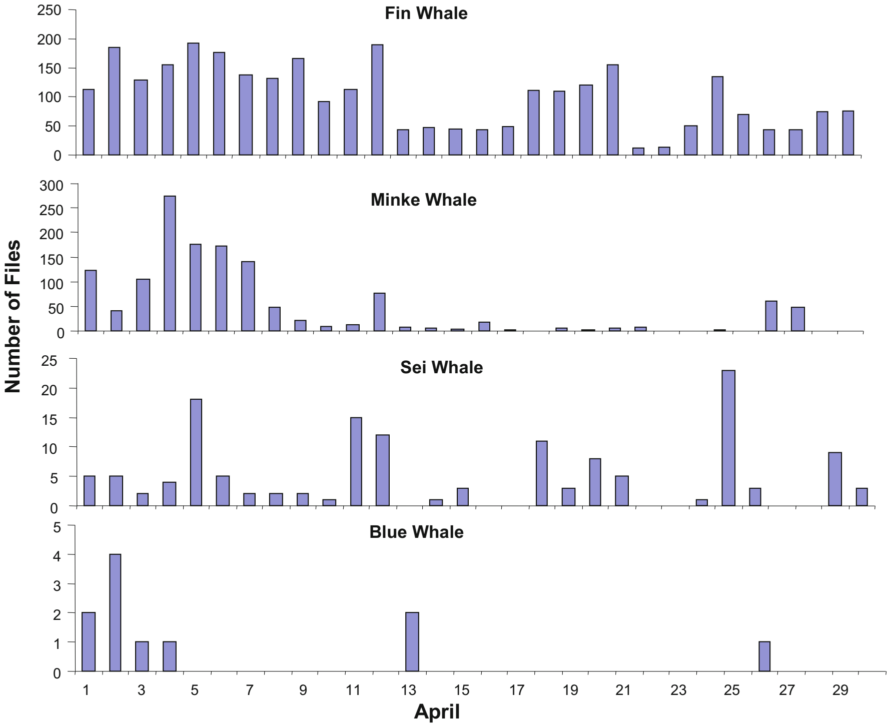

Fig. 9.9 An expanded view of the number of 5-min .wav recorded at the Station ALOHA ACO that contained sounds produced by baleen whales towards the end of the 2006–2007 baleen whale season in Hawai'i. Note that the vertical axes of the plots have different scales

and minke whale calls detected were about the same for the day and night periods. The number of sei whales calls detected was high at dawn and decreased steadily towards dusk. The number of blue whale calls detected was higher during the twilight-night hours than during the day. However, even if a pattern is shown for any of the species, the significance of the pattern is questionable. It is impossible to state whether the variability in the number of calls detected for a species was caused by a variation in the number of whales calling during a time period or if the daily movement patterns of the whales meant that the species was out of range of the ACO hydrophone, or a combination of both factors.

9.3 Discussion

The distance from the ACO hydrophone at which most of the baleen whale calls were detected cannot be estimated or approximated from the results obtained from a single hydrophone. However, sound propagation characteristics of the water column in the vicinity of Station ALOHA suggest that calling animals were likely within a

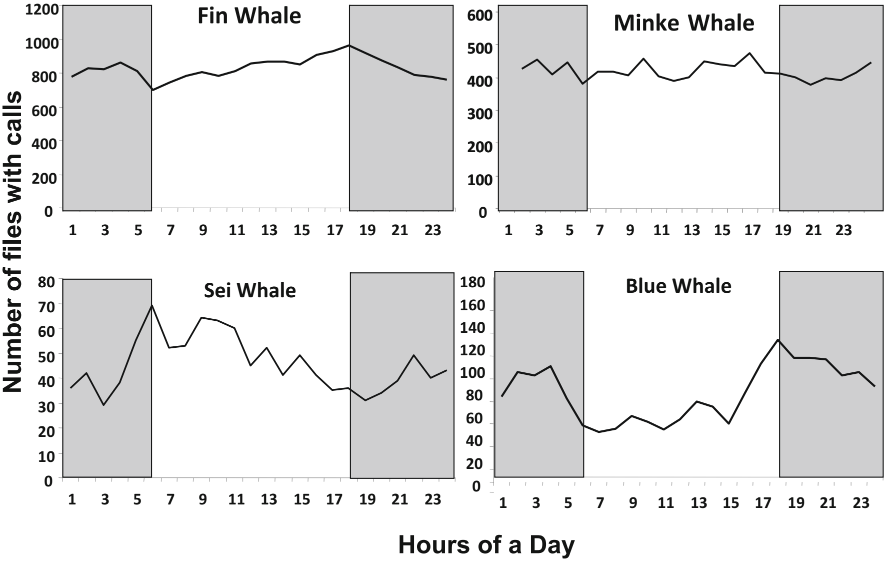

Fig. 9.10 The number of files in which baleen whale calls were detected at different hours of the day between February 17, 2007 and February 18, 2008. Shaded areas in each plot represent night time periods. Non-shaded areas represent day time

convergence zone (±30 km) of the ACO hydrophone. Long distance propagation of sound is supported by the SOFAR (Sound Fixing and Ranging) channel, which is seen at a depth of 700 m during several months at Station ALOHA (Fig. 9.11). The ACO the hydrophone is located at a depth of 4700 m, just at or slightly below the critical depth, so it is less likely to detect sound propagating from long range.

During the beginning and ending of the baleen whale season there were many days in which no whales of a given species were detected, followed by days with multiple detections. This type of variation may be attributed to the density of whales in the location of the hydrophone and to the movements of individuals. When the density of whales is relatively small and the group moves out of the detection range for the hydrophone, no calls from that species will be detected. However, as the season progresses and more whales migrate to Hawai'ian waters, animal movements have a smaller effect on acoustic detection rates since there is a higher likelihood that there will always be some whales within the detection range of the hydrophone. Therefore, as the season progressed, whales were more consistently detected.

Seasonal variation in the number of detections was not likely caused by changes in sound propagation, as the effects of the latter for an ACO hydrophone are small (Fig. 9.11).

The occurrence patterns of the four species of baleen whales included in this analysis generally corresponded with the arrival of humpback whales wintering in Hawai'ian waters. Humpback whales migrate from the waters around the Aleutian Islands and southeast Alaska to Hawai'ian waters as early as late October and leave by late April and early May (Baker and Herman 1981). One of the reasons for the humpback whale seasonal migration is for the whales to breed and give birth to their young in relatively shallow and calm inshore waters. It is not yet known why the

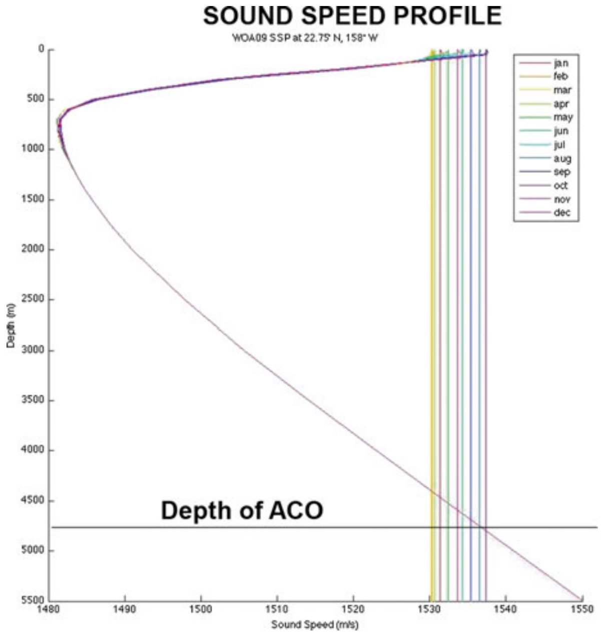

Fig. 9.11 Sound velocity profile in the vicinity of the ACO hydrophone (courtesy of L. Van Uffelen)

other species of baleen whales migrate to Hawai'ian waters. These species are not generally observed in the near shore waters frequented by humpback whales, and the waters several miles from shore are very deep and probably much rougher than inshore waters. Nevertheless, the other baleen whales may migrate to waters around Hawai'i to breed and give birth in the warm waters found at lower latitudes. We conducted a preliminary analysis to examine factors that may be related to the presence of baleen whales at Station ALOHA using oceanographic parameters measured during near monthly HOT cruises (Karl and Lukas 1996). We found no obvious correlations between the presence of baleen whales and measures of primary production, plankton community structure, and temperature. However, these were preliminary investigations and this is a topic that warrants further investigation.

The four species of baleen whales detected with the ACO hydrophone have all been observed visually in Hawai'ian waters. A NOAA cruise to estimate marine mammal abundance in Hawai'ian waters was conducted from August to November, 2002 (Barlow 2006). The four species of baleen whales detected with the ACO hydrophone were seen only late in the survey (Barlow 2006), which is consistent with our findings suggesting the arrival of these whales in October. Calls from three of the species of baleen whales discussed here (fin, blue, and minke) were also detected by Thompson and Friedl (1982) using a pair of hydrophones separated by 16 km at a depth of 731 m which was at the same depth as the SOFAR (sound fixing and ranging) axis on the north slope of Oahu. Sounds traveling in the SOFAR channel can propagate many hundreds of miles, even out to a thousand miles, making it possible to hear whales that are not in the close proximity to the hydrophone (Urick 1983), and it is not possible to determine how close the whales recorded by Thompson and Friedl (1982) were to the hydrophones that they used.

It is common knowledge that blue, fin, sei, and minke whales migrate seasonally from cooler subpolar waters at high latitudes to warmer tropical waters at low latitudes. During months when calls were not detected it may be a safe to assume that the whales have left the area on their northward migration to higher latitudes. However, in the case of fin whales, calls were still detected during the summer months, albeit at considerably lower rates than during the winter months. This suggests that at least a small number of fin whales remained in the general area of Station ALOHA all summer. Unfortunately, recordings from a single hydrophone cannot provide any information on the relative number of whales present or their distance and direction from the hydrophone.

A single hydrophone system such as the Station ALOHA ACO can provide information about the presence and temporal patterns in calling behavior for baleen whales, as well as on the relative number of calls per species. Fin whale calls were detected about ten times more frequently than blue whale calls, seven times more frequently than sei whale calls and two and a half times more frequently than minke whale calls. However, the significance of these numbers is questionable since we do not know the distances at which the whales were detected, how those distances vary among species, and how the number of calls relates to the number of animals.

Another interesting piece of information concerning the detection of baleen whale calls is that humpback chorusing sounds could be heard in the “background” of the ACO recordings during the peak of the humpback whale season in Hawai’i. Since humpback whales, to the best of our knowledge, usually inhabit in-shore waters while wintering in Hawai’i and the ACO hydrophone was about 100 km (54 nm) from shore, this suggest that some degree of long range propagation with some combination of sound channel refraction and bottom and surface scattering, and even internal wave scattering could in fact be occurring. Again, it is not possible to estimate the range at which these humpback whale chorusing sounds were detected. The addition of one or more time synchronized, and fully calibrated hydrophones to the ACO would make it possible to determine detection bearings and distances and gain more insight to the occurrence and behavior of baleen whales in this area. Nevertheless, the ACO hydrophone has provided extremely important information on the seasonality of baleen whales, their migration patterns into and out of a small area north of Oahu and the relative occurrence of different species, thus increasing our knowledge of these species in an area that is challenging to access and monitor in any other way.

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Chapter 10
Findings from U.S. Navy Hydrophone Ranges

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Abstract The U.S. Navy maintains several instrumented ranges equipped with large arrays of bottom-mounted hydrophones that are typically used to track undersea vehicles. The major ranges include the Atlantic Undersea Test and Evaluation Center (AUTEC) located in the Bahamas, the Southern California Offshore Range (SCORE) located off San Clemente Island, and the Pacific Missile Range Facility (PMRF) located off the western side of Kauai, HI. Each of these ranges provides tracking arrays covering an area in excess of 1200 km^2. These hydrophone arrays are being used to develop marine mammal passive acoustic detection, classification, localization, and density estimation methods. Hardware systems installed at all three facilities allow real-time monitoring of vocalizing marine mammals. Using these systems, Blainville's beaked whales have been detected at AUTEC and PMRF. Cuvier's beaked whales have been detected at SCORE and to a lesser extent at AUTEC. These "sonar sensitive" species are present despite the repeated use of sonar. Based on passive acoustics, the movement of these species in response to sonar has been documented. By combining passive acoustic beaked whale and sonar data with AUTEC ship track data, a risk function for Blainville's beaked whales was developed. In addition, by combining hydrophone with recording tag data, the beam pattern and source level of Blainville's beaked whale were measured along with the system's detection function. This enabled the development of passive acoustic density estimation algorithms. These algorithms are being applied to the long-term, in situ monitoring of beaked whale population at all three facilities.

10.1 Overview

Listening in the ocean typically makes use of single hydrophones or recording buoys. It is rare to have the systems necessary to monitor large areas in real-time. The U. S. Navy's major undersea ranges provide such systems. These sites include the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas, the Southern

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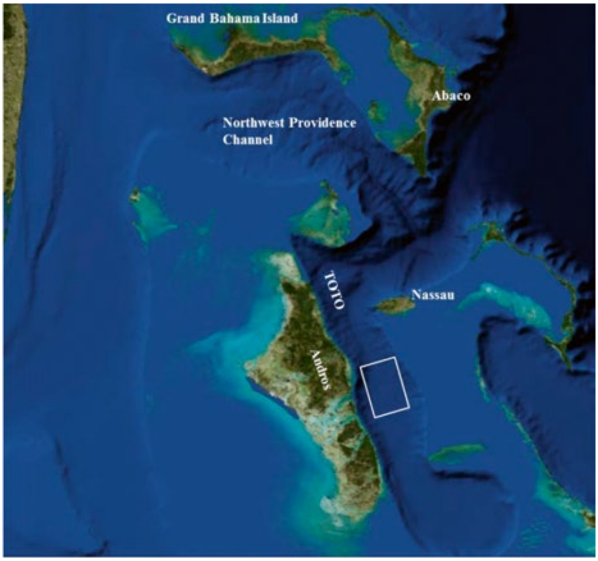


Fig. 10.1 The Bahamas including the Northwest Providence Channel and Tongue of the Ocean (TOTO). The AUTEC range off Andros Island is outlined by the *white rectangle*

California Range (SCORE) off San Clemente Island, California, and the Pacific Missile Range Facility (PMRF) off the island of Kauai, Hawaii. The ranges are composed of widely spaced, bottom-mounted hydrophones, capable of monitoring large areas of ocean basins. The AUTEC range, for example, is located in the Tongue Of The Ocean (TOTO), the southern branch of the Great Bahama Canyon, and covers over 500 Nmi^2, in waters depths ranging between 1200 and 1800 m (Fig. 10.1).

10.2 Passive Acoustic Monitoring System

Hydrophone placement on the ranges is optimized for tracking of underwater vehicles, typically submarines, targets, and torpedoes, equipped with an acoustic pinger that emits a known signal at a known repetition rate. Onshore, a massively parallel signal processor is used to monitor the hydrophones. The acoustic pings are detected and precisely time-tagged. Their Times-Of-Arrivals (TOAs) are passed to tracking computers and the three-dimensional (3D) position of the undersea vehicle is calculated using a hyperbolic tracking algorithm (Vincent 2001). Each ping must be detected on at least four hydrophones to solve for position, since latitude, longitude, depth, and time-of-emission are all unknown.

Fortunately, the ranges were designed to detect ping signals across a wide frequency band. The resultant hydrophone bandwidths (typically ~50 Hz to 50 KHz) and spacing are well suited for detecting and localizing a wide variety of marine mammal vocalizations. The number of hydrophones available varies from 91 at AUTEC to 192 at PMRF. A Linux cluster-based signal processor has been developed that allows each hydrophone to be monitored in real-time for transient signals including marine mammal vocalizations. The architecture provides a high degree of scalability. Processing nodes can be added as required when new algorithms become available.

Hydrophone signals are digitized at a sample rate of 96 kHz, packetized, and precisely time-tagged using a GPS satellite reference clock. Each data packet contains time-referenced samples from a single hydrophone with time accurate to 10 μs. These data are broadcast on a dedicated network. Processing nodes on the network receive the data from any or all hydrophones as required.

The range signal processor typically implements a matched filter receiver for the detection of tracking pings, since their signal structure is fixed and known. In contrast, marine mammal vocalizations are highly variable and their signal structure is not usually known a priori, making their detection, classification, and localization (DCL) challenging. Animals' vocalizations vary widely between species and between individuals of the same species. Within the bandwidth of the hydrophones, vocalizations range from the seconds long 25 Hz downsweep of a fin whale (*Balaenoptera physalus*) to the approximately 350 μs, 28–50+ kHz echolocation click of a Gervais' beaked whale (*Mesoplodon europaeous*) (Gillespie et al. 2009).

To monitor this wide array of signal types, a Fast Fourier Transform (FFT) based transient detector has been developed that converts the signal into the frequency domain. An exponential average is calculated in each FFT bin and compared to a noise variable threshold (NVT) maintained at a specified level above the exponential average. If the energy in any bin exceeds the NVT, a detection is registered and the bin is set to a 1. Bins below the threshold are set to 0. For each FFT, a detection report is generated which includes a binary map that records the output state (1 or 0) for each FFT bin along with the time of detection, NVT, and the peak amplitude for the bin with the maximum energy. Because the output of each FFT bin is effectively hard-limited, a data reduction of over 16-to-1 is realized relative to the full-amplitude spectra, making real-time distributed processing and continuous, year-round archiving of spectral data from all hydrophones possible. During marine mammal monitoring, the detection reports are used to isolate acoustically active hydrophones and to display a two-dimensional (2D) spectrogram, on demand, for hydrophones of interest (Jarvis et al. 2014).

Features in frequency and time can be used to identify various species. For example, Fig. 10.2 shows the low frequency downsweep of a fin whale at SCORE. Figure 10.3 shows a train of Blainville's beaked whale (*Mesoplodon densirostris*) clicks at PMRF. These clicks show the distinctive pattern associated with *Md* with energy above 25 kHz and an interclick interval (ICI) of approximately 0.3 s.

Localization of vocal animals presents a particular challenge. The majority of the hydrophones are widely spaced (~4 km) and the time of detection for any given signal can vary by seconds from the detection times on adjacent hydrophones for the same signal. For traditional pinger tracking, data embedded in each ping are used to uniquely identify a particular ping in a chain of pings. This allows a ping,

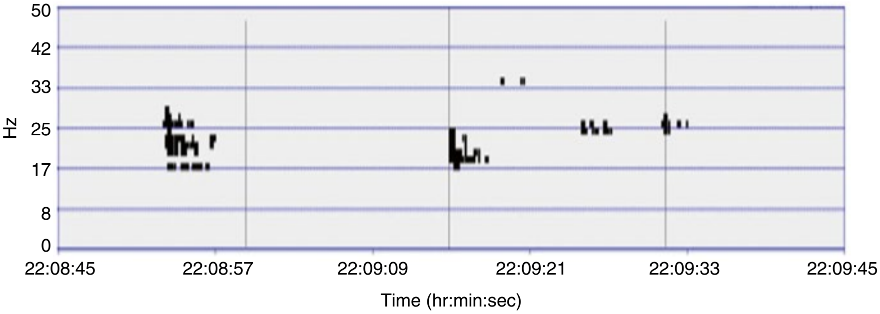


Fig. 10.2 2D spectrogram display (frequency 0–50 Hz vs. time over 60 s) of fin whale downsweeps from a Southern California Offshore Range hydrophone off the coast of California

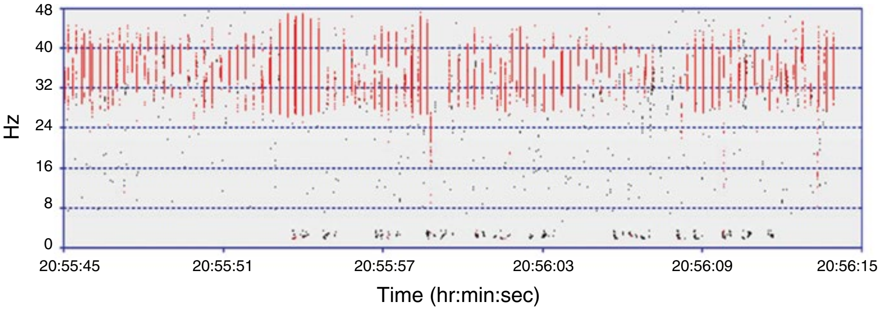


Fig. 10.3 2D spectrogram display (frequency 0–48 kHz vs. time over 30 s) of Blainville's beaked whale clicks from a Pacific Missile Range Facility hydrophone off Kauai, Hawaii. Humpback calls are visible as black flecks at the bottom of the display

detected on multiple hydrophones, to be properly associated and localized. Marine mammals may produce multiple vocalizations, including a variety of clicks and whistles. Often, animals produce long click trains where the interclick interval (ICI) is less than a second. Each click train may be received on multiple hydrophones. Individual clicks in the chain must first be properly aligned or associated to localize the animal. For arrays of widely spaced hydrophones, the challenge presented by this process of "data association" is often initially overlooked. Since the clicks may be virtually identical, associating them on multiple hydrophones is challenging and makes real-time localization difficult. Fortunately, marine mammal click trains are not precisely periodic. The times between clicks in a chain of clicks form a unique pattern. Time delayed versions of the pattern are evident on adjacent hydrophones as the clicks propagate through the water. By correlating times of detections between adjacent phones, Time Differences of Arrivals (TDOAs) emerge. These differences are then used to localize the vocalizing animal (Jarvis et al. 2014).

With the ability to detect, classify, and localize vocalizing animals, it becomes possible to study marine mammals in situ. Additionally, because the navy ranges are training centers for antisubmarine warfare, they provide a unique opportunity to study the effect of anthropogenic sound, especially Mid-Frequency Active Sonar (MFAS), on marine mammal behavior. The following case study at AUTEC demonstrates the potential benefits passive acoustic monitoring offers in evaluating such behavioral changes.

10.3 Characterizing Beaked Whale Sound Emissions

On April 17, 2000, a U.S. five-ship battle group executed a choke-point exercise in search of submarines moving through the Northwest Providence Channel in the Bahamas, approximately 50 miles north of AUTEC. While using Mid-Frequency Active (MFA) sonar, the ships moved from east to west through the Channel. Over the ensuing 2 days, 16 animals stranded including 7 Cuvier's (*Ziphius cavirostris*) and 7 Blainville's beaked whales, and 2 minke whales. At least seven animals died (Balcomb and Claridge 2001; Anon 2001). This well documented event suggested marine mammals, especially beaked whales, react to MFAS (D'Amico et al. 2009). The resulting investigation into the event fostered a targeted U.S. Navy research program into the effect of MFA sonar on cetaceans with a focus on beaked whales.

In 2002, a Woods Hole Oceanographic Institution digital recording tag (DTag) was placed on a Blainville's beaked whale (Johnson et al. 2006; Johnson and Tyack 2003). From the DTag recordings, the first positively identified *Md* echolocation clicks were documented (Johnson et al. 2006). Based on these findings, the signal processor at AUTEC was reprogrammed to extend its bandwidth from 24 kHz to 48 kHz. Almost immediately after the wide-band 48 KHz bandwidth processor was deployed, beaked whale echolocation clicks were detected. Over subsequent tests, expert observers from the Bahamas Marine Mammal Research Organization (BMMRO) were vectored to locations with vocalizing animals and the presence of Blainville's beaked whales on the AUTEC range was visually confirmed. Through the use of passive acoustic monitoring, their persistent presence has been documented; despite the repeated use of MFA sonar, yet no mass strandings of animals have been reported in the TOTO (Moretti et al. 2010; McCarthy et al. 2011).

Through repeated tests in which cetacean vocalizations were detected, recorded, and visually verified, three species of beaked whales have been identified in the TOTO. These include Blainville's, Cuvier's and Gervais' beaked whales. The frequency characteristics of these species foraging clicks are compared in Fig. 10.4. What are believed to be on-axis clicks were isolated, by capturing click trains where the difference from highest to lowest click amplitude was greater than 30 dB. The plots show a distinct difference in the energy distribution between species at AUTEC. In addition, the ICI for Gervais' was measured as 0.279 clicks/s (CI, 0.025, ten foraging dives), for Blainville's 0.303 clicks/s (CI, 0.0058, 256 foraging dives),

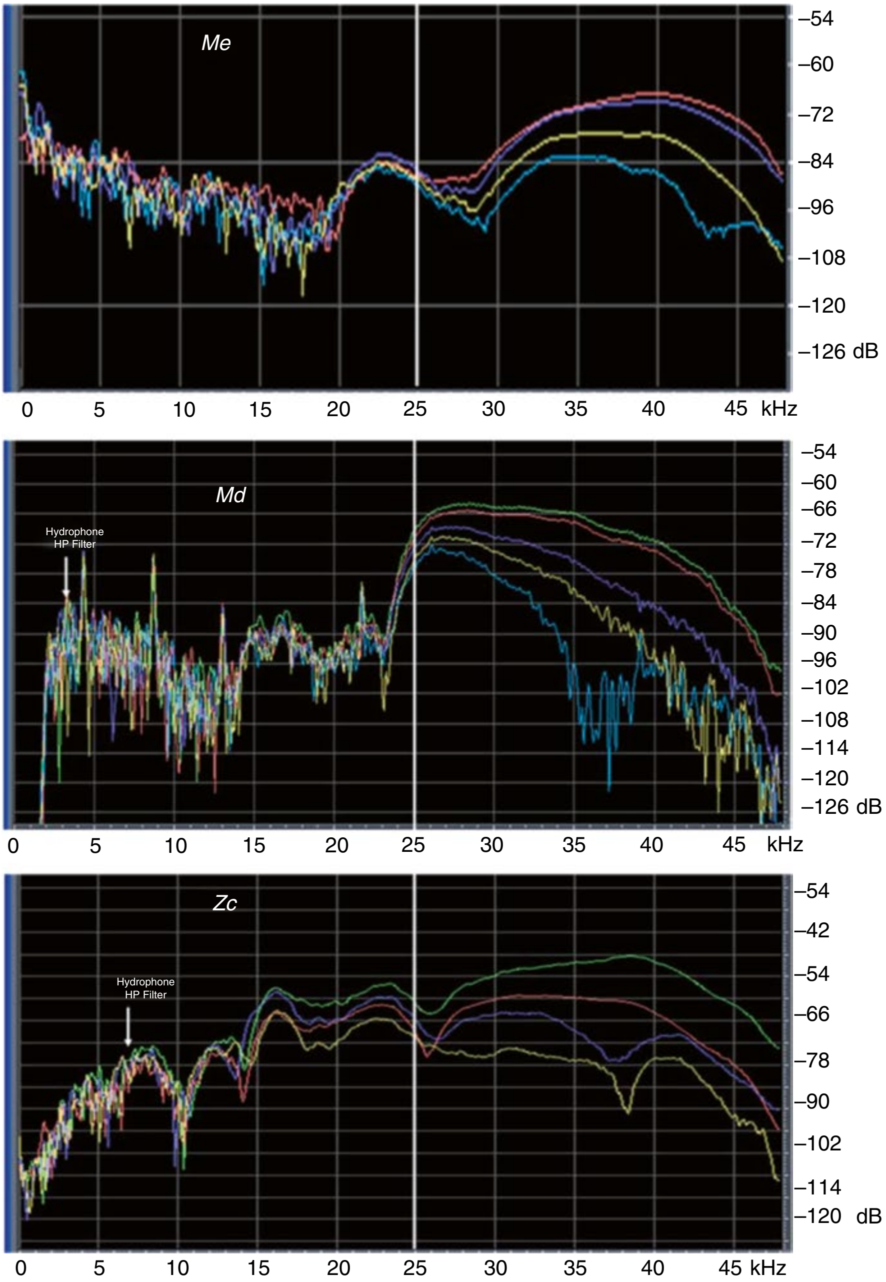


Fig. 10.4 Frequency domain plots of Gervais (*upper*), Blainville's (*middle*), and Cuvier's (*lower*) beaked whale echolocation clicks from what is believed to be head sweeps past across a hydrophone. The *white line* indicates a frequency of 25 kHz. The lower Zc plot was recorded on a hydrophone with a high pass filter at 8 kHz

and for Cuvier's 0.543 clicks/s (CI, 0.0192, 47 foraging dives). Such differences are distinctly visible in the 2D spectral displays available to monitoring personnel and provide distinct features for the development of automatic classifiers.

At AUTEC, Blainville's beaked whale is the predominant species observed, and as such, has become the focus of ongoing research. By combining passive acoustics with visual observations and tags, the animals' vocal behavior is being mapped to their physical movement and a greater understanding of their behavior is starting to emerge.

WHOI recording tags were placed on six Blainville's beaked whales on the AUTEC range. Echolocation clicks recorded on the whales were compared with the same clicks recorded on surrounding hydrophones. Using the combined tag and hydrophone data, click source level and received beam pattern were measured. The tags include a three-axis accelerometer, magnetometer, and pressure transducer from which pitch, roll, heading, and depth were derived (Johnson and Tyack 2003). Based on sensor measurements and knowledge of the Global Positioning System (GPS) location at tag-on, dead-reckoning or pseudo-tracks were produced. Since the animals often dive in small groups, the tag recorded clicks from both the tagged animal and nearby conspecifics. The click trains produced by the animal were identified and used as a correlation template to isolate the same clicks on the surrounding hydrophones. Time Difference of Arrivals (TDOAs) between the clicks on the tag and those on the surrounding hydrophones, along with depth from the tag, were used to acoustically track the animal. For each calculated position, the corresponding pitch, roll, and heading were extracted from the recordings on the tag. For a single click, detected on multiple hydrophones, the orientation of the animal to each hydrophone was calculated. The receive level was measured from recordings on the hydrophones and used to back-propagate to the animal to obtain an estimate of the source level. By combining multiple individual clicks on multiple surrounding hydrophones, a composite measurement of the beam pattern of the animal was obtained. The mean Apparent Source Level (ASL) was measured as 199.17 dB_{rms97} (Figs. 10.5 and 10.6). By fitting the data to a piston model, a −3 dB beam width of 11.7° (std. 0.39) was estimated (Shaffer et al. 2013).

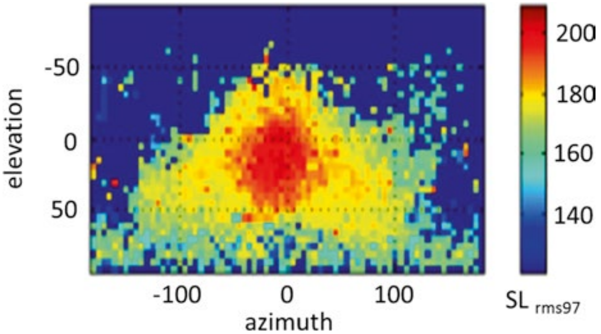
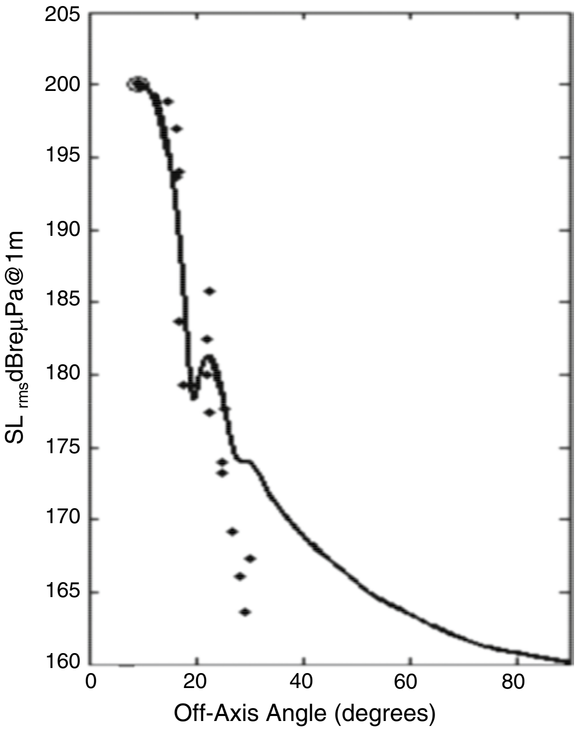


Fig. 10.5 Blainville's beaked whale beam pattern in degrees azimuth versus elevation with level (dBreμPa at 1 m) based on 97 % energy criteria (Shaffer et al. 2013)

Fig. 10.6 Measured versus modeled beam pattern during a single scan across a hydrophone. Note that the maximum ASL is recorded 0° off-axis angle (*circle*). The *solid black line* is the fitted piston model transmission beam pattern (Shaffer et al. 2013)



Receiver statistics were also derived. With a record of clicks emitted versus clicks received on the surrounding hydrophones, the probability of detection for a linear match filter detector was calculated along with the corresponding detection range from the hydrophones (Jarvis et al. 2014). This measured detection range is particular to the clicks from deep diving animals received on bottom-mounted hydrophones. For a downward refracting sound channel, which is often the case at AUTEC, such hydrophones have a distinct advantage over those suspended near the surface. For animals at depths below 500 m, refraction is minimal for sound propagating to a bottom-mounted hydrophone (Fig. 10.7) allowing for long distance direct path propagation. For one tagged animal in 2006, clicks were detected at a range in excess of 6000 m if the hydrophone was located in the center of the beam (Fig. 10.10). These measurements show that beaked whale clicks are directional but very loud, which for bottom-mounted hydrophones, such as those on navy ranges, makes the probability of detection of groups foraging within the field of hydrophones high (Fig. 10.8).

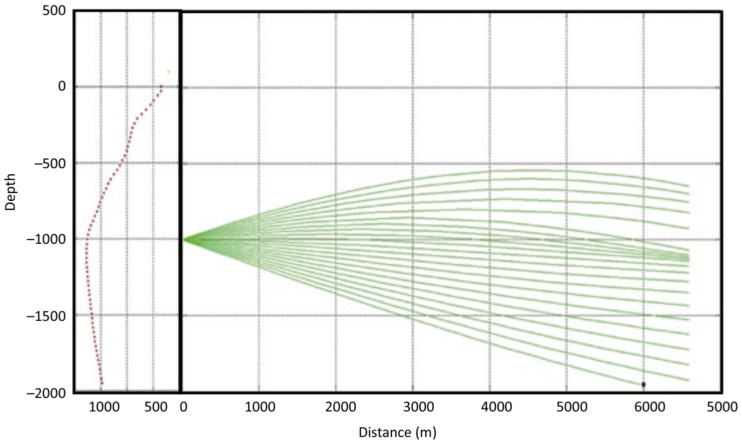


Fig. 10.7 Ray trace (*right*) calculated using a typical August AUTEC Sound Velocity Profile (*left*) with source at 1000 m depth and receiver (*black dot*) at 6000 m range

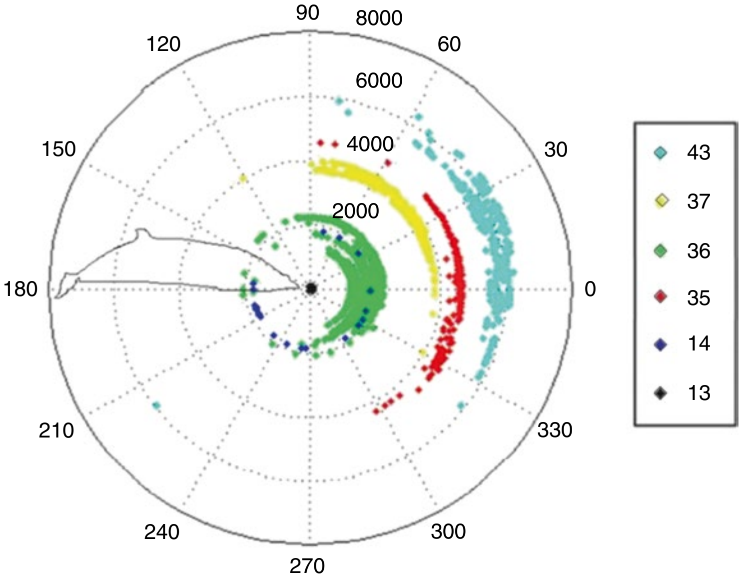


Fig. 10.8 Detection range vs. angle relative to the tagged whale's heading for a linear matched filter matched detector. Detections associated with individual hydrophones are indicated by *color*

10.4 Measuring Population Level Disturbance

For the navy ranges, understanding the cumulative effect of sonar on a population basis is critical. The use of range hydrophones, the development of passive acoustic tools, and access to precise range, ship track data provided a powerful combination for such studies. With the fields of hydrophones present on navy ranges, one can listen to the ocean over broad spatial and temporal scales. The detection of a species' vocalizations can infer its physical behavior provided there is a reasonable understanding of this relationship and the performance of the applied Detection, Classification and Localization (DCL) algorithms has been measured. For the Hawaiian population of Blainville's beaked whales, analysis of DTag recordings has established that echolocation clicks only occur during deep foraging dives below 300 m (Baird et al. 2008; Johnson et al. 2006). Therefore, the detection of deep foraging dives, which occur throughout the day and night at a known rate, can be used as a proxy for their spatial and temporal distribution and foraging behavior.

The first step in measuring disturbance was to establish if Blainville's beaked whales react to sonar and if so the extent of their reaction. To this end, passive acoustic detection reports were archived around multiship sonar operations which spanned over 3 days and included multiple periods of extended MFA sonar use. Typically, the ships' movements were constrained within the range boundaries. This resulted in an intense sound field within a restricted area (Fig. 10.9).

From the detection archives, Blainvilles' beaked whale click trains were extracted. Trains on adjacent hydrophones were associated into groups with the start of the vocal period assigned to the start time of the earliest chain and the stop time to the last detection time in the click train. These represent vocal periods produced by groups of Blainville's beaked whales during deep foraging dives. The group vocal periods were isolated before, during, and after sonar and used to examine the animals' foraging behavior and spatial and temporal distribution. Fig. 10.10 shows a histogram of group vocal periods binned into five-hour intervals. A distinct drop in vocal periods during sonar operations is evident. This measured drop, based purely on passive acoustic measurements, strongly suggests the animals react to MFA sonar transmissions (McCarthy et al. 2011; Tyack et al. 2010). However, there are several possible explanations as to the exact nature of the behavioral change since, based purely on passive acoustics, it is difficult to know if the animals remained on range but stopped foraging, or moved off range and continued foraging in a different location.

In Fig. 10.11, the corresponding distribution of echolocation click detections throughout the exercise is presented. During sonar operations, no echolocation clicks are detected near the center of the range, which represents the area with highest sonar activity. In the final period, there is a significant increase in activity, especially on the periphery of the range. This suggests the animals move off-range and return from outside the range boundaries. However, this example again illustrates the limits of the technology. If vocalizations cease, the passive acoustic window is shut. Additionally, once outside the hearing radius of the hydrophones, there is no way to infer behavior without the addition of sensors or integration of alternate technologies such as tags (McCatrhy et al. 2011).

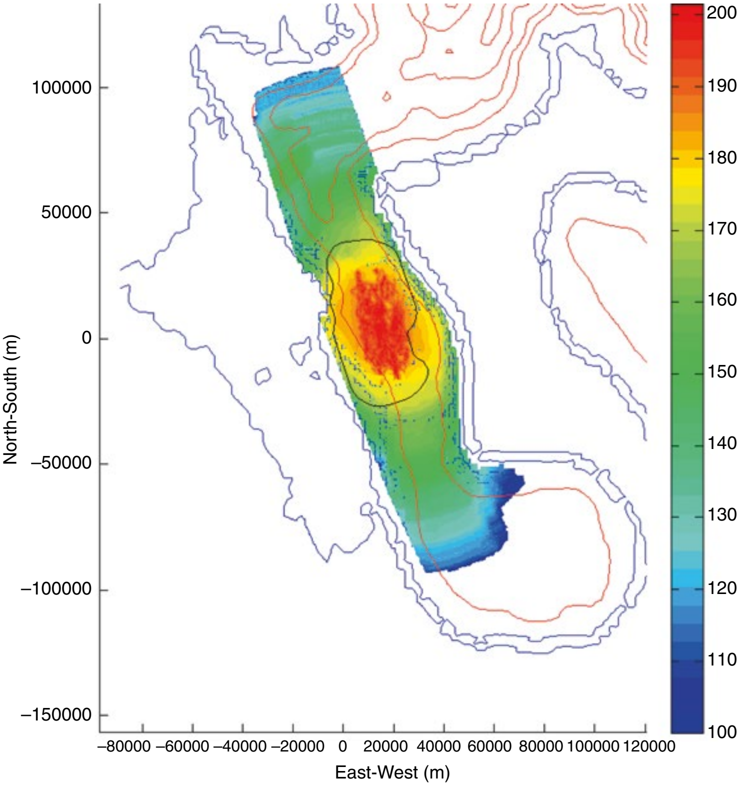


Fig. 10.9 The sound field as shown by the Sound Exposure Level (SEL) (dB re 1 μPa^{2}s) over a 3-day MFA sonar operation on the AUTEC range the boundary of which is outlined in *black* (McCatrhy et al. 2011)

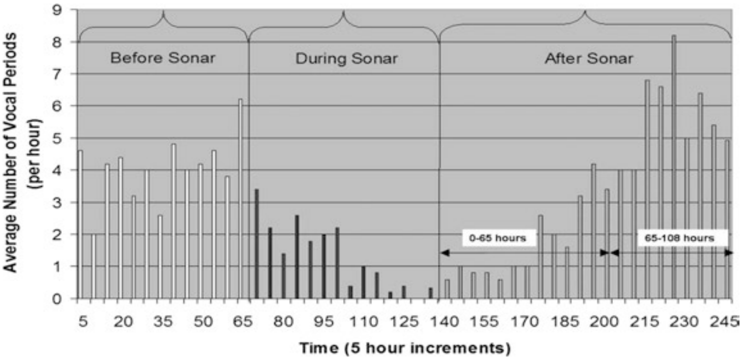
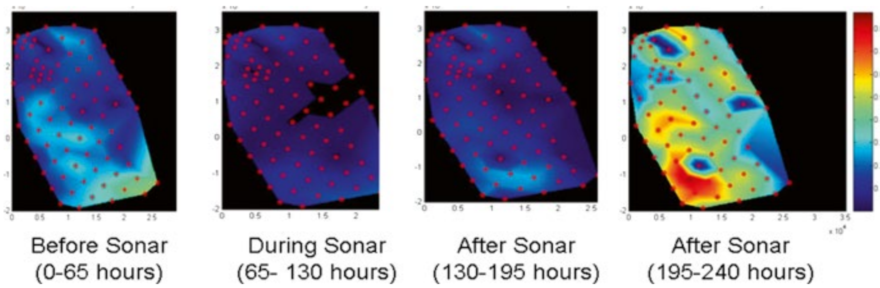


Fig. 10.10 Average number of vocal periods per hour in 5-h intervals before, during, and after a multiship MFA operation



Before Sonar (0-65 hours)

During Sonar (65- 130 hours)

After Sonar (130-195 hours)

After Sonar (195-240 hours)

Fig. 10.11 AUTEC hydrophone map showing average number of *Md* vocalizations per hour on each hydrophone during the 2007 exercise. Hydrophones are shown as *red circles*. The *color bar* indicates the average number of vocal periods per hour detected on each hydrophone. These images were created by plotting the number of times a hydrophone was at the center of a vocalizing group and using a triangle-based linear interpolation in MATLAB (McCatrhy et al. 2011)

10.5 Beaked Whale Passive Acoustic Density Estimation

Passive acoustics combined with visual observations established the presence of Blainville's beaked whales at AUTEC and strongly suggest a behavioral reaction to MFA sonar. How many animals are affected was also answered through the application of passive acoustic methods (Marques et al. 2013). For deep diving cetaceans, these density estimation methods provide a robust means of making such measurements, provided the species' vocal behavior is understood, the necessary sensors are available, and the detector performance has been quantified.

For such cases, passive acoustic methods may supplant or augment traditional visual line transect surveys from either a ship or plane. Such surveys can only be conducted during daylight hours, and in conditions conducive to visual observation. For deep diving species such as beaked whales, obtaining a sufficient number of visual observations is challenging. By contrast, passive acoustic methods provide around the clock measurements and are far less weather dependent, although the rise in background noise due to high seas must be considered.

Blainville's beaked whales are particularly well suited for such passive acoustic density estimation. Recording tags together with combined passive acoustic and visual observations have established that small groups of animals only vocalize at depth during coordinated deep foraging dives. Further, the dive rate at AUTEC and the mean number of clicks produced by an individual during a dive are known (Marques et al. 2009). The clicks are loud (>200 dB) and well within the bandwidth of the hydrophones. Two separate methods for estimating Blaivnille's beaked whale density based on either click or dive counting have been developed (Marques et al. 2013).

Click counting assumes the mean click rate, and for a particular detector, the probability of detection, the false positive rate, and the detection range are known. Detector performance must be well known and completely characterized to extrapolate density. Interestingly, detector performance is not important, provided it is well characterized.

The general method requires counting the number of clicks detected over a specified period of time and area of coverage (Marques et al. 2013). The following formula is then applied,

$$D = \frac{n(1-c)}{K\pi\omega 2PTr}$$

D = animal density estimate
n = number of detected cues
c = estimated proportion of false positives
K = number of replicate sensors
$\pi\omega^2$ = circular area defined by the detection range ω
P = average probability of cue detection within range ω
T = time period over which the measurement was made
r = cue production rate

A second dive counting method of density estimation was also developed (Moretti et al. 2010). This method assumes that the probability of detecting the start of a dive, the dive rate, and the area of coverage are known.

For loud Blainville's beaked whale groups at AUTEC surrounded by multiple hydrophones, a dive start probability of detection of 1 was assumed. Detections were recorded over 10 days and groups of vocalizing animals were isolated. The following equation was then applied:

$$D = \frac{D_s \mathrm{g}}{dTAP}$$

D = *animal density estimate*
g = average group size
D_s = total dive starts
d = dive rate (dives/h)
T = time period over which the measurement was made
A = measurement area
P = probability of detecting a vocalizing group

Both methods provided similar estimates of animal density for periods with no MFA sonar present. Click counting yielded a density of between 25.3 (17.3–36.9) and 22.5 (15.4–32.9) beaked whales per 1000 km^2 depending on the estimate of false positives that was applied. The dive counting methodology was used to estimate the density around a multiship MFA sonar operation. Estimates for the 65-h periods before, during, and after the exercise along with a final period of 43.23 h were completed and yielded densities of 16.99 (13.47–21.43), 4.76 (3.78–6.01), 8.67 (6.87–10.94), and 24.76 (19.63–31.23) respectively.

These passive acoustic methods provide a means of estimating density without the need for costly visual surveys. By utilizing the hydrophones, repeated and long-term estimates are possible across seasons and years. Such long-term population monitoring is especially important in areas of repeated noise exposure. In addition, the application of these methods around actual operations begins to provide insight into the behavioral response of beaked whale on a population level. The decrease in density coincident with MFA use strongly suggests disruption of foraging behavior when animals are exposed to MFA sonar operations. Placing this disruption in the context of population health is the primary goal of any such monitoring.

10.6 A Passive Acoustic Method for Measuring Risk to Behavioral Disruption

For Blainville's beaked whales, the application of passive acoustic methods provides data that suggest a behavioral reaction in response to sonar exposure. To apply these findings within a regulatory framework, a measure of probable risk of biologically significant behavioral disruption at a given exposure level is required. A risk function that maps an exposure level to the probability of causal effect is typically used (Southall et al. 2007). The analysis of Blainville's vocalizations and density around sonar exercises presented above suggests such a relationship.

Initial investigations have led to the development of a risk function that maps sonar exposure levels to the probability of foraging disturbance (Moretti et al. 2014). The function was derived by combining AUTEC passive acoustic and ship track data along with sound field estimates from a propagation model.

Blainville's group vocal periods were isolated from detection archives before and during a 2009 MFA sonar operation. The data were divided into 30-min periods, a time span which approximates the mean time of a vocal period. The estimated baseline probability ($\hat{P}_E$) of a foraging dive on any hydrophone, with no sonar present immediately during the 19-h period before an exercise, was calculated as:

$$\hat{P}_{\mathrm{E}} = \frac{S}{KT}$$

where:

S = the number of group dive starts
T = total number of hydrophones (91)
K = total number of half-hour periods (39)

with w_{ij} taking on the value of 1 if a dive is centered during the period on hydrophone i during the half-hour period j.

The estimated probability of disturbance, ($\hat{P}_{\mathrm{d(rms)}}$), is the probability of a dive not starting at a particular received level of sonar within a 30-min period and is defined as:

$$\hat{P}_{\mathrm{d(rms)}} = \frac{\min(0,\ \hat{P}_{\mathrm{B}} - \hat{P}_{\mathrm{rms}})}{\hat{P}_{\mathrm{B}}}$$

where,

$\breve{P}_{\mathrm{B}}$ = the baseline probability of a dive starting on a hydrophone
P_{rms} = the level received at each hydrophone throughout the exercise

To calculate $\breve{P}_{\mathrm{d(rms)}}$, the level received at each hydrophone throughout the exercise was estimated using the Navy's Comprehensive Acoustic Simulation System/Gaussian Ray Bundle (CASS/GRAB) model (Weinberg & Keenan 1996). Included in the model were the appropriate source characteristics including beam pattern, deflection angle, and source level along with the ships' positions and the times of sonar ping transmissions isolated from the detection archives. For each hydrophone, the maximum receive level (dB re 1 μPa) for each 30-min period of sonar transmission was calculated and those hydrophones with dive starts for each period noted. A Generalized Additive Model (GAM) with a binomial distribution and a logit link function was fit to the data to estimate $\breve{P}_{\mathrm{rms}}$ (Fig. 10.12).

The probability of disturbance ($\breve{P}_{\mathrm{d(rms)}}$) then was calculated using the above equation and a sigmoidal function fit to the data using a Generalized Linear Model with a probit link function (Fig. 10.13). The resulting function provides the probability of acoustic disturbance as a function of RMS receive level, where disturbance is defined as the disruption of foraging.

This provides a parametric equation which can be readily applied in subsequent effects models as follows:

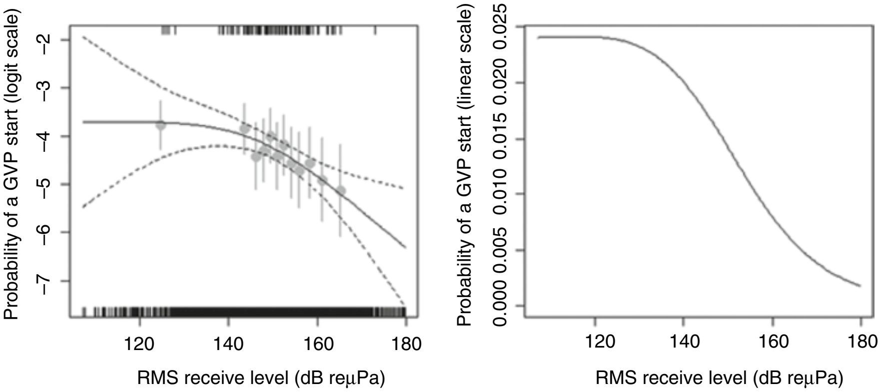


Fig. 10.12 Estimated probability of a GVP start as a function of maximum RLrms in a 30-min segment on a given hydrophone on the logit (*left plot*) and linear (*right plot*) scale. *Dashed lines* indicate point-wise 95 % confidence limits on the fitted relationship. *Short vertical lines* at the *top* and *bottom* of the plots show the data used in the model: those at the *top* indicate the RLrms where GVP starts were observed, while those at the *bottom* of the plots indicate RLrms where GVP starts were not observed. The *grey dots* provide a summary of these data, and can be used to assess the goodness-of-fit of the fitted relationship—they are the proportion of the data where a GVP start was observed, each calculated using approximately 1/12th of the data going from lowest to highest RL. *Grey vertical lines* indicate 95 % binomial confidence intervals on these proportions (Moretti et al. 2014)

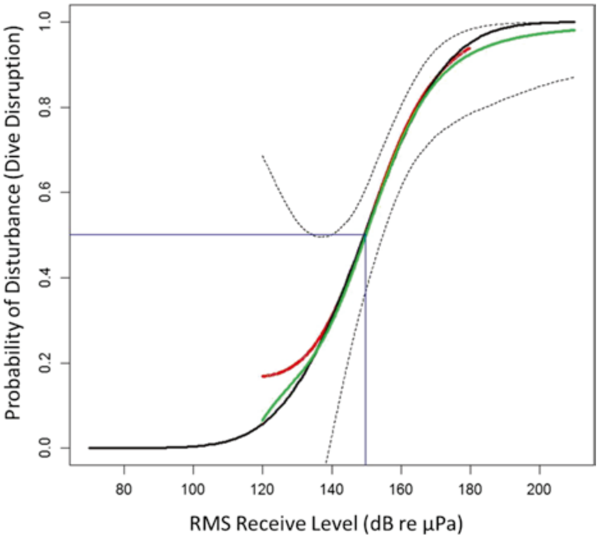


Fig. 10.13 The probability of disturbance $(\breve{P}_{\mathrm{d(rms)}})$ as a function of sonar RLrms. The GAM fit to the recorded data is shown in red with the bootstrap mean shown by the *green* with the pointwise 95 % confidence limits indicated by *dotted lines* from the bootstrap. The parametric GLM approximation is shown in *black*. There is a 0.5 probability of disturbance at a RLrms of 149.8 dB; this is indicated in *blue* (Moretti et al. 2014)

$$P[\text{disturbance}] = F(-8.073 + 0.054 RL_{\text{rms}})$$

where $F(z)$ is the cumulative normal distribution function.

For activities which include acoustic transmissions, environmental compliance demands an estimate of behavioral takes which is defined as a biologically significant change in behavior. To estimate behavioral takes, effect models such as the Navy's Acoustic Effect Model (NAEMO) are used. Typically a risk function is embedded into the model and used to determine the number of takes for a given exercise scenario. The functions used in the past for beaked whales were derived with data from other species including North Atlantic Right whales, captive bottlenose dolphins, and killer whales (Southall et al. 2007). This is the first risk function that is based on both actual navy sonar and in situ beaked whale data.

10.7 Lessons learned

By listening to the ocean, significant advances can be made in our understanding of the environment. The case study of the effect of sonar on Blainville's beaked whales at AUTEC provides an example of how "listening" can be used to answer a question of great concern. It illustrates the steps necessary to apply passive acoustics to the in situ study of animal behavior.

The first step in this process is to have access to the necessary sensors. The navy ranges are unique facilities with a high density of hydrophones spread over large, deep-ocean basins. The listening capability that these facilities provide is unprecedented. It is hard to duplicate such facilities for most applications, but the lessons learned here are applicable at any scale.

The second step is to understand the source. In the case of Blainville's beaked whales, the combined use of passive acoustics, visual observations, and recording tags allowed a species' vocal behavior to be mapped to its physical behavior. A reasonable understanding of when vocalizations were produced, the context in which they were produced, and the rate at which they were produced was documented.

Third, the performance of the passive acoustic tools used and the characteristics of the source were measured. These measurements included the detection probability with range, and the animal's beam pattern and source level.

In the year 2000, little was known about Blainville's beaked whales. By completing these three steps, within 10 years, data necessary to infer the behavior of the animal in the presence of MFA sonar operations were collected. For the first time, a risk function which predicts the probability of behavioral disturbance as a function of sonar exposure level was derived from Blainville's beaked whale and MFA sonar data.

The cumulative population effect of sonar on Blainville's beaked whales at AUTEC remains unanswered. It is unlikely to be answered solely through the application of passive acoustic methods. An area of over 500 nmi^2 can be monitored using the AUTEC hydrophones, but once an animal stops vocalizing or moves off the field of hydrophones, listening becomes impossible. Satellite tags with depth recording capabilities help fill this knowledge gap. The tags document both the extent of movement and of dive disruption.

If animals move off range but continue to execute deep foraging dives, do they suffer a loss in calories? Again, without knowledge of dive success and prey fields off range, it is difficult to know. Prey field mapping using echo sounders may provide the answer.

Do animals within the TOTO represent an enclosed population? Observational studies coupled with biological sampling can be used to determine the extent of mixing between separate study areas.

For Blainville's beaked whales at AUTEC, many open questions remain, but steady progress is being made. For locations with fixed hydrophones like navy ranges, passive acoustic tools provide a means of documenting both short-term and long-term effects of anthropogenic activities on the marine environment. The combining of passive acoustics with complementary technologies multiplies the power of each and helps paint a more complete picture of a given ecosystem. With time, determining the population effect of anthropogenic sound including sonar on cetaceans is possible.

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Chapter 11
Pinniped Sounds in the Polar Oceans

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Abstract New developments and applications of autonomous Passive Acoustic Monitoring (PAM) technology in polar regions have come at time of increased interest in the Arctic and Antarctic due to predictions of global climate change. Information gained with autonomous PAM systems has provided new information on polar pinniped communication, mating systems, distribution, and the relationships between these species and their environment. Although new discoveries continue to be made, there is still much that remains to be learned about these species. This chapter is organized into a review of species specific information known prior to 2000, case studies describing new knowledge gained through the use of autonomous PAM systems since 2000, and future projection on how autonomous PAM systems can be used to address and fill data gaps related to polar pinnipeds.

11.1 Introduction

The topic of climate change has brought renewed interest to polar areas. As glaciers, ice caps, ice shelves, and seasonal sea ice extent decrease, a cascading chain of events is impacting all levels of the ecosystem, as well as human use of Arctic and Antarctic regions. Phytoplankton and zooplankton regime shifts are already being observed in both polar and subpolar environments (Grebmeier et al. 2006; Clarke et al. 2007; McClintock et al. 2008), and human activities related to energy

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exploration and production, shipping, recreation, and tourism are increasing in the Arctic (Arctic Climate Impact Assessment 2005). Changes in marine mammal distribution patterns in the Arctic have been linked to a warming climate (Moore and Huntington 2008). Gray whales (*Eschrichtius robustus*), historically observed to migrate south in winter, were recorded throughout the winter in 2003–2004 in the Beaufort Sea (Stafford et al. 2007), and walrus (*Odobenus rosmarus*) are hauling out on land near feeding areas instead of ice because as the ice retreats further north, walrus are unable to traverse the expanding distances between their shallow feeding areas and resting areas on ice (Metcalf and Robards 2008; Moore and Huntington 2008). In sub-Arctic waters, measurable decreases in Steller sea lions (*Eumetopias jubatus*) and Pacific harbor seals (*Phoca vitulina richardsi*) have been documented in the Gulf of Alaska (Loughlin et al. 1992; Hill and DeMaster 1999; Pitcher 1990). It is hypothesized that the primary driver for the declines is large scale ecosystem changes related to climate change (Kelly 2001). Compared to the extensive efforts that have been launched to monitor and understand changing ecosystem dynamics at lower trophic levels and for marine mammals typically encountered at lower latitudes, the understanding of changing environmental conditions on pinnipeds living in high latitude regions is limited. This is most likely due to a lack of baseline information about polar pinniped ecology resulting from their inaccessibility.

Of the 17 pinniped species encountered in polar and subpolar waters, there are 13 phocid species, three species of otariids, and one odobenid species (Table 11.1). The subpolar regions are loosely defined as (1) the area between the Antarctic Convergence and north of the Polar Front extending to approximately 45° S, and (2) south of the Arctic Circle to approximately 50° N including the Bering Sea, Sea of Okhotsk, North Sea, Labrador Sea, and Hudson Bay (Van Opzeeland and Miksis-Olds 2012). Throughout this work, reference to polar automatically includes the subpolar regions unless specifically designated. The information contained in this chapter reflects the disproportionate number of phocid species and only odobenid species in polar regions by devoting more discussion to the review of information related to phocids and walrus. Information on otariids is provided to enhance the overall understanding of polar pinnipeds by highlighting the similarities and differences between the functional groups. The defining characteristic of all polar pinnipeds is association with sea ice. This is the same characteristic that has made these species so hard to study and why so little information is known about them compared to more temperate pinniped species. Ice-obligate, or ice-dependent, species require ice as a platform for critical life functions such as breeding or moulting [bearded seal (*Erignathus barbatus*), ringed seal (*Phoca hispida*), walrus (*Odobenus rosmarus*), crabeater seal (*Lobodon carcinophagus*), leopard seal (*Hydrurga leptonyx*), Weddell seal (*Leptonychotes weddellii*), and Ross seal (*Ommatophoca rossii*)]. These species have historically never been found far from sea ice. Ice-associated species have evolved morphological, physiological, or behavioral adaptations to exploit sea ice habitats [harp seal (*Pagophilus groenlandicus*), hooded seal (*Cystophora cristata*), grey seal (*Halichoerus grypus*), ribbon seal (*Phoca fasciata*), spotted or Largha seal (*Phoca largha*), and harbor seal (*Phoca vitulina*)] (Tynan et al. 2010). The otariids and southern elephant seals (*Mirounga leonina*) are

Table 11.1 Characteristics related to polar pinniped acoustics known prior to 2000

1	2		3	4	5	6	7	8	9	10	11	12
	Range (P, SP, T)[a]											
Species	Winter	Non-winter	Mating substrate (A, I, L)[b]	Whelping habitat (L, F, P)[c]	Lactation duration (days)[d]	Foraging during breeding /lactation (♂ Y/N, ♀ Y/N)	# Aquatic call types	Aquaticvocal dialects	Sex-specific vocs	Aquatic vocal displays	Repro. strategy	Indiv-specific vocs
Arctic phocids												
Grey seal	P,SP	P,SP	A	L, F, P	12–21	♂Y ♀Y	10	0	0	0	Y_2	Y(air)$_2$
Ringed seal	P,SP	P	A	F	39–41	♂Y ♀Y	4	0	0	0	0	0
Spotted seal	P,SP	P	A	P	14–21	♂Y ♀Y	6	0	0	Y_1	0	0
Ribbon seal	SP	SP	A	P	21–28	♂Y ♀Y	2	0	0	0	0	0
Bearded seal	P,SP	P	A	P, F	12–24	♂Y ♀Y	6–8	0	Y_1	Y_1	Y_1	0
Harbor seal	SP,T	P,SP,T	A	L, F	21–42	♂Y ♀Y	5	0	Y_1	Y_2	Y_2	Y(air)$_2$
Hooded seal	P, SP	P,SP	A	P	4	♂Y ♀N	6	0	Y_1	Y_1	Y_1	0
Harp seal	P, SP	P	A	P	9–15	♂Y ♀Y	26	0	Y_2	0	Y_2	0
Arctic otariids												
Northern fur seal	SP,T	P,SP,T	L	L	120	♂Y ♀Y	2	0	Y_1	0	Y_3	Y(air)$_2$
Steller sea lion	SP,T	P,SP,T	L	L	365–1095	♂N, ♀Y	2	0	Y_1	0	Y_3	Y(air)$_2$
Odobenid												
Walrus	P,SP	P	A	L,P	530	♂Y ♀Y	>10	0	Y_1	Y_2	Y_2	Y(water)$_2$

(continued)

Table 11.1 (continued)

1	2		3	4	5	6	7	8	9	10	11	12
	Range (P, SP, T)^{a}											
Species	Winter	Non-winter	Mating substrate (A, I, L)^{b}	Whelping habitat (L, F, P)^{c}	Lactation duration (days)^{d}	Foraging during breeding /lactation (♂ Y/N, ♀ Y/N)	# Aquatic call types	Aquaticvocal dialects	Sex-specific vocs	Aquatic vocal displays	Repro. strategy	Indiv-specific vocs
Antarctic phocids												
Weddell seal	P	P	A	F	33–53	♂^{b}, ♀Y	>34	Y_2	Y_1	Y_1	Y_1	0
Crabeater seal	P	P	A	P	17–28	♂N, ♀N	6	0	0	0	Y_1	0
Ross seal	P	P	A	P	28–30	0	5	0	0	0	0	0
Leopard seal	SP, P	P	A	P	30	0	12	Y_1	N_1	0	0	Y(water)$_1$
Southern elephant seal	SP	SP, P	A, L	L	20–25	♂N, ♀N	0	0	Y_2	N_2	Y_3	Y(air)$_3$
Antarctic otariid												
Antarctic fur seal	SP,T	P,SP,T	L	L	120	♂N, ♀Y	0	0	Y_1	0	Y_2	Y(air)$_2$

This summary table is a compilation of information known about polar pinnipeds prior to 2000. Information in columns 2–6 relate to the distribution, behavior, and substrate use of each species associated with critical life functions. This information is needed for appropriate comparison and contrast of behavioral and acoustic characteristics between species. Information in columns 7–12 are either acoustic parameters directly related to acoustic communication or behavioral parameters concluded from the analysis and interpretation of acoustic data. Unless otherwise designated, the level of information for each parameter is evaluated by the authors on a 0–3 scale where zero indicates no known information and three indicates a detailed level of information that has been directly observed or measured

[a] *P* polar, *SP* subpolar, *T* temperate

[b] *A* aquatic, *I* ice, *L* land

[c] *L* land, *F* fast ice, *P* pack ice

[d] Length of the fasting period differs substantially between the sexes, with females fasting for ~4 weeks and males up to 3 months (Riedman 1990)

seasonal inhabitants of polar waters and can often be found in the open pack ice, but ice is largely a barrier to these species (Tynan et al. 2010).

The ice-associated existence of polar seals has historically prevented study of these animals by direct observation, capture, or tagging due to the hazardous conditions of their remote and extreme locations on unstable ice or near the ice-edge. Much of the basic biological information on polar pinnipeds prior to 2000 resulted from captive studies, acoustic telemetry of information transmitted from animals tagged on land or during the summer, and traditional ship-based surveys during the non-winter months. Acoustic recordings made during visual surveys in combination with knowledge gained from captive recordings has provided the foundation for the interpretation of signals detected in acoustic recordings recently acquired with autonomous passive acoustic sensors or systems. Information gained through the use of autonomous passive acoustic technology has increased our knowledge about the acoustic communication of specific polar species, which has in turn provided new insights on polar pinniped mating behavior and strategies, seasonal movements and distribution, and acoustic ecology.

The structure of this chapter functions as a road map to describe how autonomous passive acoustic monitoring (PAM) devices are being used to fill data gaps in our understanding of polar pinniped species. In order to fully appreciate the state of our current knowledge and the potential for future knowledge gains with autonomous PAM, we must first review the state of the field prior to the use of this technology and the challenges that have been overcome in the application of autonomous PAM technology in polar environments. Research that applied data obtained from an autonomous PAM system to the study of polar pinnipeds first appeared in the scientific literature in 1982. Thomas and DeMaster (1982) deployed a single element system from an ice floe to record leopard and crabeater seals off the Antarctic Peninsula. Over a decade later, at the very end of 1999, information gained through the use of autonomous PAM sensors and systems started to consistently be reported in the scientific literature. Early work applied autonomous recordings to the study of harbor seals (a seasonal polar inhabitant) in nonpolar waters (Van Parijs et al. 1999). The first study to apply knowledge gained from autonomous recordings in Arctic waters used recordings made in the early 1980s to provide new information about bearded seals. This work was first published in the mid-2000s (Van Parijs and Clark 2006). The year 2000 was selected as the benchmark for discussing new acoustic information about polar pinnipeds because it represents a time when new PAM technology started to be applied directly to the study of polar pinnipeds and when information on polar pinnipeds mined from past recordings targeting other marine mammal species started to appear in the scientific literature.

11.1.1 Polar Pinniped Life History

Pinnipeds often are used to demonstrate trends in mammalian reproductive strategies (e.g., Le Boeuf and Reiter 1988). They offer numerous advantages for studying reproductive success in polygynous, long-lived mammals. All pinnipeds evolved from a terrestrial ancestry to a mainly aquatic life style, retaining certain terrestrial traits while adapting to pelagic foraging (Stirling 1975, 1983). In 1970, Bartholomew identified terrestrial parturition and aquatic foraging as the prerequisites for the evolution of polygyny in pinnipeds. This spatial and temporal separation of feeding from reproduction is a fundamental component influencing the reproduction of all pinnipeds, regardless of their breeding system (Van Parijs et al. 1997). Therefore, the critical factors shaping mating systems in pinnipeds, such as foraging behavior and distribution, may vary considerably from land mammals. Studies of pinniped reproductive strategies offer an opportunity for examining the evolutionary adaptations of a long-lived mammal to a semiaquatic environment. Of these, polar pinnipeds present the greatest challenge due to the inaccessibility of these species (Van Parijs 2003; Van Opzeeland et al. 2008).

Adaptations to aquatic feeding have resulted in reproductive patterns that incorporate varying periods of time spent fasting on land or ice and feeding at sea. In most pinnipeds, oestrus is seasonally synchronous. Females, therefore, are highly synchronized in the timing of parturition (Stirling 1975, 1983). In addition, the relative rarity of suitable pupping sites on land or ice also results in females being highly aggregated. Consequently, females are often clumped in both time and space during parturition, estrus, and weaning (Boyd 1991). Previously, studies of pinniped reproductive strategies concentrated on those species that remain ashore during the entire breeding season. However, the Odobenidae and at least 15 out of the 18 phocid species mate aquatically, representing 47 % of the pinnipeds (Van Parijs 2003). All the ice-obligate or ice-dependent pinnipeds (seven species) are thought to mate aquatically. While all ice-associated species, mate either wholly or partially in the water.

In pinnipeds, the role of vocal behavior in the breeding season differs between land-breeding and aquatic-mating species. On land, the relative rarity of areas suitable for pupping and haul-out leads to the formation of dense female breeding aggregations, which enables males to defend harems and compete with other males for a place within the female breeding group (Bartholomew 1970). In aquatic mating species, females are more dispersed causing female movements to be both spatially and temporally less predictable (Van Parijs 2003). As a consequence, females are less efficiently monopolized by males and therefore males must aim to attract females for the purpose of mating (e.g., Harcourt et al. 2007). For those species of aquatic mating pinnipeds where data are available, males are known to retain under water display areas using vocal and dive displays which are thought to function in male-male competition and/or male advertisement to females (see Van Parijs 2003 for a review). In land-breeding pinnipeds some species produce in-air vocalizations, but these are mainly directed towards other males and serve to maintain boundary areas (Warneke and Shaughnessy 1985; Fernandez-Juricic et al. 1999; Tripovich et al. 2008).

As acoustic behavior is in most cases assumed to have a dual function (i.e., male-male competition and mate attraction), the proportional usage of different call types could be expected to vary on a seasonal or daily scale reflecting different social contexts in which vocalizations are used. Nevertheless, as many aquatic mating pinnipeds are ice-breeding species and occur at high latitudes, acoustic measurements are often only possible during restricted time periods (e.g., Stirling 1973; Møhl et al. 1975; Thomas and DeMaster 1982; Thomas and Kuechle 1982; Pahl et al. 1997; Watkins and Ray 1985; Cleator et al. 1989). In addition, studies on polar species that include recordings over multiple years have been rare because of the difficulties of obtaining repeated recordings. Despite the challenges associated with observing and acoustically recording polar pinnipeds, especially aquatic mating species, pioneering work describing the biology, ecology, and vocal repertoire of these species prior to 2000 fueled the evolution of autonomous PAM technology appropriate for use in the harsh polar climates and provided the necessary information to begin to interpret acoustic recordings made without concurrent visual observations. The next section describes the state of knowledge of polar pinniped behavioral ecology prior to 2000 with a particular emphasis on sound production.

11.1.2 State of Knowledge Prior to 2000

11.1.2.1 Antarctic Phocids

As three of the Antarctic phocid species (crabeater, leopard and Ross seal) breed on pack ice, access to colonies or individual animals to collect data on behavior and overall biology is logistically challenging. Much of the knowledge of these species prior to 2000 is based on opportunistic observations and physiological measurements conducted during sealing expeditions (e.g., Øritsland 1970), or (anecdotal) information that was collected alongside other research programs (e.g., Bertram 1940; Siniff and Bengtson 1977; Thomas et al. 1980). Most of these early studies focused on physiology, foraging and breeding biology, and provided data on diet from stomach contents as well as information on the timing of parturition, lactation behavior, and in some cases interactions between male and female animals on the ice (e.g., Brown 1957; Corner 1972; Siniff et al. 1980; Shaughnessy and Kerry 1989). Following these initial studies, studies in the mid-nineties started using time-depth-recorders (TDRs) and GPS tags to investigate diving behavior and movement patterns (e.g., Bengtson and Stewart 1997; Nordøy et al. 1995). For the Weddell and southern elephant seal that breed on fast-ice and land, respectively, easier access to animals allowed early dedicated field campaigns to investigate the species-specific ecology and colony behavior on a larger number of animals (e.g., Lugg 1966; Klopfer and Gilbert 1966; Stirling 1969; Kaufman et al. 1975; Muller-Schwarze et al. 1978).

Since the days of the early Antarctic explorers some of the Antarctic phocids had been known to produce in-air and underwater vocalizations (Wilson 1905; Perkins 1945). The first published record of Antarctic pinniped underwater vocalizations accounts are from Lindsey (1937 in Kooyman and Kooyman 2009) who used a phonograph to record sounds of Weddell seals in the Bay of Whales, off the Ross Ice Shelf. Further acoustic recordings of Antarctic phocids were made around 1965 when portable acoustic recording equipment that could be taken into the field became available (e.g., Watkins 1963; Schevill and Watkins 1965).

Crabeater seals are year-round residents of the Antarctic pack-ice and forage predominantly on Antarctic krill (*Euphausia superba*). Despite their widespread distribution across the Southern Ocean and their abundance, estimated population size between 7 and 14 million (Southwell 2008), most of the behavioral studies that have been conducted on this species are based on opportunistic encounters and observations on the ice of single or few individuals over time spans ranging from hours to days during the breeding season (e.g., Corner 1972; Siniff et al. 1979; Shaughnessy and Kerry 1989). Consequently, prior to 2000, relatively little was known on their behavior throughout the year and the role sound plays in their survival. On some occasions, stranded crabeater seals have been caught and studied in captivity (Ross et al. 1976; Klages and Cockcroft 1990). However, animals did not survive long and no sounds were reported to have been recorded. Stirling and Siniff (1979) were the first to describe the underwater crabeater moan or groan, a relatively simple and short broadband grunt-like call. Prior to 2000, no further function could be ascribed to these vocalizations, although calls were thought to be agonistic in nature given their growl-like sound and the fact that courtship and mating were known to occur during the period that recordings were made (Stirling and Siniff 1979). Thomas and DeMaster (1982) sampled underwater vocal behavior of crabeater and leopard seals and provided information on the hourly variations in vocalization rates, suggesting data on diurnal patterns in vocal behavior might be used during a census to calculate correction factors that compensate for submerged seals. In-air vocalizations have been reported to occur in crabeater seal mother–pup pairs if the pair is separated (Siniff et al. 1979). However, it is not known if these calls exhibit individually specific acoustic cues and what role vocal communication plays in relocation and recognition of crabeater seal mother–pup pairs.

Leopard seals migrate to and beyond the outer fringes of the Antarctic sea ice in austral winter and move back to the inner pack ice to breed in austral summer (Siniff and Stone 1985). Their solitary nature, pack-ice habitat, and the hazard of potential leopard seal attack complicate investigation; consequently, only very few have studied the behavior of free-ranging leopard seals. Prior to 2000, Brown (1957) and Dearborn (1962) were the first to provide verbal descriptions of in-air leopard seal vocalizations. Ray (1970) first published part of a spectrogram of a leopard seal underwater call. Complete spectrograms of four leopard seal underwater calls were provided by Stirling and Siniff (1979), whereas information on diel patterns in their vocal activity was provided by Thomas and DeMaster (1982). Stirling and Siniff (1979) described alternate cycles of vocalizing and breathing, and suggested calls may have a territorial function. Leopard seal calls were also found to vary between different recording locations around the Antarctic continent (Thomas and Golladay 1995). Much of the more detailed knowledge on leopard seal vocal behavior and the behavioral context in which calls are produced, stems from studies on captive animals. Rogers et al. (1995, 1996) studied two males and a female leopard seal in captive facilities and found that they produced twelve call types throughout much of the year (local calls), whereas six call types (broadcast calls) were produced by lone seals during December and January, the months during which breeding is thought to take place in wild leopard seals. By deducing hormonal concentrations from the captive animals, Rogers et al. (1995) were also able to show that the female only vocalized when sexually receptive. As leopard seals are a solitary species, broadcast calls may specifically function to communicate with and/or attract potential mating partners over long distances (Rogers et al. 1996).

Ross seals are frequently described as the least known of the Antarctic pinnipeds. Surveys often yield few Ross seal sightings relative to the other Antarctic species; until 1972, only 200 sightings were reported (Hofmann et al. 1973). Ross seals occur in low densities in heavy pack ice regions throughout the Antarctic (Riedman 1990). Early Antarctic explorers noted the typical Ross seal sounds, which animals produce in air with closed mouths (Wilson 1905; Perkins 1945). Ross seal vocalizations were first recorded by Ray (1970). Watkins and Ray (1985) recorded both in-air and underwater Ross seal vocalizations, describing them as "siren calls" referring to the frequency modulation within many of their vocalization types. Interestingly, as noted by Watkins and Ray (1985), calls often consist of two independently varying tones, modulated at the same rate. Little is known on sound production mechanisms, but Racovitza (1900 in King 1969) suggested that the palate is very expansible and could be distended with air potentially functioning like a bagpipe to produce the siren-like sounds. Alongside the siren calls, Ross seals also produce pulsed chugging sounds, both in-air and underwater. Prior to 2000, all Ross seal calls had been recorded opportunistically either in December or January by Ray in 1966, Rogers in 1997, and Stirling in 1999 (summarized in Stacey 2006). Nevertheless, there was little to no recording effort (in pack-ice areas) outside these months during that time, leaving it unresolved if the animals also vocalized during other months. Watkins and Ray (1985) noted that calls were likely to come from seals which were spread out over the area and not from congregated groups. As calls are so conspicuous, standing out from other springtime noises, Watkins and Ray (1985) further hypothesized that the sounds may function for Ross seals to locate other individuals.

Weddell seals occur in greatest abundances in the Antarctic coastal regions, where they occupy fast-ice areas during much of the breeding season (Riedman 1990). Both the Weddell seal's land fast-ice habitat and the ease with which animals can be approached have enabled detailed investigation of their behavior and ecology, relative to the other Antarctic pinniped species. Weddell seal calls were first described by James Weddell (1825), a British sealing captain who speculated he heard mermaids "making a musical noise." Lindsey (1937) was the first to record Weddell seal underwater sounds, whereas the first quantitative analysis of Weddell seal vocal behavior was not conducted until 1982 (Thomas and Kuechle 1982). Weddell seals have an extensive vocal repertoire, consisting of up to 34 different call types (Thomas and Kuechle 1982). Calls are in some cases relatively complex, consisting of multiple elements and often are frequency and/or amplitude modulated. Both male and female seals produce underwater vocalizations, although females are thought to be less vocal underwater than males (Thomas and Kuechle 1982). The "trill" vocalization, a long-duration call decreasing in frequency, is thought to be produced exclusively by males in defense of underwater territories and/or to attract females (Kooyman 1981; Thomas et al. 1983). Some of these underwater call types are also produced with closed mouths in air (Thomas and Kuechle 1982; Terhune et al. 1994). In addition to these in-air calls produced with closed mouths, Weddell seal mother–pup pairs produce bawling vocalizations with open mouths while hauled out, which presumably function for the pair to maintain contact and to relocate each other once they get separated (Kooyman 1975)

To investigate the function of vocalizations, two studies performed playback experiments in Weddell seal breeding colonies (Watkins and Schevill 1968; Thomas et al. 1983). They both found that in most cases seals responded to specific playbacks with particular vocalizations, with responses being less common in non-breeding colonies, further supporting the hypothesis that calls are related to breeding behavior. Accordingly, Weddell seal call rates show a peak in November during the breeding season, decreasing in numbers again in December (Green and Burton 1988). Without speculating on the potential function, Green and Burton (1988) also report that they recorded, albeit few, Weddell seal vocalizations between January and June. Weddell seal calls exhibit geographic variation in composition and acoustic characteristics between different breeding populations along the Antarctic coastline (Morrice et al. 1994; Thomas et al. 1988). This is likely a consequence of the species' pronounced breeding site fidelity. Morrice et al. (1994) compared the vocal repertoires of two breeding groups separated by 20 km and found both groups only had a small percentage of their repertoire in common, reflecting that there is little to no exchange between neighboring groups.

Southern elephant seals have a circumantarctic distribution, occurring mainly in subantarctic waters, with the subantarctic islands as the predominant locations where animals haul out to rest, breed, and moult (Ling and Bryden 1981). Although most haul outs occur on land, animals in the southern sector of their range have been observed to haul out on ice (Laws 1953). Most studies on elephant seals have been conducted on the relatively smaller sister-species of the southern elephant seal, the northern elephant seal (*Mirounga angustirostris*). Patterns in behavior of southern elephant seals nevertheless show many similarities with the northern species, which is why some information on the northern species is included here as well.

Breeding, including mating, in elephant seals occurs on sandy beaches, with dominant males defending harems of up to several dozens of females (Riedman 1990). Although much is still unknown on southern elephant seal behavior during their pelagic phase, many detailed accounts exist of social behavior during the breeding season as individuals can be easily observed while on land (e.g., Laws 1953; Carrick et al. 1962; Ling and Bryden 1981). Southern elephant seals produce in-air calls during the breeding season. The most common vocalizations are male threat calls consisting of a train of low pitched sounds resembling drum beats, which can be further subdivided in syllables and syllable parts (Shipley et al. 1981). These male threat calls are produced during stylized displays between dominant males. Although many displays are ritualized once dominance is established, some also result in combat. In contrast to the sound records of aquatic mating phocids, acoustic recordings of southern elephant seal threat calls can be combined with visual observations of vocalizing individuals on the breeding beaches, potentially enabling inclusion of dominance-related parameters such as age, size and reproductive status in analyses. Prior to 2000, the only data published on southern elephant seal acoustic behavior included a few recordings (LeBoeuf and Petrinovich 1974). Northern elephant seal bull threat calls are known to be individually distinctive which was hypothesized to enable males to recognize each other thereby avoiding energy expenditure and injury risk of fighting subordinate bulls (Shipley et al. 1981). Shipley and Strecker (1986) also found that in northern elephant seals, levels of vocal activity were greatest in the hours following sunset, presumably suggesting that animals avoid vigorous physical activity during the warmest period of the day. Apart from threat calls, a wide variety of snorts, sneezes, whistles, grunts also contribute to the vocal repertoire, albeit without apparent behavioral significance (Ling and Bryden 1981). Female southern elephant seals with pups produce a high frequency moaning sounds which fall and rise in pitch and are accompanied by vertical head shakes with open mouths (LeBoeuf et al. 1972). Females produce this call shortly after giving birth and in response to pup distress calls. Pups emit a sharp barking sound which occasionally receives a response from the mother (Ling and Bryden 1981). Northern elephant seals mothers are known to discriminate between playbacks of own and alien pups, suggesting that in this species' calls serve to facilitate relocation once the pair gets separated in the breeding rookery (Klopfer and Gilbert 1966; Petrinovich 1974). Nothing has been reported on underwater sound production in elephant seals.

11.1.2.2 Arctic Phocids

Ringed seals are the most numerous and widely distributed Arctic phocid (King 1983). These ice-breeding seals overwinter in landfast sea ice and in dense pack ice where they self-maintain breathing holes with the claws on their foreflippers. In winter and spring, ringed seals dig subnivean lairs in snow accumulated over breathing holes for protection from polar bears, their primary predator, and for whelping and parturition. Both males and females actively defend territories that may include several breathing holes and subnivean lairs (Smith and Stirling 1975). Although studies of the physiology, morphology, life history, and distribution of this species have been undertaken since the early 1900s, relatively few behavioral studies were conducted in the wild prior to 2000, likely due to sea ice habitat preferences and the fact that animals remain hidden from view at the surface for a significant portion of the year. Ringed seals were thought to be silent until Stirling (1973) described their high and low-pitched yelps, barks, and growls from underwater recordings made in the High Canadian Arctic, also noting that the seasonal proportion of call types recorded changed from winter to spring, with more barks than yelps in winter and the opposite in spring. Ringed seal calls often occur in alternating sequences of barks and yelps, which Stirling (1973) hypothesized may be call–countercall sequences, involved in maintenance of social structure around breathing holes. Further studies expanded the repertoire to include medium and low pitched barks and woofs (Stirling et al. 1983) and analyzed geographical variation in the detection rates of calls (Stirling et al. 1983; Calvert and Stirling 1985), finding that ringed seal call detections were highest near the mouths of bays and in areas with the most suitable sea ice conditions for construction of birth lairs. Calvert and Stirling (1985) also showed a diel cycle in vocalization rates, with the highest number of calls recorded during the day.

Bearded seals are widely distributed across the Arctic and sub-Arctic, preferring drifting pack ice and polynya habitats over the continental shelf in water less than 200 m deep (Burns 1981; Stirling et al. 1982). They make distinctive frequency-modulated trills that at times are audible in air above the sea ice (Freuchen 1935; Dubrovskii 1973; Chapskii 1938). Estimates of underwater propagation distance of these powerful vocalizations suggest that they can be detected with hydrophones from distances of 25 km or more (Stirling 1983; Cleator et al. 1989). These calls are most likely produced by males as a display to attract females and establish territory during the mating season (Poulter 1968; Ray et al. 1969; Burns 1981; Stirling et al. 1983; Cleator et al. 1989; Cleator and Stirling 1990). However, it has been suggested that females also produce a small number of sounds (Cleator et al. 1989).

Stirling et al. (1983) provided a general description of the acoustic repertoire of bearded seals and found that vocalization rates increased from winter to early summer at some, but not all recording sites. Diel patterns in calling rate also exist, with a daily peak in vocalizations in the early morning and in some cases a smaller peak between afternoon and early evening (Cleator et al. 1989). A quantitative analysis of the bearded seal call repertoire described seven types of trills, recorded at five sites in the Canadian Arctic and one location in Alaska (Cleator et al. 1989). Several call types showed significant geographic variation in frequency and duration, and proportion of call type use across recording sites (Cleator et al. 1989). Bearded seals also produce stereotyped sequences of calls, the proportion of which varies geographically as well (Cleator et al. 1989). Additionally, recordings made of a lone seal suggest that bearded seals have some level of individual variation in spectral characteristics of trills (Cleator et al. 1989). Acoustic recordings have also been used to investigate the relative abundance and habitat preferences of bearded seals. An analysis of spring calling rates across seven sites in the Northwest Territories from 1982 to 1984 provided an assessment of suitable habitat conditions and indicated that they preferred areas of less stable sea ice where breakup occurred early and avoided stable, landfast ice or areas heavily used by walruses (Cleator and Stirling 1990).

Spotted seals mate, whelp, nurse, and moult primarily on sea ice in subarctic waters of the Bering Sea, Yellow Sea, and Sea of Okhotsk in winter and spring (Burns 1970; Lowry 1985; Mizuno et al. 2002). In open water, they are more closely associated with coastal areas as far north as the Chukchi and Beaufort Seas and typically haul out on shore (Frost et al. 1993; Lloyd et al. 1998). There have been very few studies of spotted seal behavior and only one published analysis of their vocalizations by Beier and Wartzok (1979). One unique behavioral aspect of the species among Arctic phocids is the formation of monogamous breeding pairs that remain stable throughout a mating season (Tikhomirov and Kosygin 1966; Burns 2002). Beier and Wartzok (1979) conducted the first extensive study of the underwater mating behavior of a seal species with two captive spotted seals. Mating was observed over 4 years and observations of behavior were recorded before, during, and after copulation. The captive spotted seals produced six call types, described as growl, drum, snort, chirp, bark, and creaky door. While most call types were produced by both the male and female, 94 % of growls were from males and 82 % of barks were from females. Mating attempts were preceded and followed by increases in vocalizations, especially growls and drumming. This study is unique in its detailed correlation of vocalizations with visual observation of other behaviors associated with mating. Beier and Wartzok (1979) hypothesized that increases in the rates of interactions and vocalizations prior to mating may facilitate successful pair bonding during the mating season and could help to maintain pair contact in sea ice habitat.

Harp seals are a migratory species of Arctic phocid that feed in northern waters during summer and fall then move south in winter to ice-covered areas where they aggregate in large groups for whelping, breeding, and moulting during spring (Lavigne and Kovacs 1988; Sergeant 1991; Lydersen and Kovacs 1999). During early spring, harp seals form dense breeding herds in which most females synchronize delivery of pups to within a one week period, resulting in many pups on the ice at one time (Sergeant 1991).

Harp seals produce a large variety of underwater sounds during their breeding season (Møhl et al. 1975; Watkins and Schevill 1979; Terhune and Ronald 1986). Møhl et al. (1975) described 18 call types that varied from constant tones to calls that were broadband and highly variable in frequency. Watkins and Schevill (1979) noted that harp seal calls most commonly occur in pairs and that 75 % of vocalizations exhibit some or all of the characteristics of increasing frequency, increasing amplitude, increasing within-call pulse rate, and repetition. These common characteristics likely help to overcome the effect of masking caused by high calling rates within a herd and/or high levels of ambient noise from sea ice, and make calls more detectable at near and far distances (Watkins and Schevill 1979; Terhune and Ronald 1986). Calling rates of 32–88 calls/min and within-call repetition rates of 1.9–4.7 sound pulses/call have been documented (Terhune et al. 1987).

Harp seal vocalizations likely play an important role in courtship and other breeding-related activities (Terhune and Ronald 1976, 1986; Watkins and Schevill 1979). Increases in calling activity occur in mid-March, when courtship and mating are known to begin (Terhune and Ronald 1976). Additionally, direct observations of captive and free-ranging harp seals have shown that individuals produce vocalizations while engaged in what appear to be threat displays, associated with mating (Møhl et al. 1975; Merdsoy et al. 1978). Another function for these calls is likely to aid in the formation and maintenance of the large breeding herds (Watkins and Schevill 1979; Terhune and Ronald 1986).

Harp seal pups produce in-air vocalizations from shortly after birth (Kovacs 1987). These vocalizations are highly variable and structured and may facilitate mother–pup interactions (Miller and Murray 1995). Kovacs (1995) found further evidence that this calling aids mothers in locating pups in dense breeding herds with many pups. The wide variety of acoustic structures within pup vocalizations may also reflect the basis for development of the large and relatively complex acoustic repertoire exhibited by adults (Miller and Murray 1995).

Geographic variation and a high degree of stability in the vocal repertoires of harp seal herds were well-documented prior to 2000. Terhune and Ronald (1986) found no change in the repertoire of harp seals from underwater recordings made during the breeding season in the Gulf of St. Lawrence, Canada over 10 years. In subsequent studies, the repertoire of that herd differed significantly from Jan Mayen Island, Norway (Terhune 1994; Perry and Terhune 1999) and was similar to the repertoire of the herd breeding at the ice front east of Labrador, Canada (Perry and Terhune 1999). These results support those of satellite telemetry studies, suggesting that interbreeding occurs between St. Lawrence and Labrador, but not with the Jan Mayan herd (Sergeant 1991).

Harp seals have been hunted extensively and some studies have investigated the impact that the associated vessel traffic may have on their behavior. Ronald and Terhune (1978) and Terhune and Ronald (1979) found that the presence of sealing vessels affected the vocalization rates of harp seals. In both studies, the vocalization rates decreased when vessels were in the recording area.

Hooded seals tend to be mostly pelagic and solitary outside the breeding and moulting season, which is reflected in a rather simple vocal repertoire typical of nonsocial species (Kovacs 2009). Hooded seals are aquatic mating animals that breed on pack-ice. They form three unit breeding herds, or triads, composed of an adult male, adult female, and pup, which is not sired by the attending male, but is offspring from the previous breeding season (Boness et al. 1987; Kovacs 1990). The breeding season lasts only a few weeks with a lactation period of 4 days, the shortest of any pinniped species (Bowen et al. 1985). Their solitary, pelagic existence outside the short breeding season has not lent to detailed observational studies resulting in little information about their behavior, ecology, or life history.

The first study to report any information about the vocal repertoire of hooded seals was by Schevill et al. (1963). This study recorded low frequency click sounds from a young captive male. Terhune and Ronald (1973) recorded wild hooded seals in a pupping area and described in-air vocalizations from adult females and pups. Underwater vocalizations were recorded from adult males and were described as low-intensity pulsed calls and clicks that all appeared to be variations of a single call type. The subtypes were referred to as grungs, buzzes, and snorts based on their audible characteristics (Terhune and Ronald 1973). Ballard and Kovacs (1995) recorded both in air and underwater sounds from hooded seals during breeding seasons in the late 1980s in the Gulf of St. Lawrence, Canada. The sounds produced with inflation of the hood and septum were observed to be produced by males hauled out on the ice. This was also noted by Terhune and Ronald (1973). Females produced growls and roar vocalizations in-air more often than males and mostly during agonistic interactions (Ballard and Kovacs 1995). Four different in-air vocalizations were recorded from pups prior to and following weaning (Ballard and Kovacs 1995). Ballard and Kovacs (1995) described additional underwater vocalizations as clicks, knocks, and short trills. Snorts, as described by Terhune and Ronald (1973), were heard in the Ballard and Kovacs (1995) study but not described due to low signal-to-noise ratios. Buzzes were not recorded at all by Ballard and Kovacs (1995), and the knocks were similar to the grung sound recorded by Terhune and Ronald (1973).

Gray seals have a cold temperate to sub-Arctic distribution in North Atlantic waters over the continental shelf (Bonner 1981). There are three populations isolated both geographically and by timing of reproduction. Gray seals mate both on land and in the water (e.g., Cameron 1969; Anderson et al. 1975; Boness and James 1979; Godsell 1991). Recent genetic evidence confirmed that a significant proportion of copulations occur in the water either around the haul out site or further out to sea (Worthington Wilmer et al. 1999). This suggests that aquatic mating may be a component of male gray seal reproductive strategies. Gray seals give birth on land, floe, and fast ice with lactation lasting between 12 and 17 days (Boness et al. 1994).

The first gray seal vocalization to be described were underwater clicks recorded from captive gray seals (Schevill et al. 1963). Clicks occurred at random and in series. Additional underwater gray seal vocalizations were described by Schusterman et al. (1970), and in-air calls were described by Fogden (1971). Underwater sounds produces by captive, 6–7 month old gray seals were described as clicks, buzzes, humming, and moaning (Schusterman et al. 1970). A more recent study on ice breeding gray seals described up to seven underwater vocalizations, the rate of which increased at the height of the breeding season (Asselin et al. 1993). Detailed studies on mother–pup vocalizations in air have also been conducted (Caudron et al. 1998; McCulloch et al. 1999; McCulloch and Boness 2000). Playback experiments demonstrated that gray seals mothers can discriminate between pup calls using the stereotyped and individually distinctive vocalizations of their pup (McCulloch and Boness 2000). However, they also showed difference in discrimination abilities between sites, suggesting that different locally differing selective pressures may be in operation.

Harbor seals have the broadest distribution and inhabit the widest range of habitats of any other pinniped (e.g., Stanley et al. 1996). Denizens of the coastal and continental shelf waters of the North Atlantic and Pacific Oceans, harbor seals haul out on land or glacial ice floes to rest, breed, moult, and nurse their young. Their lactation period can range from 24 to 42 days in length (Bowen et al. 1992). Females forage at sea during late lactation (e.g., Bowen et al. 1992; Boness et al. 1994; Thompson et al. 1994). Therefore, females are mobile at sea when they become receptive and cannot be economically monopolized by males on land or on the ice.

Harbor seals are of the key species where male aquatic mating vocal behavior has been studied in detail prior to 2000. The first underwater vocalizations were recorded by Schusterman et al. (1970). In-air vocalizations were examined in a captive harbor seal that demonstrated an ability to mimic various human sounds (e.g., Ralls et al. 1985). Other studies also showed that harbor seals can produce a range of in-air sounds, some which serve as mother–pup calls while others are related to male agonistic encounters at the haul out site (Sullivan 1982). In water, male harbor seals form underwater display territories (Hanggi and Schusterman 1994; Van Parijs et al. 1997) and produce low frequency underwater growls that are used in male-male competition (Nicholson 2000; Hayes 2002). No clear data exist to prove that vocalizations are used for female attraction, mainly due to the difficulties of assessing female responses in reaction to male vocalizations at sea. Within-species variation in male vocal and display behavior appears to be closely linked with habitat type and resulting changes in female behavior (Perry 1993; Coltman et al. 1997; Van Parijs et al. 1997, 1999, 2000). These studies suggest that males adapt their mating strategies in accordance with the degree of uncertainty in female movement patterns between the haul out sites and feeding habitats. Studies from all habitat types report that male harbor seals perform stereotypic underwater displays consisting of short dives combined with the production of underwater roar vocalizations during the period when females are in estrus (e.g., Hanggi and Schusterman 1994; Bjørge et al. 1995; Coltman et al. 1997; Van Parijs et al. 1997; Nicholson 2000). The occurrence and frequency of display behavior can vary among geographical areas and habitat types. For example, males in Scotland restrict their displays to the breeding season (Van Parijs et al. 1997), while males in California display all year round with a peak in frequency during the breeding season (Nicholson 2000; Hayes 2002). Prior to 2000, it was not known if there was geographic variation in the vocalizations used in displays.

The ribbon seal is an aquatic-mating species endemic to the North Pacific with three recognized populations: two in the Okhotsk Sea and one in the Bering Sea (Fedoseev 2002). Ribbon seals are not able to maintain breathing holes in ice thicker than 10–15 cm, which was thought to limit their northern range and restrict habitat use in the Bering Sea to areas of thick, stable but broken sea-ice near the ice-edge. In the Bering Sea, ribbon seals become pelagic and remain in the area during the ice-free months (Burns 1970). Little is known about their distribution, behavior, or communication outside the winter breeding season. Compared to other aquatic-mating pinnipeds in polar regions, relatively little is known about the mating system, foraging, or vocal behavior of ribbon seals (Van Parijs 2003; Van Opzeeland et al. 2008). This is most likely due to their pelagic and ice-edge associated existence which makes direct observation, capture, and tagging difficult, unsafe, and for the most part logistically unfeasible. Prior to 2000, there was only one publication describing the vocalizations of the ribbon seal. Watkins and Ray (1977) described intense downward frequency sweeps and broadband "puffing" sounds. These sounds were recorded in the presence of ribbon seals off the coast of St. Lawrence Island, Alaska in the Bering Sea in 1967. Prior to 2000, there was no published information about mating behavior, in-air vocalizations and underwater acoustic behavior outside the sub-Arctic regions and outside the winter/spring breeding period.

11.1.2.3 Polar Otariids

Compared to polar phocid species that mate aquatically, polar otariid life history characteristics have provided greater accessibility for observation on land, which has resulted in a disproportionate amount of information on land-based vocalizations and behavior. Otariids (Antarctic fur seal [*Arctocephalus gazelle*], Northern fur seal [*Callorhinus ursinus*], and Steller sea lion) are seasonal inhabitants of polar regions, breed on land, and have significantly longer on-substrate lactation periods compared to phocids (Table 11.1). Additionally, walrus and polar otariid species were maintained in captivity prior to 2000 (Ridgway and Harrison 1981). The combination of natural and captive accessibility led to detailed studies of behavior, foraging, breeding, diseases, population dynamics, and physiology prior to the development of passive acoustic monitoring technology ([Steller sea lion review (Schusterman 1981)], [Northern fur seal review (Gentry 1981)], [Antarctic fur seal review (Bonner 1981)]).

Airborne vocal communication between mothers and pups was the first category of vocalizations to be described for polar otariids species ([Northern fur seal (Bartholomew 1959)], [Steller sea lion (Orr and Poulter 1965)], [Antarctic fur seal (Bonner 1968)]). These contact vocalizations were likely to be the most visible to observers during the lactation period and most easily associated with the specific function of maintaining mother–pup contact. Insley (1992) showed that mother–pup contact calls were stereotyped and individually distinctive in Northern fur seals, which aids in mother–pup recognition following separation during the mother's foraging bouts. Individual vocal recognition has also been shown between mothers and pups for subantarctic fur seals (*Arctocephalus tropicalis*) (Roux and Jouventin 1987) and Steller sea lions (Higgins 1984). Early observation of vocal threat exchanges were also seen in association with establishment and maintenance of breeding and birthing territories between males and females, respectively ([Northern fur seals (Gentry 1968, 1970; Sandegren 1970)], [Steller sea lions (Gisiner 1985)], [Antarctic fur seals (Bonner 1968)]).

Underwater vocalizations from Steller sea lions were first recorded in captivity and described as clicks and barks (Poulter 1963; Schevill et al. 1963; Schusterman et al. 1970; Poulter and DeCarlo 1971). Northern fur seals produce underwater clicks and bleating sounds (Poulter 1968; Cummings and Fish 1971). The function of the underwater vocalizations was not well understood prior to 2000, and we are not aware of any reports or descriptions of underwater Antarctic fur seal vocalizations.

A comprehensive look at the information related to vocal production, use, and function of all polar fur seals and sea lions prior to 2000 shows that more information is available for airborne than underwater sounds. Most in-air vocalizations are used during mother–pup interactions and in aggressive interactions associated with establishing and maintaining on-land territories. Pattern of use and call structure across polar otariids is similar to that of other colonially breeding pinniped species (Boness 1990; Campbell et al. 2002), so it may be appropriate to extrapolate the large amount of information known about more temperate otariids to the polar fur seals and sea lions.

11.1.2.4 Walrus

In-air vocalizations from wild walrus were first documented in 1975 (Miller 1975) and further described and categorized in 1985 (Miller 1985). In 1995, a 120 dB re 1 pW source level was first calculated for an in-air whistle and estimated to propagate approximately 1 km in air (Verboom and Kastelein 1995). The primary function of the different category of airborne sounds produced by walrus are social and attributed to maintaining mother–offspring contact and signaling distress, threats, and reproductive status (Miller 1985; Verboom and Kastelein 1995).

Information pertaining to the production and use of underwater vocalizations by walrus was much more extensive in contrast to the amount of information available on otariid underwater vocalizations prior to 2000. The relative lack of knowledge of otariid underwater vocalization use could be due to the challenges of recording underwater vocalizations from these animals when they are dispersed from haul-out sites. Alternatively, aquatically mating walrus have evolved more elaborate visual and vocal displays as part of their mating system which has led to the elevated use of underwater vocalizations compared to otariids that mate on land. The first detailed description of underwater vocalizations from a walrus resulted from a captive study by Schevill et al. (1966). Three types of vocalizations were described: rasps, clicks, and bell-like sounds. Traditional and anecdotal accounts of underwater walrus bells from Inuit existed prior to the 1960s (Brooks 1954; Fay 1960). Ray and Watkins (1975) first attributed a social function associated with mating displays to the pattern of underwater vocalizations by male walrus. Additional underwater vocalizations and the first evidence of stereotyped acoustic displays from wild walrus were published in the 1980s (Stirling et al. 1983, 1987). In these studies, a single hydrophone was lowered through the ice and was recorded onto a tape recorder with opportunistic visual observations. Data suggesting that male walrus have individual identifiable vocalizations was first presented in Stirling et al. (1987), but additional studies are still needed to confirm the stability of vocalizations from the same individuals over multiple years. The final information on walrus acoustics gained in the twentieth century was a detailed examination of the stereotyped vocal display of wild walrus using TDRs (Nowicki et al. 1997). The combination of dive details obtained with the tag and vocal recordings from a single hydrophone revealed that prolonged underwater displays by walrus are physiologically possible because the walrus do not exceed the anaerobic dive limit.

Much of what was known about polar pinniped biology and behavior prior to 2000 was obtained from direct measurements or observations of animals from hunting, stranding, targeted species surveys that combined visual and acoustic observations, and research performed in captivity (Table 11.1). Portable data collecting platforms, or tags, attached directly to animals started to provide more detailed information about the underwater behavior of free-ranging pinnipeds in the 1990s (Bengtson and Stewart 1992; Nordøy et al. 1995; Nowicki et al. 1997). Early acoustic recordings were made with single hydrophones deployed from land, boats, or through holes drilled in the ice. Recording systems required constant monitoring due to the storage medium and capacity of tape recorders, lack of ruggedized equipment to withstand the harsh polar climate, and need to collect concurrent visual observation to associate acoustic signals with specific animals or species in an area. It was the pioneering work of dedicated researchers under extreme working conditions that initially documented species-specific vocalizations of polar pinnipeds and laid the foundation for autonomous passive acoustic monitoring during times when traditional surveys were not feasible.

The value of passive acoustic monitoring was recognized prior to 2000 as having enormous application to marine mammal censusing, the study of the movements, survival of individuals between years, and geographic variation in vocalizations (Stirling et al. 1983, 1987). Stirling et al. (1983) recognized the challenges and obstacles that needed to be addressed and overcome in achieving such lofty goals. Basic information related to individual and species biology and vocal behavior was identified as prerequisites for the successful application of passive acoustic monitoring to future polar pinniped research.

> In order to approach this goal, specific research is required on each species to determine: diel, between day, and seasonal patterns of vocalizing in order to determine the optimum recording times; the length of the recording period required to obtain a representative sample; the age, sex, and social status of calling individuals; variability in vocalization rates and repertoires of individuals; how far from the source vocalizations can be recorded; and how much pinnipeds move underneath the ice during the winter. We recognize the difficulty of conducting such research and recommend that all opportunities be taken to relate data obtained through recordings with direct observations on pinnipeds (Stirling et al. 1983).

The evolution of manned, single hydrophone recording systems to multi-element, open-water, autonomous PAM systems was initiated by Thomas and DeMaster (1982). Recordings of leopard and crabeater seals were recorded in the Southern Ocean from a single hydrophone system placed on an ice floe for 24 h. The first autonomous recordings of pinnipeds known to us in Arctic waters are from Clark et al. (1986, 1996). That system was developed to monitor cetaceans, and it was not until after 2000 that information from these autonomous recordings was applied to the study of polar pinniped species (Van Parijs and Clark 2006). Compact Acoustic Probes (CAP) were the first tags with acoustic recording capabilities (Burgess et al. 1998). Single hydrophone CAPs were first deployed on northern elephant seals in 1995; Burgess et al. (1998) was the first publication describing these efforts. Today autonomous PAM systems are being designed specifically for recording polar marine mammal vocalizations in extreme habitats. The amount of information gained about polar pinniped species through autonomous PAM systems over the past decade has transformed the lofty vision of PAM applications by Stirling et al. (1983, 1987) into a reality. Autonomous PAM of polar pinnipeds has provided information on seasonal presence and distribution, geographic variation, mating systems, and overall acoustic ecology of polar regions. This information will be critical to assessing the impact of a changing global climate on Arctic and Antarctic pinniped species.

11.2 Evolution of Autonomous Passive Acoustic Monitoring Systems in Polar Regions

The development of autonomous PAM monitoring systems has produced hardware and system configurations that come in a variety of shapes and sizes. For the purposes of discussing the application of autonomous PAM systems to the acoustic ecology of polar pinnipeds, we have considered a PAM system to be autonomous if it produces a long time series recording without concurrent visual observations or human oversight at the receiving end of the system. This includes fully autonomous recorders that are remotely deployed and store all data internally, remotely deployed sensors that transmit data back to ship/shore stations, and cabled systems that transmit data back to shore stations. In all cases, the recording hardware must meet the criteria of withstanding the harsh polar elements, be able to consistently acquire data under ice and without constant oversight for months to years, and operate with a sampling frequency adequate to record the full frequency spectrum of polar pinniped vocalizations.

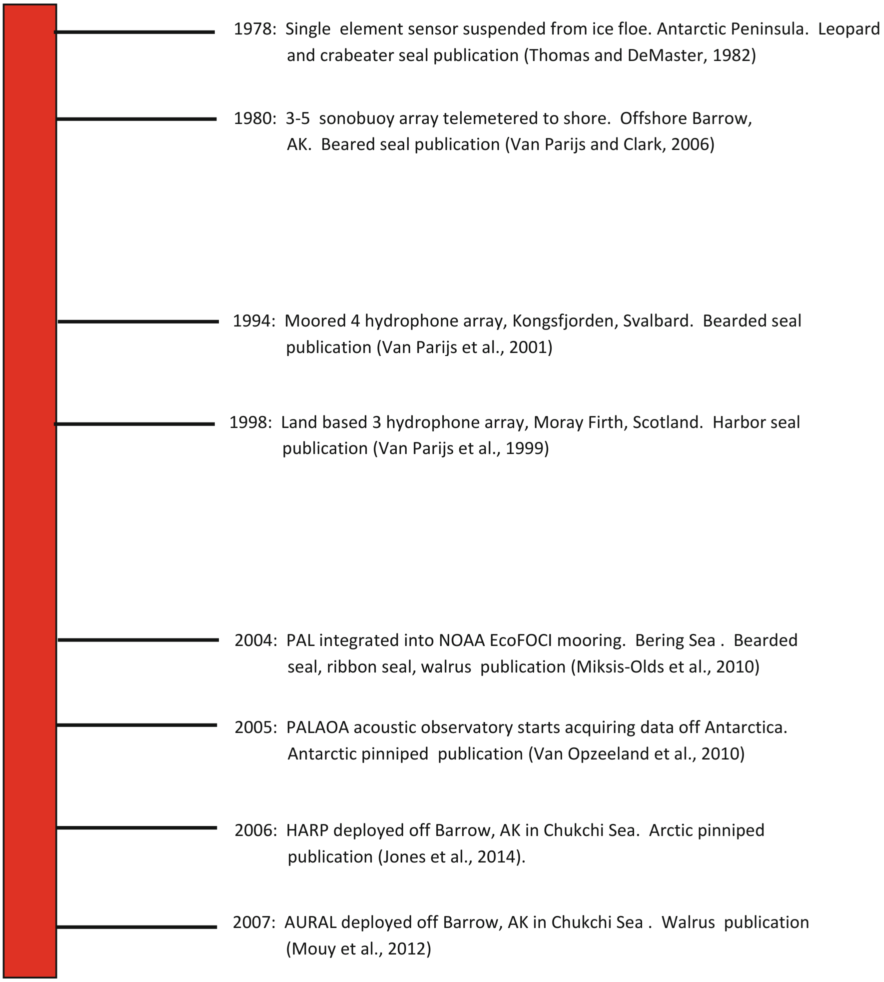
New developments of PAM technology for polar regions have aimed to meet these criteria. This has largely been driven by advances in storage capacity for internally logging systems and the reduction of power requirements related to the sensor electronics. Compact flash cards are the preferred data storage medium for self-contained, autonomous PAM recorders. Compact flash technology has improved from a limit of 2 MB in 1994 to 128 GB flash cards of similar size in 2012 (CompactFlash Association: http://compactflash.org/). Power requirements are the primary factor shaping the size, shape, and maximum deployment length of all autonomous PAM systems. There is a constant trade-off between the size of the battery or power packages, sampling strategy (continuous vs subsampling), and operational bandwidth. Although subsampling is often a prerequisite to obtain long term recordings, it does restrict the type of questions that can be addressed over short time frames (e.g., order of call type usage, repertoire usage over time). Advances continue to be made with respect to availability of power, as innovative technologies that harness power from the movement of the water, sun, and wind are now being incorporated into PAM systems (Boebel et al. 2006; Zimmer 2011).

Not all passive acoustic monitoring techniques are equally well suited for collecting data in polar areas, as the specific physical conditions of polar environments complicate the use of certain acoustic instrumentation types. Van Opzeeland et al. (2008) provided an overview of new and emerging passive acoustic recording techniques and discussed their suitability for use in polar environments, and Chap. 1 (in this volume) provides a more general description of the evolution of autonomous PAM technology. Autonomous acoustic recording devices can be used in polar environments, but only in areas or at depths at which drifting icebergs cannot cause damage to moored instruments. Cabled recording stations have the advantage that they can record continuously and over broad frequency band widths, allowing real-time monitoring and—in the case of a hydrophone array—localization of marine mammals, while having few restrictions to data storage, data access and power supply. However, in polar environments, acoustic monitoring using a network of hydrophones cabled to shore-based stations requires substantial cable length, increasing the chances of damage due to ice movements and cable melt-in.

New applications of PAM in polar regions have been designed to overcome some of these issues. One such example is the PerenniAL Acoustic Observatory in the Antarctic Ocean (PALAOA), which features the advantages of a cabled system using an ice-shelf-based, energetically autonomous recording station, but uses a wireless local area network to transfer acoustic data to the nearby German Antarctic Neumayer Station III (for more detailed information, see Boebel et al. 2006; Klinck 2008; Chap. 8 in this volume). Recent developments of profiling systems, autonomous underwater vehicles, and gliders have enabled instruments to make unassisted decisions on when and where to surface to communicate and transfer data that now supports their use in ice-covered waters (Owens 2006; Eichhorn 2009; Wong and Riser 2011). Self-contained PAM recorders, such as the Passive Aquatic Listener (PAL), have been designed with an adaptive-sampling strategy through onboard processing algorithms. This supports the recording at higher frequencies during periods of high acoustic activity, while conserving energy and storage space during periods of relatively low acoustic activity that sustains year-long deployments in polar regions with limited seasonal access (Miksis-Olds et al. 2010). More generally, advances in data storage techniques, the size and weight of energy suppliers as well as the use of alternate energy sources (solar, wind), have contributed to the development of PAM instruments that can now be deployed over longer time frames in areas where instrument retrieval is seasonally restricted.

The history of autonomous PAM recorders and systems in polar regions that have contributed new knowledge of polar pinnipeds is depicted in Fig. 11.1. The first overwinter, long-term autonomous recorder used in the Arctic was designed to track migrating bowhead whales in the Beaufort Sea (Clark et al. 1986). Early recordings made in association with the bowhead (*Balaena mysticetus*) whale project were then reanalyzed to provide information on bearded seals (Van Parijs and Clark 2006). In the Antarctic, the first autonomous PAM recording was made by Thomas and DeMaster (1982) over a 24 h period. Širović et al. (2004) acquired the first long-term, over-winter autonomous PAM dataset using ARPs (Acoustic Recording Packages) (Wiggins 2003). These recordings targeted blue and fin whales off the Western Antarctic Peninsula and were deployed for nearly 2 years. They, however, have not yet produced any new information on pinnipeds.

The time scale over which single PAM units or arrays operate determines the type of research questions that can be addressed, and the application of autonomous PAM systems in polar regions has provided unique insights into animal presence, distribution, calling behavior, and broader acoustic ecology of specific species. Passive acoustic recordings made over a period of several days to weeks for example, are generally suitable to determine diel patterns in acoustic activity (within the recording period), but are unsuitable to reliably assess the duration of the period during a year during which a species is vocally active. Recordings made over longer time frames (i.e., months to years) in principle allow investigation of processes at time scales ranging from seconds to interannual patterns. The following section contains four case studies on how different autonomous PAM systems across the Arctic, Antarctic, and subpolar regions have contributed new knowledge of polar pinnipeds.



1978: Single element sensor suspended from ice floe. Antarctic Peninsula. Leopard and crabeater seal publication (Thomas and DeMaster, 1982)

1980: 3-5 sonobuoy array telemetered to shore. Offshore Barrow, AK. Beared seal publication (Van Parijs and Clark, 2006)

1994: Moored 4 hydrophone array, Kongsfjorden, Svalbard. Bearded seal publication (Van Parijs et al., 2001)

1998: Land based 3 hydrophone array, Moray Firth, Scotland. Harbor seal publication (Van Parijs et al., 1999)

2004: PAL integrated into NOAA EcoFOCI mooring. Bering Sea . Bearded seal, ribbon seal, walrus publication (Miksis-Olds et al., 2010)

2005: PALAOA acoustic observatory starts acquiring data off Antarctica. Antarctic pinniped publication (Van Opzeeland et al., 2010)

2006: HARP deployed off Barrow, AK in Chukchi Sea. Arctic pinniped publication (Jones et al., 2014).

2007: AURAL deployed off Barrow, AK in Chukchi Sea . Walrus publication (Mouy et al., 2012)

Fig. 11.1 Timeline of first autonomous PAM recorders to acquire and produce published information on polar pinniped vocalizations. Initial deployment of autonomous PAM recorders occurred prior to 2000, but information relating to polar pinnipeds was rarely analyzed or published prior to 2000

11.3 Polar Pinnipeds and Autonomous PAM: New Insights

We would be remiss if we did not acknowledge the wealth of information gained from captive work and PAM coupled with visual observations prior to the presentation of case studies describing new knowledge gained from autonomous PAM technology. These studies provided the necessary information on vocal repertoires that are a prerequisite to any study utilizing autonomous PAM. Without detailed knowledge about the regional sounds being recorded by autonomous sensors, far removed from human oversight, there would be little to be gained from the interpretation of autonomous data.

11.3.1 Information Gained by Long-Term Deployments of Single Elements or Sparse Arrays

Over the last decade, advances in audio and computer technology have enabled acquisition and processing of long-term acoustic data. Development of reliable autonomous recording units has been of particular significance for the study of polar pinnipeds as year-round collection of acoustic data by a recordist is often challenging, if not impossible in many polar habitats. As Sect. 11.2 in this chapter illustrated, the earliest recordings of polar pinniped sounds mostly served to provide a confirmation on the identity of the species that produced the sound as well as an initial acoustic description of vocalizations (e.g., Schevill and Watkins 1965; Ray 1970; Stirling 1973; Cleator et al. 1989). The limited duration of these recordings often severely restricted the amount of information that could be derived on seasonal or diel patterns in vocal behavior. Much of the current knowledge on the seasonal presence, distribution, and timing of mating in polar pinnipeds stems from PAM studies over time spans up to several years using pinniped underwater sounds as a measure (e.g., Van Parijs et al. 2004; Rouget et al. 2007; Van Opzeeland et al. 2010; Miksis-Olds and Parks 2011). Deployment of autonomous acoustic recording units has however not only increased the time scale over which polar pinniped acoustic behavior can be monitored and questions regarding their behavior addressed; the spatial scale over which investigations can be carried out has also changed significantly. The logistic effort of deploying single PAM elements often leaves it feasible to simultaneously operate several recorders within a certain area so that, for example, movements of vocalizing individuals can be tracked using sparse arrays (e.g., Širović et al. 2007). Furthermore, the relative "ease" with which acoustic data are collected throughout various polar habitats, has contributed to the collection of more acoustic data from different sites enabling comparative investigation of geographic variation in vocal behavior of polar pinnipeds (e.g., Risch et al. 2007).

The following case studies focus on polar phocid species and walrus because relatively little has been learned about polar otariids through the application of PAM due to their limited use of underwater vocalizations.

11.3.1.1 Case Study: Antarctic Phocids

In the Antarctic, the coastal pack-ice and fast-ice environments are important habitats for the ice-breeding phocids (Riedman 1990). Nevertheless, in the coastal regions off the Antarctic continent, drifting icebergs can cause damage to PAM devices when instruments are moored in areas shallower than 200 m (Rettig et al. 2013).

Consequently, only few acoustic records exist of the Antarctic coastal regions, with long-term recordings to investigate seasonal trends in vocal behavior, being even rarer.

Instead of being moored, the PerenniAL Acoustic Observatory in the Antarctic Ocean (PALAOA, Atka Bay, 70°31′ S 8°13′ W) on the eastern Weddell Sea coast, uses an ice shelf-based energetically autonomous recording station which transmits the acoustic data to the German Antarctic Base Neumayer III through a wireless local area network (Kindermann et al. 2008; Klinck 2008). The ice shelf provides protection from damage by drifting icebergs. We refer to Chap. 8 in this book for further information on data acquisition and handling by PALAOA.

For this case study, acoustic data from PALAOA from January 2006 until February 2007 were analysed, exploring temporal patterns in acoustic behavior of ice-breeding Antarctic pinnipeds. A total of eleven months of acoustic data (no recordings for July and November 2006) were sampled for analysis. To provide a standardized sample across the year, data were sampled on every fifth day for the first 10 consecutive minutes of each hour. A total of ten 730 min of PALAOA recordings were analysed across the entire 11 month period (Van Opzeeland et al. 2010).

The recordings contained calls of all four ice-breeding Antarctic pinnipeds occurring in this region (Weddell, leopard, Ross, and crabeater seal). Weddell seal vocalizations were present in the recordings throughout the year, except in February. Preliminary inspection of PALAOA recordings from other years showed that calls were also present in July and November, the months for which no recordings were available for 2006 (indicated in Fig. 11.2 by the dotted line in the shaded areas). The pack-ice breeding species (leopard, Ross, and crabeater seal), on the other hand, were only seasonally present in the PALAOA recordings: leopard seal calls occurred from October to January, Ross seal calls were present between December and February, and crabeater calls were recorded between August and December. The Weddell seal vocal repertoire was found to consist of 14 relatively complex call types, which differed in proportional usage throughout the year. Leopard and Ross seals have a medium-sized vocal repertoire, consisting of seven and five stereotyped call types, respectively. For leopard and Ross seals, proportional usage of different call types did not differ throughout the period of vocal activity. Crabeater seals were found to produce two relatively simple broadband call types, the low and high moan.

Although all four species are aquatic mating species, each species exhibits a different mating strategy, and calls are therefore likely to serve different functions. Weddell seal vocalizations are produced by both sexes, with males using calls to maintain underwater territories below the Antarctic fast-ice (e.g., Bartsch et al. 1992; Rouget et al. 2007). The Weddell seal vocal repertoire is comparatively large, consisting of relatively complex calls. Calls are thought to serve a function in intrasexual and intersexual communication within and between breeding colonies and Weddell seal communication signals are therefore relatively unconstrained by signal propagation needs (Rogers 2003). The fact that calls are recorded almost year-round, suggests that a number of Weddell seals remains in the breeding area throughout the year. For males that occupy territories year-round this potentially

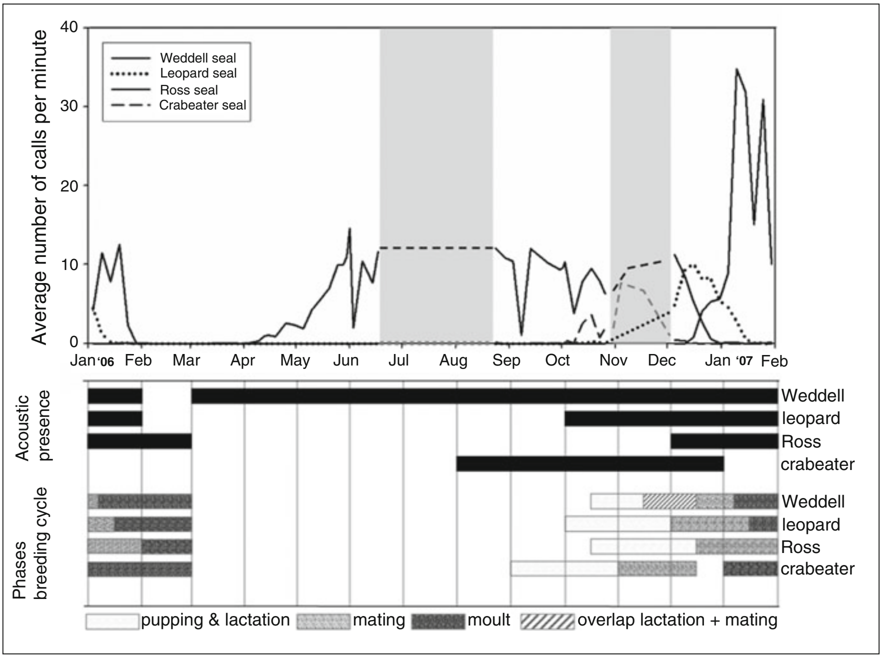


Fig. 11.2 Overall call activity for all four species in the period January 2006 to February 2007. The average number of calls per minute is calculated per day for all days that were included in the analyses. Call activity in the *grey shaded areas* represents counts of 1-min PALAOA samples from 2007, as recordings from these months were not available from 2006. For crabeater seals, call activity in November was based on PALAOA data from 2007 from Klinck et al. (2010). The *lower schema* shows acoustic presence for all four seal species and the timing of the pupping, mating and moulting periods based on literature (Weddell seal: Lugg 1966; Kaufman et al. 1975; Reijnders et al. 1990, leopard seal: Riedman 1990; Rogers et al. 1996; Southwell et al. 2003; Ross seal: King 1969; Thomas 2002; Southwell et al. 2003, crabeater seal: Siniff et al. 1979; Bengtson 2002; Southwell et al. 2003)

provides an advantage over males that move away in winter in that they are already present when the land-fast ice forms and/or the females arrive in the breeding area (Harcourt et al. 2007, 2008). Furthermore, vocal activity and the proportion of call types with presumed threat-function showed a peak in austral winter and spring, suggesting that males are also actively engaged in territorial displays outside the breeding season. Weddell seals likely depend on the availability of a stable fast-ice environment for establishing and defense of their underwater territories (Miller 2009; Van Opzeeland and Miksis-Olds 2012). The absence of Weddell seal vocalizations in the PALAOA recordings in February may therefore reflect a short period following fast-ice breakup during which seals either cease to be vocally active or leave the area because of fast-ice breakup, thereby moving out of the observatory's recording range.

Based on the acoustic data from the PALAOA observatory, the pack-ice breeding species are likely to be seasonal inhabitants of the coastal region off the Antarctic continent. Their exclusive acoustic presence during the breeding season may reflect a seasonal migration to particularly suitable coastal pack-ice regions to breed. Leopard seals for example, may be specifically attracted to Atka Bay as the presence of emperor penguin (*Aptenodytes forsteri*), Weddell and crabeater seal colonies provides an attractive feeding area. Given that leopard seals are known to be a solitary species, the presence of food sources that are reliably present in Atka Bay each year might function to attract leopard seals to the breeding area, thereby increasing the likelihood of finding a mating partner. For Ross seals, the availability of specifically suitable ice conditions for breeding in the coastal region may drive migration to the area off PALAOA (Van Opzeeland and Miksis-Olds 2012). Leopard seals use calls to attract mating partners over long distances and have a promiscuous mating system in which females also actively display sexual receptivity by emitting calls (Rogers et al. 1995, 1996). Leopard seal vocal repertoire composition remained relatively similar throughout the breeding period, potentially reflecting that the function of these vocalizations is uniform throughout the breeding season and that there are no stages within the mating season causing gradual change in repertoire composition as observed in Weddell seals (Van Opzeeland et al. 2010). To date, nothing is known on the Ross seal mating system. However, the parallels between the leopard and Ross seal call characteristics, vocal repertoire size and proportional call type usage (see Van Opzeeland et al. 2010), suggest Ross seals may also use long-distance communication during the breeding season and exhibit a similar mating strategy.

Crabeater seals may be attracted to the coastal region by the availability of suitable ice for breeding; crabeater seals are known to select specific ice floes based on size and physical characteristics for breeding (Siniff et al. 1979, 2008). Crabeater seals are serially monogamous, with males guarding a female with her pup on the ice against intruder males until the pup is weaned and the female enters estrus (Siniff et al. 1979). Once the pup is weaned and the female leaves the ice, the male is thought to mate with the female, thereafter leaving her to guard and mate with a next female. Moans are thought to be produced by males defending females from other males. A complex loud vocal display would likely attract males to the female that the male is defending, whereas a simple vocal repertoire and the acoustic characteristics of the moan limit the signal to be received only by rival males in the direct vicinity (Rogers 2003). For crabeater seals, the likelihood of encountering predators, such as leopard seals and killer whales (*Orcinus orca*) might be a further factor influencing the timing of vocal activity.

Interestingly, the timing of vocal activity in all four species is staggered throughout the austral summer period, in spite of the relatively short period during which breeding in all four species is to take place. Partitioning of the acoustic environment or sequencing of acoustic activity, either based on time, space, or frequency bandwidth of signals is referred to as acoustic niche forming (e.g., Sueur 2002) and might function in Antarctic pinnipeds to reduce acoustic interference between calling individuals and increase the efficiency of signal propagation. Particularly for species such as the leopard and Ross seal that are likely to rely on signal propagation over long distances to find a mating partner, acoustic niche forming might significantly reduce interspecific acoustic interference. Complete separation of the period during which each species is vocally active might, on the other hand, not be possible as factors such suitable ice conditions and availability of prey are likely to further restrict the breadth of the acoustic niche of each species.

11.3.1.2 Case Study: Sub-Arctic Phocids and Walrus

The Bering Sea is a sub-Arctic region where seasonal ice cover drives ecosystem dynamics and the presence of marine mammals. During seasons of open water, temperate and subpolar species (e.g., humpback whales [*Megaptera novaeangliae*], gray whales [*Eschrichtius robustus*], Steller sea lions, killer whales [*Orcinus orca*]) migrate poleward to feed in the region's productive waters. In the winter, Arctic species migrate down into the Bering Sea in conjunction with the seasonal ice advance. Arctic pinnipeds are present in the Bering Sea in particularly high numbers during the winter because they rely on the ice for breeding, foraging, resting, and moulting. The winter season has also historically been the period when visual, acoustic, and aerial observation efforts are lowest due to the extreme weather conditions. The development of autonomous PAM recorders that are capable of recording throughout the winter has provided new information about the Arctic pinnipeds during the winter and early spring when they are engaged in critical life functions such as breeding.

A PAL recorder was first deployed in the Bering Sea during the summer of 2004. This self-contained autonomous recorder was integrated into a subsurface NOAA mooring on the southeastern Bering Sea shelf (Site M2: 56.87°N, 164.05°W), which is the most southern of four Bering Sea mooring sites in the Ecosystems and Fisheries Oceanography Coordinated Investigations (Eco-FOCI) Program (Stabeno et al. 2010; Nystuen et al. 2010). The first over-winter deployment of this technology occurred from 2007 to 2008 at mooring site M5 (59° 54.58′N, 171° 42.47′W) on the 70 m isobath in the central region of the eastern Bering Sea shelf (Miksis-Olds et al. 2010) and from 2009 to 2010 at site M2 (Fig. 11.3). The seasonal ice cover in the Bering Sea oscillates between periods of high and low interannual variability and sea ice extent (Stabeno et al. 2012; Danielson et al. 2011). The winters of 2007–2010 have been characterized as cold years with low interannual variability and high ice extent/concentration (Stabeno et al. 2012). During the PAL deployments, both mooring sites were covered by ice for a portion of the winter season (Fig. 11.4). The ice typically advanced over site M5 in early January and retreated in May. Ice cover at M2 was shorter with the ice advance typically occurring in February and the seasonal retreat in April.

The most salient vocalizations detected at both mooring sites over the winter seasons were from bowhead whales, walruses, bearded seals, and ribbon seals. In almost every month of the winter season when pinniped vocalizations were detected, the onset of acoustic presence was tightly associated with ice presence in the regions, and the detection of all three pinniped species overlapped in time and location (Fig. 11.4). The tight coupling of ice and acoustic activity was further illustrated

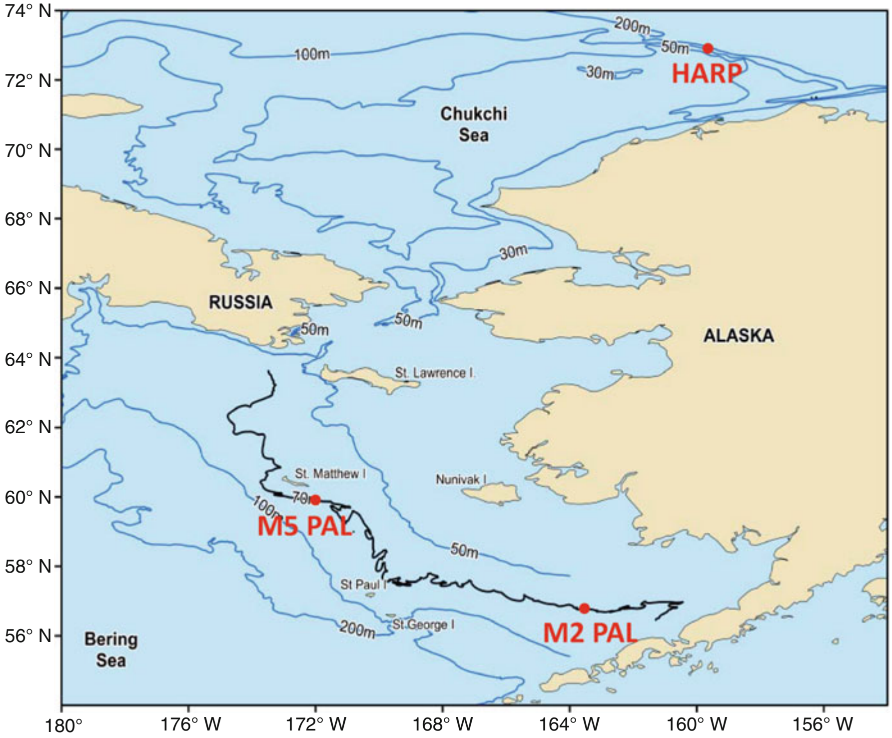


Fig. 11.3 Map of the Bering and Chukchi Seas show the mooring locations of the PALs and HARP (High-frequency Acoustic Recording Package)

by observations made during a mid-winter, temporary retreat when there was open water over the M5 mooring for two weeks in March 2009. There were no acoustic detections of either ribbon or bearded vocalizations, whereas there was an increase in walrus vocal detections during this time that indicates the species have different relationships with ice presence and ice characteristics (Miksis-Olds and Parks 2011; Miksis-Olds et al. 2013). Without concurrent visual observations or GPS tag locations, it was not possible to know whether the seals left the area in conjunction with the ice or whether vocal activity stopped while the animals remained in the area but engaged in behaviors other than mating displays. The decrease in vocal detections does indicate that local mating behaviors were temporarily impacted by the retreat. If the seals did leave the area, it is not known whether they did so passively by drifting on the ice or actively followed the ice edge (Miksis-Olds and Parks 2011; Miksis-Olds et al. 2013). There were no acoustic detections of any polar pinniped species detected at either site outside the winter/spring season when ice was not present.

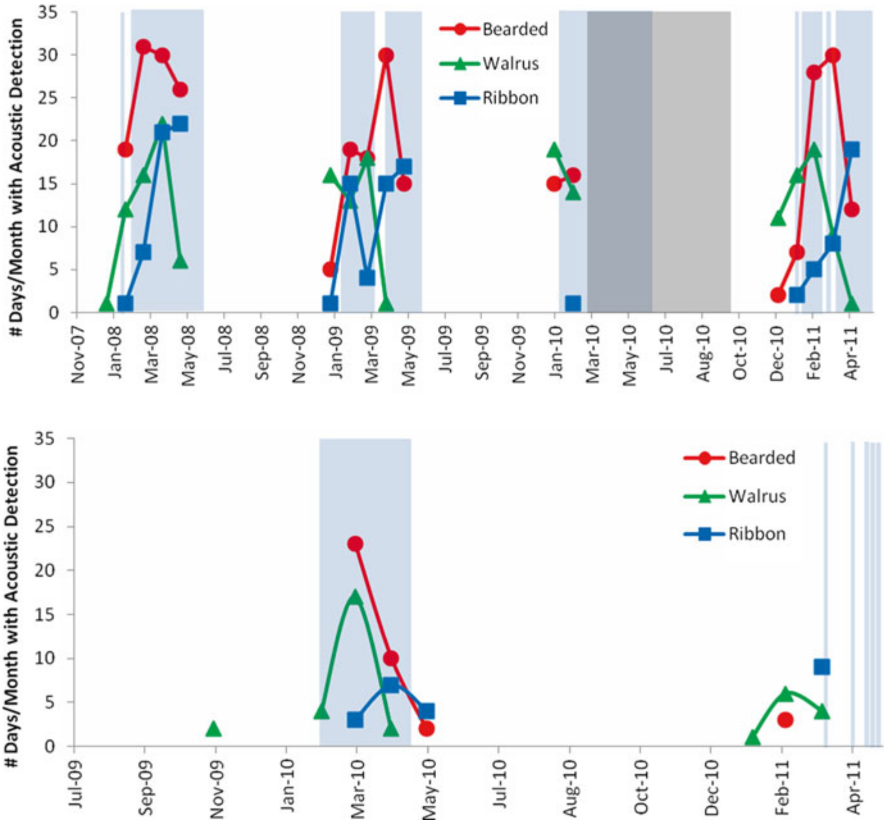


Fig. 11.4 Monthly detection rates for the three Arctic pinniped species detected in the central (M5: *top*) and southeastern (M2: *bottom*) Bering Sea. *Blue shaded areas* indicated ice presence over the acoustic mooring. Ice presence was determined in a 20 km × 20 km area around the mooring from data provided by the NWS Alaska Sea Ice Program. The *dark shaded area* in the *top figure* indicates a period of no data collection

At both sites it was common to observe a seasonal staggering of peak vocal activity from each species where walrus detections peaked first, followed by bearded seal, and then ribbon seal. Although the pattern and timing of vocal detections was similar at both sites, the overall number of detections at the southern site was less than that of the northern site (Fig. 11.4). This was most likely due to the shorter duration and more sporadic ice cover at the southern site. A high level of acoustic activity at the central shelf location during the time when the ice edge extended beyond the southern site also suggests that all three pinniped species utilize a large area of the ice covered eastern Bering Sea and are not restricted to areas associated with the ice edge or the more solid ice cover in the central shelf region. The spatial overlap in species coupled with the staggering of peak vocal activity supports the theory of acoustic niche partitioning to reduce acoustic interference also observed in the Antarctic between pinniped species overlapping in time and space (Van

Opzeeland et al. 2010). There is currently no information available about the age composition or difference in social status/structure between the animals that migrate south with the ice edge or remain in the more concentrated ice regions of the central shelf during the winter breeding season.

The consistent, long-term time series provided by the PAL over the course of a single season and between years and locations has also provided new information about the vocal repertoire of the ribbon seal. Prior to 2000, very little was known about ribbon seal communication and biology due to the difficulty of studying the species during the winter and elusiveness of ribbon seals during their pelagic existence in open water periods. Two new categories of vocalizations were described by Miksis-Olds and Parks (2011) by conducting a multiyear, multilocation coefficient of association analysis between salient ribbon seal downsweeps and other previously unknown categories of vocalizations. It has been suggested that ribbon seal vocalizations detected during the winter/spring season are associated with breeding activity (Boveng et al. 2008; Miksis-Olds and Parks 2011). The absence of acoustic detections in the central and southeastern Bering Sea does not indicate a corresponding absence in physical presence of these animals, but does suggest the absence of breeding behaviors related to vocal activity. The extent to which ribbon seals migrate out of these areas during open water seasons or remain in an acoustically silent mode of behavior typical of less social or solitary species outside the mating season is not currently known. Recordings in the Chukchi Sea described in the next case study are now providing some new information on the acoustic presence and distribution of these animals.

11.3.1.3 Case Study: Arctic Phocids

Little is known about the seasonal movements and behavior of phocid species in offshore areas of the Arctic during much of the year. To date, most vessel studies have been carried out relatively near shore. Aerial surveys that extend offshore to greater than 100 km are typically restricted by weather and take place between the months of March and July. Additionally, although some species such as bearded and ribbon seals are known to make seasonal migrations from the Arctic to lower latitudes (Miksis-Olds et al. 2010; Miksis-Olds and Parks 2011; Van Opzeeland and Miksis-Olds 2012), the timing of these movements and the extent to which individuals may overwinter in Arctic waters is not well understood. To investigate the seasonal differences in the presence and acoustic behavior of ringed, bearded, and ribbon seals, data recorded by a High-frequency Acoustic Recording Package (HARP) deployed in the Chukchi Sea 120 km NNW of Barrow, Alaska from 2006 to 2009 were analyzed for the calls of these species (Figs. 11.3 and 11.5). Repertoires were described for each species and compared to previous studies. Seasonal variation in calling behavior was examined where possible, and the acoustic presence of each species was compared to sea ice presence and regional ice cover.

More than 99 % of ringed seal calls were detected between mid-December and late May when sea ice cover was between 96 and 100 %. The peak in calling occurred each year between December and early February (Fig. 11.5). There were significantly more winter calls occurring when the ice cover was between 99 and 100 % than could be explained by the amount of time that the region spent at that ice state during recording ($\chi^2=8.96$, DF=2, $p=0.01$). Less calls were observed during spring, even though sea ice cover continued to reach 100 % periodically through late spring ($\chi^2=17.19$, DF=5, $p=0.15$). Calls made by ringed seals fit previous descriptions of barks, yelps, and growls (Stirling 1973; Stirling et al. 1983). Seasonal analysis of ringed seal call types showed that there were more barks and growls in winter and more yelps in spring of all 3 years. Furthermore, yelps in spring tended to be longer in duration and more variable in frequency (Jones et al. 2014).

Bearded seal calls were detected between mid-December and the end of recording in June of each year (Fig. 11.5), which was earlier than previously documented (December–January). Although detection of bearded seal trills was sporadic, the duration of calling events and number of calls detected increased and showed some

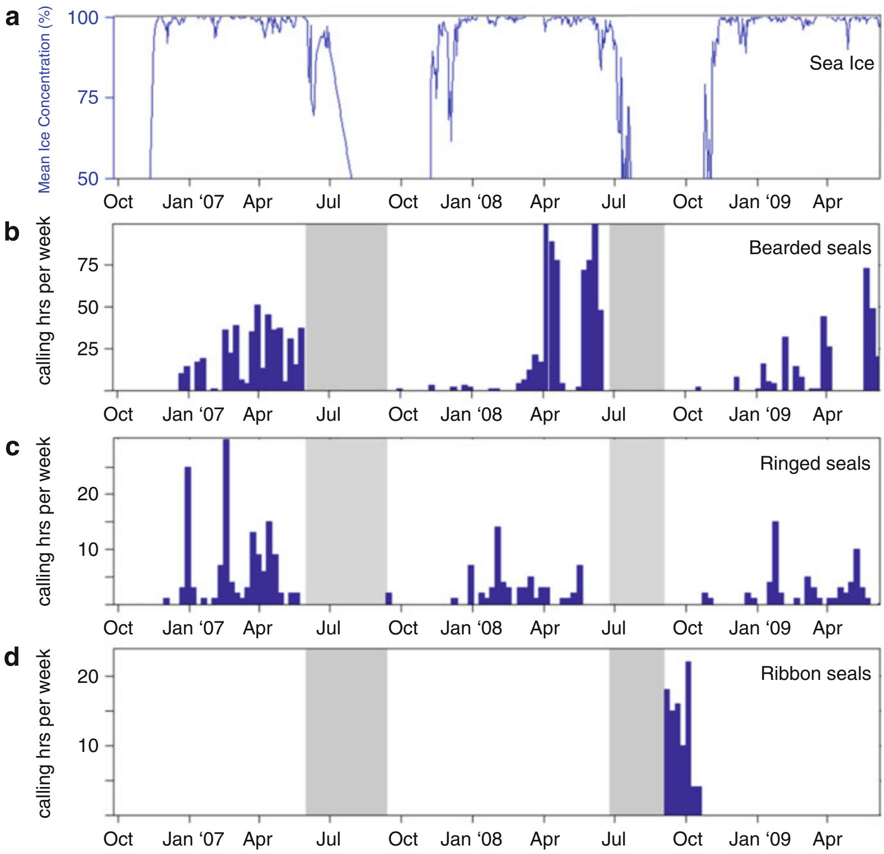


Fig. 11.5 Ice seal acoustic detections in hourly bins per week from September 2006 to June 2009 aligned with sea ice cover. (**a**) Mean daily % sea ice cover, (**b**) bearded seal detections, (**c**) ringed seal detections, and (**d**) ribbon seal detections. All call types are included for each species. *Shaded areas* indicate periods with no acoustic data. Reproduced from Jones et al. 2014

differences in call selection from winter to spring. Seasonal analysis of calling behavior indicated that the AL7 call type, which ascends in frequency throughout the call, was more common in winter than in spring and that the longest duration trills were more common in spring and early summer. Bearded seal calls were detected in a variety of sea ice conditions, present in 95–100 % ice cover in winter and 80–100 % ice cover in spring. Bearded seal calls closely matched those described by Risch et al. (2007) from recordings made close to the land-fast ice edge near Barrow, Alaska.

Ribbon seal calls were only detected during the fall open water season of 1 year and in sea ice cover less than 50 % (Fig. 11.5). A greater variety of calls showed clear co-occurrence with the characteristic downsweeps than were previously described for this species (Watkins and Ray 1977; Miksis-Olds and Parks 2011). In total, six call types were attributed to ribbon seals: downsweeps, grunts, roars, yowls, growls, and screams. Grunts and roars were first attributed to ribbon seals from recordings by Miksis-Olds and Parks (2011) in the Bering Sea during the ice covered spring season. The yowls, growls, and screams are newly attributed vocalizations to this species from the HARP recordings off Barrow, AK. Ribbon seal calls in the Arctic often occurred in highly stereotyped sequences. The most common of these were grunt–yowl–grunt sequences ($n=83$) that often ended with a low-frequency growl (Jones et al. 2014). This was one of the first studies to record ribbon seal vocalizations in open water outside the spring breeding season (Moore et al. 2012). Along with Moore et al. (2012), it was also one of the first to record ribbon seal vocalizations in the High Arctic. All previous publications of ribbon seal vocalizations occurred in the subpolar waters of the Bering Sea (Watkins and Ray 1977; Miksis-Olds and Parks 2011). This new information raises an important question of why ribbon seals produce intense bouts of calls, including stereotyped sequences, at a location far from their known breeding grounds and outside of their mating season. Male bearded seals in the Beaufort Sea produce trills throughout the winter (MacIntyre et al. 2013). Calling behavior of bearded and ribbon seals outside the breeding season could possible function to establish or retain territories well in advance of their breeding season. It is also possible that the ribbon seal sounds may have functions in addition to mating, such as facilitating contact between foraging individuals or helping to coordinate movements. Acoustic detection of ribbon seal calls in the Arctic during periods of open water or relatively light ice cover suggests that the Chukchi slope is at least an occasional foraging destination for ribbon seals in summer and fall and could also indicate an expansion of this species range associated with climate change.

11.3.2 Information Gained from Autonomous Acoustic Arrays

Acoustic localization using arrays of three or more recorders is a valuable tool for helping to understand the acoustic behavior of an individual or groups of pinnipeds. Arrays are relatively unobtrusive to the animals, and data can be collected over large spatial and temporal scales. This allows multiple focal individuals to be observed for extended periods of time. Information from acoustic arrays has been used to provide detailed and long term insights into the reproductive strategies and life history of pinnipeds. The detail is so fine-scale that small-scale changes due to changing environmental conditions can be detected as well as changes due to exposure to anthropogenic disturbances. To date the use of archival acoustic arrays has significantly advanced our understanding of the reproductive ecology of aquatic mating pinnipeds such as the harbor seal (Van Parijs et al. 2000), the bearded seal (Van Parijs et al. 2003a, b, 2004, 2009) and the Weddell seal (Harcourt et al. 2007). In addition, integration of polar pinniped movements with ice maps have shown how their behavior is influenced by changing ice conditions and provides insights into what that might mean for their long term reproductive success and survival.

11.3.2.1 Case Study: Arctic Bearded Seals

Archival arrays of 3–5 buoys were used to record the trill vocalizations of male bearded seals at two Arctic sites, one in the Svalbard archipelago over 2 consecutive years, and one near Barrow, Alaska over a 16-year period. Males show stereotypical dive and vocal displays, with clear individual variation (Van Parijs et al., 2003a, b). In Svalbard, acoustic localization provided at-sea locations for 17 males based on variation in trill parameters. Kernel home range analyses showed that 12 individuals displayed at fixed locations (95 % kernels = 0.27–1.93 km^2), while five other males displayed over considerably larger areas (95 % kernels = 5.31–12.5 km^2) (Fig. 11.6; Van Parijs et al. 2004). Movement patterns of males suggest that those with small areas patrolled aquatic territories, while those that used larger areas appeared to roam. These data thus provide evidence of alternative mating tactics in this species.

In Alaska, acoustic localizations provided at-sea locations for 100 males based on variations in trill parameters, with six males being present over the entire 16-year period (Van Parijs and Clark 2006). The acoustic data indicate that male mating tactics tend to show long-term stability in vocal characteristics, site fidelity and periods of tenure that cover a significant proportion of a male's adult life span. Ice cover was found to restrict the number of roaming males, whereas territorial males were present during all ice conditions, suggesting that varying ice conditions affect individual male strategies and reproductive success (Van Parijs et al. 2004). Therefore, acoustic arrays can provide detailed and long-term information on pinniped species in key areas such as their mating grounds. This information can be so detailed that changes can be detected in individual area usage and behavior as a result of both intraspecific competition and varying environmental conditions.

New information about polar pinnipeds described in the case studies, as well as new information resulting from other polar pinniped studies, is summarized in Table 11.2. This table includes the information known prior to 2000 (Table 11.1) and highlights cells where new information has been gained through the use of autonomous PAM sensors or systems. The areas of greatest learning resulting from autonomous

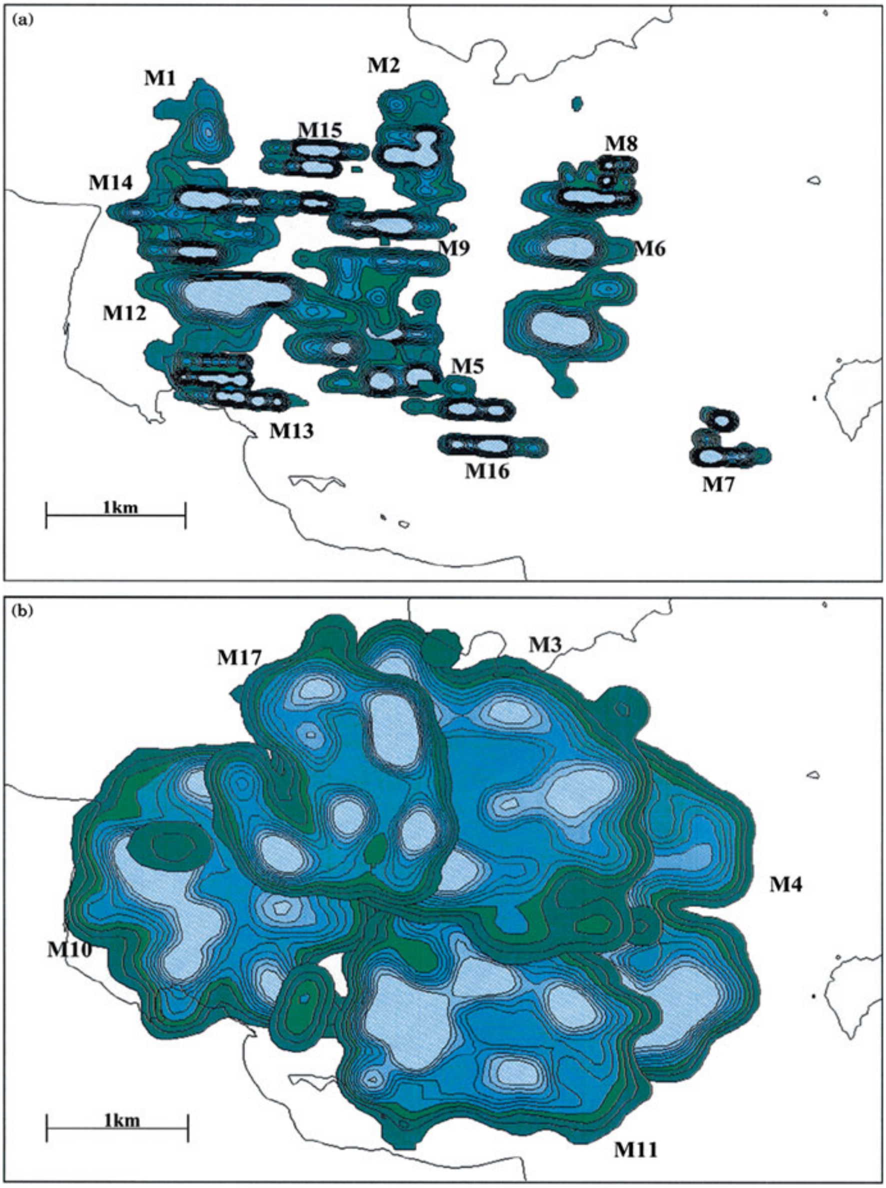


Fig. 11.6 The kernel home range plots of 95–50 % isopleths, represented by the different color shades, for the trill locations, as calculated using three archival acoustic hydrophones, of (**a**) 12 individual "territorial" male bearded seals with small areas and (**b**) five "roaming" males with large areas in Svalbard, Norway (reproduced from Van Parijs et al. 2004). The *light colors* depict the area of highest use by males (95 %), compared with the *darker colors* that depict the area of lesser use (50 %)

Table 11.2 Current characteristics related to polar pinniped acoustics

1	2		3	4	5	6	7	8	9	10	11	12
Species	Range (P, SP, T, ST, TR)^a		Mating substrate (A, I, L)^b	Whelping habitat (L, F, P)^c	Lactation duration (days)^d	Foraging during breeding /lactation (♂ Y/N, ♀ Y/N)	# Aquatic call types	Aquaticvocal dialects	Sex-specific vocs	Aquatic vocal displays	Repro. strategy	Indiv-specific vocs
	Winter	Non-winter										
Arctic phocids												
Grey seal	P,SP	P,SP	A	L, F, P	12–21	♂Y ♀Y	10	0	0	0	Y_2	Y(air)$_2$
Ringed seal	P,SP	P	A	F	39–41	♂Y ♀Y	3	0	0	Y_1	0	0
Spotted seal	P,SP	P	A	P	14–21	♂Y ♀Y	6	0	0	Y_1	0	0
Ribbon seal	SP, P	SP, P	A	P	21–28	♂Y ♀Y	6	0	0	0	0	0
Bearded seal	P,SP	P	A	P, F	12–24	♂Y ♀Y	6–8	Y_2	Y_3	Y_3	Y_2	0
Harbor seal	SP,T	P,SP,T	A	L, F	21–42	♂Y ♀Y	5	0	Y_3	Y_3	Y_2	Y(air)$_2$
Hooded seal	P,SP	P,SP,T,ST,TR	A	P	4	♂Y ♀N	6	0	Y_1	Y_1	Y_1	0
Harp seal	P, SP	P	A	P	9–15	♂Y ♀Y	26	0	Y_2	0	Y_1	Y^e(air)$_2$
Arctic otariids												
Northern fur seal	SP,T	P,SP,T	L	L	120	♂Y ♀Y	2	0	Y_1	0	Y_3	Y(air)$_2$
Steller sea lion	SP,T	P,SP,T	L	L	365–1095	♂N, ♀Y	2	0	Y_1	0	Y_3	Y(air)$_2$
Odobenid												
Walrus	P,SP	P	A	L, P	530	♂Y ♀Y	>10	0	Y_1	Y_2	Y_2	Y(water)$_2$
Antarctic phocids												
Weddell seal	P	P	A	F	33–53	♂^{f}, ♀Y	>34	Y_2	Y_2	Y_2	Y_2	Y(air)$_2$
Crabeater seal	P	P	A	P	17–28	♂N, ♀N	6	0	0	0	Y_1	0
Ross seal	P	P	A	P	28–30	0	5	0	0	0	0	0

(continued)

Table 11.2 (continued)

1	2		3	4	5	6	7	8	9	10	11	12
Species	Range (P, SP, T, ST, TR)[a]		Mating substrate (A, I, L)[b]	Whelping habitat (L, F, P)[c]	Lactation duration (days)[d]	Foraging during breeding /lactation (♂ Y/N, ♀ Y/N)	# Aquatic call types	Aquaticvocal dialects	Sex-specific vocs	Aquatic vocal displays	Repro. strategy	Indiv-specific vocs
	Winter	Non-winter										
Leopard seal	SP, P	P	A	P	30	0	12	Y_1	N_1	0	0	Y(water)$_1$
Southern elephant seal	SP	SP, P	A, L	L	20–25	♂N, ♀N	0	0	Y_2	N_2	Y_3	Y(air)$_3$
Antarctic otariid												
Antarctic fur seal	SP,T	P,SP,T	L	L	120	♂N, ♀Y	0	0	Y_1	0	Y_2	Y(air)$_2$

This summary table is a compilation of information currently known about polar pinnipeds and is provided in contrast to Table 11.1. Highlighted cells denote new information gained through PAM systems. Information in columns 2–6 relate to the distribution, behavior, and substrate use of each species associated with critical life functions. This information is needed for appropriate comparison and contrast of behavioral and acoustic characteristics between species. Information in columns 7–12 are either acoustic parameters directly related to acoustic communication or behavioral parameters concluded from the analysis and interpretation of acoustic data. Unless otherwise designated, the level of information for each parameter is evaluated by the authors on a 0–3 scale where zero indicates no known information and three indicates a detailed level of information that has been directly observed or measured. New information reflected in Table 11.2 that was not cited elsewhere in the chapter text is listed in a separate reference section at the end of the chapter

[a] *P* polar, *SP* subpolar, *T* temperate, *ST* subtropical, *TR* tropical

[b] *A* aquatic, *I* ice, *L* land

[c] *L* land, *F* fast ice, *P* pack ice

[d] Length of the fasting period differs substantially between the sexes, with females fasting for ~4 weeks and males up to 3 months (Riedman 1990)

[e] Female harp seal pups were found to exhibit individually stereotyped in-air calls (Van Opzeeland and Van Parijs 2004)

[f] Feeding during the breeding season by Weddell seal males is thought to be facultative (Harcourt et al. 2007)

PAM recordings have occurred in the polar phocids compared to otariids. This is best explained by the fact that otariids are only seasonal inhabitants of polar regions with less documented use of underwater vocalizations, resulting in an absence of acoustic presence in most polar recordings.

As seen in the case studies, knowledge is not only being gained about the repertoires and behaviors of individuals and specific species, but also about the relationships among and between the species (e.g., acoustic niche partitioning). The information about underwater vocal repertoire of aquatic mating pinnipeds continues to grow for a majority of species and varies considerably in size between species (e.g., Stirling 1973; Stirling and Siniff 1979; Thomas and Kuechle 1982; Hanggi and Schusterman 1994; Serrano 2001). Increased knowledge about individual species enabled Rogers (2003) to examine the role of various behavioral and ecological factors on the size of the male acoustic repertoire in aquatic mating seals. Several factors such as the degree of sexual size dimorphism, stability of the pupping substrate, breeding colony density, and the degree to which female distribution is predictable to males were shown to influence the size of the vocal repertoire. Based on the acoustic characteristics of the calls, the repertoire size and the function of male vocal behavior, Rogers (2003) discriminates three groups of vocalization strategies in aquatic mating seals. (1) The first group comprises hooded, grey, and crabeater seals. The repertoire of these species is small and consists of short and broadband calls that have a function in agonistic interaction between males over relatively short distances. (2) Bearded, ribbon, and Ross seals use stereotyped narrowband calls to signal to rival males and/or potential mates over long distances and have a moderately sized vocal repertoire. (3) The third group, consisting of harp, harbor, Weddell, and ringed seals, has the largest vocal repertoire of the three groups consisting of varied types of sounds that function in shorter-range mate attraction and/or territory defense (Van Opzeeland et al. 2008).

The knowledge gained from autonomous PAM has advanced our understanding of polar pinniped communication, basic biology, and overall acoustic ecology of polar regions in the past decade. Vocal repertoires have become more readily quantifiable using wide bandwidth recording devices, high-resolution spectrograms, and spectral analysis that were not available in studies from the 1960s to 1980s. This has resulted in a clearer picture of the seasonal and geographic variation in ringed and bearded seal calls indicative of a transition in behavior from maintenance and defense of breathing holes to mating-related behavior and mating strategy, respectively. Single sensors and arrays have also contributed to our knowledge of the geographic variation and vocal development in harbor seals. Comparative analyses of the roar vocalization of male harbor seals from ten sites throughout their distribution showed that vocal variation occurs at the oceanic, regional, population, and subpopulation level (Van Parijs et al. 2003b). Genetic barriers based on the physical distance between harbor seal populations presented a likely explanation for some of the observed vocal variation. However, site-specific vocal variations were present between genetically mixed subpopulations in California. A tree-based classification analysis grouped Scottish populations together with eastern Pacific sites, rather than among Atlantic sites, as would be expected if variation was based purely on genetics. Lastly, within the classification tree, no individual vocal parameter was consistently responsible for consecutive splits between geographic sites. Combined, these factors suggest that site-specific variation in habitat type influences the development of vocal structure in harbor seals.

Comparisons of acoustic presence with sea ice characteristics are particularly insightful. Understanding the details of the relationships between ice and different species or, more specifically, specific age groups or sexes within a species will lead to greater predictive power of impacts on portions of the population as the environment changes. This new information comes at a critical time, as polar regions are undergoing considerable change in response to global climate change. Much of the information gained from polar PAM provides baseline information about species which will form the basis for climate change impact predictions for these species. There is also great potential to mine data relating to polar pinnipeds from historical autonomous PAM datasets originally made for the study of cetaceans. Ongoing, long-term, regional recordings made possible with autonomous PAM technology will be critical in monitoring polar pinniped distribution shifts, impacts to mating activity, and changes in acoustic soundscapes.

11.4 Future Challenges

Although the application of autonomous PAM has provided many new insights into the behavioral ecology of polar pinnipeds, several aspects still remain unknown. Firstly, the gaps in our current knowledge of polar pinnipeds that have not yet been bridged by the use of PAM are partly related to the lack of visual confirmation and information on calling individuals; for almost all polar pinniped species, it is not known if both sexes produce all vocalization types or if some calls are sex-specific. Likewise, little to nothing is known on the ontology of acoustic behavior in many species. The existing knowledge on vocal learning and development in polar pinnipeds largely stems from captive studies, where calling individuals could be closely monitored during the time they developed their acoustic behavior, albeit in absence of conspecifics and a natural sound environment (e.g., Davies et al. 2006; Schusterman 2008). Furthermore, as this chapter also illustrated, there still are many questions left with respect to the function of calls and the behavioral context in which they are produced. In aquatic mating species, for example, most calls are thought to be produced in mating context, but it remains unclear which call types have an intrasexual competition and/or a mate attraction function. Several species are also known to call outside the breeding season, which may indicate that calls are potentially also used in other behavioral contexts than mating.

Acquiring visual data alongside the acoustic data requires underwater observation which has been collected sporadically using cameras in fixed position or mounted on animals (e.g., Davis et al. 2004; Heaslip and Hooker 2008). However, poor underwater visibility in most polar waters severely limits the observation range, complicating spatial coverage by observing systems of underwater pinniped habitats. Mounting cameras on animals adds drag and is a fairly invasive method, requiring catching and sedation of animals, leaving it questionable if behavior is representative—at least over shorter time scales—after deployment (Heaslip and Hooker 2008). Also, most mounted cameras have to be retrieved in order to acquire the data, leaving successful deployments dependent on the retrieval of the instrument upon release or recapture of the equipped animal. Alternative to visual information, the application of acoustic tags, registering acoustic behavior of the focal animal provides data on sex-specific usage of calls and, if deployed over longer time spans, the ontology of vocal behavior. Nevertheless, application of acoustic tags also requires catching the animal and in most cases retrieving the tag, which can be specifically complex when the tag comes off in ice-covered areas or at night. Long-term acoustic monitoring of pinniped underwater vocal behavior using acoustic tags is further complicated by the annual moult, during which the hair to which the tag is glued comes off. As to the gaps in knowledge with respect to sex-specific vocal behavior and the behavioral function of calls, tracking of underwater movements of calling individuals using acoustic arrays, when possible in combination with visual observation of the animals while at the surface (e.g., Van Parijs et al. 2004), is most promising as this PAM technique provides reliable individual- and/or sex-specific behavioral locations which can be coupled to acoustic recordings. Furthermore, combining PAM with other observation techniques, albeit over restricted temporal and spatial scales (e.g., acoustic tags, underwater cameras) will contribute further pieces to the puzzle.

The vocal repertoire is another aspect of polar pinniped acoustic behavior that warrants further investigation for many species. New call types are still being discovered for various species (McCreeery and Thomas 2009; Klinck et al. 2010; Van Opzeeland et al. 2010; Miksis-Olds and Parks 2011; Jones et al. 2014), illustrating that we do not yet know the full vocal repertoire of many polar pinniped species. Knowledge of the full vocal repertoire of a species is important when using acoustic observation to assess physical presence of a species and to study distribution patterns. Much of the uncertainty with respect to the vocal repertoire of many species is likely caused by the migratory nature of many polar pinnipeds, whereas passive acoustic recorders are static, sampling acoustic data only at one location. In cases in which the full distributional range of a species is not covered by acoustic recordings, it cannot be excluded that a species changes its vocal behavior and/or call type usage between areas. Similarly, vocal behavior of many species is likely to vary between seasons as illustrated by some of the case studies in this chapter. Currently, descriptions of the vocal repertoire of polar pinnipeds are skewed towards studies that recorded during the breeding season only, which is likely due to the remoteness and inaccessibility of polar regions during other times of year. Clearly, to describe the full vocal repertoire of a polar pinniped species, the spatial and temporal scale of recordings needs to be matched with what is known on the timing and range of animal movements. Given that for many species details on migratory behavior are still unknown, data from passive acoustic recorders deployed in the context of cetacean research should also be considered for use as initial exploration of spatial and temporal distribution patterns of polar pinnipeds.

Recent studies suggest that polar pinniped species are likely to interact acoustically, timing their acoustic activity possibly to reduce interspecific acoustic interference (Van Opzeeland et al. 2010; Van Opzeeland and Miksis-Olds 2012). However, direct evidence of the existence of such a mechanism is lacking. Further research into acoustic niche formation requires long-term acoustic observation of such staggered acoustic activity, so that interannual variation in abiotic and biotic factors can be used to disentangle acoustic and non-acoustic drivers that determine the onset of each species' vocal activity. Furthermore, investigation of the acoustic (noise) budgets or soundscapes of regions where potentially interacting species occur is likely to provide information on the actual acoustic space each species occupies. Finally, using an experimental setup, underwater playbacks of calls could be used to test hypotheses on acoustic interactions between species.

Lastly, we still know very little on how current climatic changes will affect polar pinnipeds in their habitats. Given that in most species acoustic behavior is closely linked to the breeding season, which in turn is often linked to the availability of suitable ice for breeding and haul-out, changes in ice conditions will likely be reflected in changes in vocal behavior. To monitor trends in the effects on polar pinnipeds of climate-induced changes, long-term acoustic observation using PAM techniques provides a relatively low-cost tool to acquire valuable data on pinnipeds in their potentially changing polar habitats. Similarly, the increased human activity in polar waters has, in some areas, led to significant changes in the overall soundscape (Clark et al. 2009). Increasing underwater sound levels have the potential to reduce communication space for marine animals that rely on sound for communication, orientation, and foraging. If and by what mechanisms anthropogenic sound in the ocean affects polar pinnipeds is still largely unknown. The applications of PAM, in particular over longer time spans, will also further our understanding on the effects of anthropogenic noise on polar pinnipeds.

This chapter provided an overview of how autonomous PAM techniques are and can be used to study polar pinnipeds. From this it can be concluded that the application of autonomous PAM sensors and systems appropriate for studying polar pinnipeds are surprisingly rare, in particular when compared to the number of autonomous PAM applications in the field of cetacean research over the last years (e.g., Moore et al. 2006; Mellinger et al. 2007). As we have shown in our overview of knowledge gained using acoustic techniques since 2000, autonomous PAM sensors have significantly furthered research on polar pinnipeds, leading to new questions and hypotheses on their behavior and biology. In both the Arctic and the Antarctic, a vast number of autonomous PAM recorders have been deployed over the last 5 years (for PAM devices deployed in the Arctic see: http://data.aoos.org/maps/arctic_assets/). It is therefore expected that within the coming years, the recently gained multiyear data will be used in studies investigating trends in acoustic behavior and the role of factors that drive interannual variation in pinnipeds and many other vocalizing polar animals.

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Chapter 12
Listening in the Ocean: New Discoveries and Insights on Marine Life from Autonomous Passive Acoustic Recorders

David Mann, James Locascio, and Carrie Wall

Abstract Passive acoustics provides a near perfect ocean observatory sensor for biological activity in fishes. For species whose sounds have been documented, we can use passive acoustic recording to learn about their ecology. In this chapter we review the history of the development of passive acoustics research on fishes. Today, fish passive acoustic monitoring is in a rapid stage of development as an additional tool for fisheries research. The latest studies have focused on temporal and spatial patterns of sound production of fishes, including many commercially important species such as groupers and cods. These studies have been conducted with long-term fixed passive acoustic recorders and more recently with gliders and other autonomous platforms. These methods are complementary, as long-term recorders provide excellent temporal coverage and gliders provide excellent spatial coverage. The greatest impediment to further advance is that for most fishes we still do not know what sounds they make. We suggest that miniature acoustic tags may be one way to increase our library of known fish sounds. The main challenges remaining are the development of tools to automatically analyze large datasets, and experimental studies to enable quantification of fish numbers and spawning using passive acoustics.

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12.1 Fish Sound Production

Many fishes have been known to make sounds ever since humans started catching them. In this chapter, we focus on recent advances in the use of passive acoustics to study fish distribution and behavior using autonomous acoustic recorders. Fish passive acoustic monitoring is in a rapid stage of development as an additional tool in fisheries research (Rountree et al. 2006; Luczkovich et al. 2008). Recent developments in fish passive acoustics build on the results of decades of research into the mechanisms and physiology of fish sound production and hearing. Several excellent texts thoroughly review mechanisms of fish sound production, hearing, and acoustic communication (Fay and Popper 1999; Ladich et al. 2006; Webb et al. 2008).

Fish sounds are generally low frequency (usually below 1000 Hz), with some large fishes like the goliath grouper producing sounds as low as 60 Hz (Mann et al. 2009). The acoustic characteristics of fish sounds are directly tied to the mechanisms of sound production. For example, toadfish twitch their sonic muscles to drive the swimbladder to produce sound. The swimbladder does not act as a resonator in these species; it is highly damped (Fine et al. 2009). Thus, the fundamental frequency of the toadfish boatwhistle sound reflects the muscle contraction rate. In these species, the frequency of the sound can change seasonally as the water warms, allowing faster muscle contraction rates (Fine 1978). Many of the loudest species, such as the croakers and drums, have specialized muscles located on (intrinsic), or next to (extrinsic), the gas filled swimbladder, and the contraction rate produces the fundamental frequency of sounds. Other species, such as the catfishes, produce sounds by stridulating bones (Parmentier et al. 2010).

Fish sounds are stereotypical, like insect and frog sounds. While there is some interindividual variation, it is small compared to variation between species. Still, different species in the same family often produce similar sounds. Many toadfish produce the distinctive “boatwhistle” call, but the contraction rate and number of elements varies between species (Tavolga 1958; Amorim et al. 2011). The stereotypical nature of fish sounds makes it relatively easy to identify which species (or family) of fish made which sound, once the sound has been characterized.

For species whose sounds have been documented, we can use passive acoustic recording to learn about their ecology. Passive acoustics provides a near perfect ocean observatory sensor for biological activity in fishes. Biofouling does not cause calibration issues with hydrophones as it does with many other environmental sensors, and available systems are very low power. Since sound production is often linked to reproductive activities, passive acoustics provides an indirect way to determine spawning seasons and identify areas where fish may migrate to spawn. Still, there is a paucity of confirmed sounds from the total number of likely sound producing fishes, and even less where simultaneous behavioral data have been collected. Identifying unknown fish sounds and the specific behavioral context in which they are made is critical for the expansion of ecological studies using passive acoustics.

12.2 Fish Passive Acoustic Monitoring

12.2.1 *Mobile Hydrophone Monitoring*

The beginning of the scientific use of eavesdropping on fish sounds to study behavioral patterns in fishes can be traced to Charles Breder's pioneering study listening to the sounds produced by fishes in Lemon Bay, off the Gulf of Mexico in southwest Florida (Breder 1968). Breder lowered a hydrophone off of a dock, and listened for fish sounds that had been previously identified, such as by the gulf toadfish and marine catfish (Tavolga 1958). By collecting data over a 5 year period he quantified patterns in sound production that likely reflect the seasonal patterns of reproductive activity of these species (Fig. 12.1). One of the most interesting aspects of this paper was that he described other fish sounds, which were named the "galloper" and "repeater," but whose identities remain unknown.

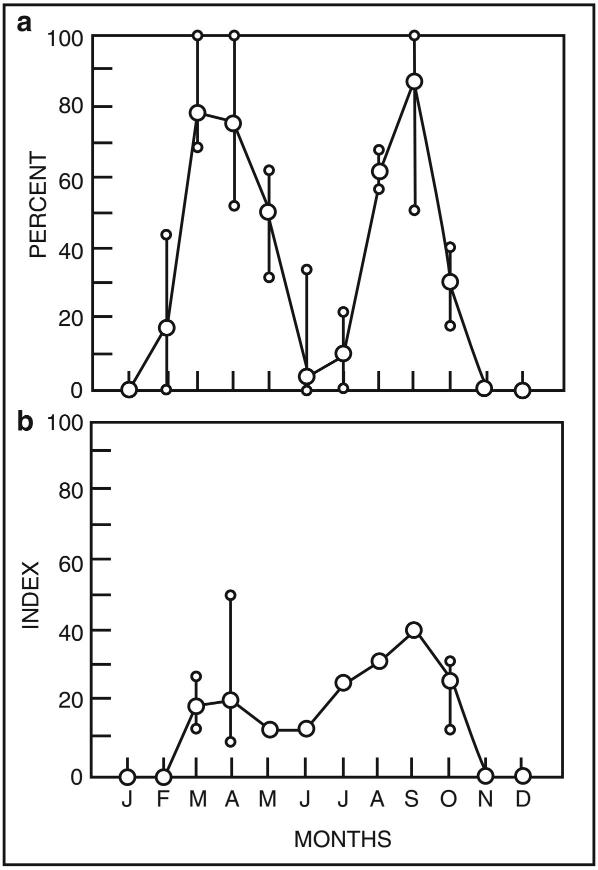

Fig. 12.1 Monthly sound production by the gulf toadfish, *Opsanus beta*, recorded from a dock in terms of (**a**) percent days of occurrence and (**b**) intensity index. From Breder (1968)

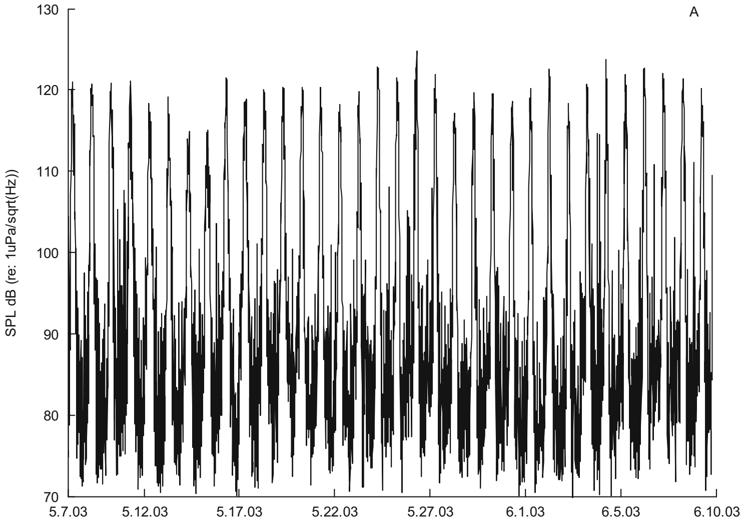

Fig. 12.2 Sound pressure level in the 300–400 Hz band recorded over 10 s every 10 min in Charlotte Harbor, Florida, USA during May-June 2003. The sound levels at dusk and at night are dominated by the sand seatrout, which is a type of sciaenid fish. Peaks during the day are due to boat engine noise. From Locascio and Mann (2008)

The mobile hydrophone mapping technique has been used to map sound-producing fish distributions across entire estuaries, such as Tampa Bay, Florida (Walters et al. 2009). Luczkovich et al. (1999) showed that they could locate areas and times of spawning weakfish by combining mobile passive acoustic recordings with plankton tows to catch floating eggs.

12.2.2 Patterns of Fish Sound Production Using Fixed Recorders

Most recently, effort has gone into the development and use of autonomous passive acoustic recorders to extend observational scales. These recorders use flash memory to record sounds, usually at programmed intervals. In most cases (particularly for sciaenids) fish sound production is frequent enough that interval recordings are sufficient to characterize daily and seasonal patterns in sound production (Locascio and Mann 2008), and this also extends the recorder's deployment period (Fig. 12.2). The main advantage of autonomous recorders is that they enable recordings to be made over large spatial and temporal scales. They also allow recording at times when it would not be possible to be on the ocean. For example, sound production of sand seatrout was recorded before, during, and after a hurricane passed directly overhead, and was found to be little affected (Locascio and Mann 2005).

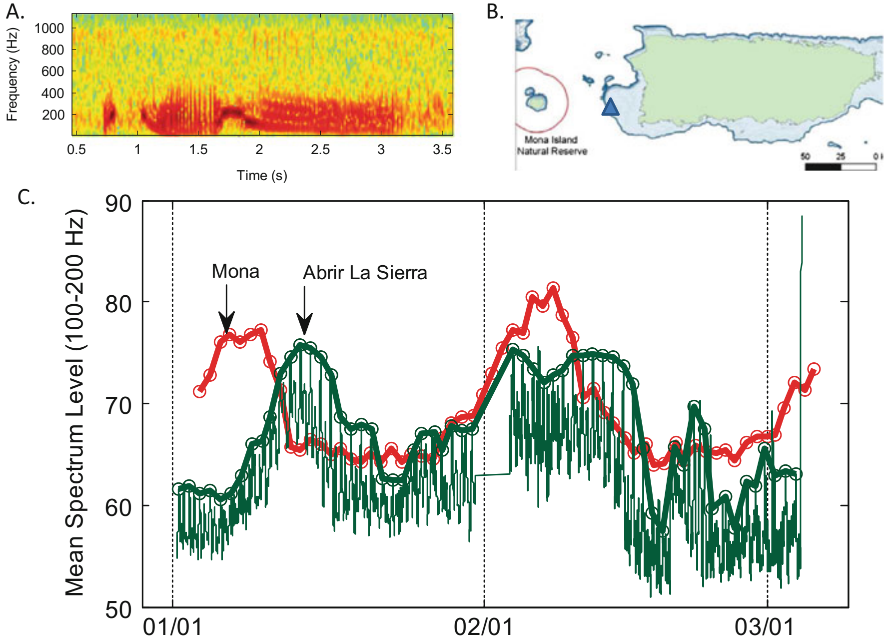

Fig. 12.3 (**a**) Spectrogram of red hind grouper sound. (**b**) Map showing two autonomous recorder sites at Mona Island and Abrir La Sierra (*triangle*). (**c**) Sound level from 100 to 200 Hz. *Thin green line* shows Abrir La Sierra sound level every 10 min. *Thick lines* are daily maximum sound levels from Mona Island (*red*) and Abrir La Sierra (*green*). Note the offset in the timing of the peak sound level between the two locations. From Mann et al. (2010)

Long-term acoustic recorders have been used to record sound production by red hind grouper at spawning aggregation sites in Puerto Rico (Mann et al. 2010). During territorial behavior, red hind males produce a pulsed sound that grades into a tonal harmonic sound (Fig. 12.2). Sound production peaks daily in the late afternoon, but there are also peaks associated with the lunar cycle (Fig. 12.3). Comparing daily peaks in sound production at two aggregation sites, one at Mona Island and the other 36 km away off mainland Puerto Rico, showed that there was approximately a 6 day difference in the monthly peak in sound production. It had been previously thought that all grouper spawning aggregations were tightly tied to the lunar cycle, yet passive acoustics show large differences in the timing of sound production at two relatively close, yet isolated, sites.

12.2.3 Ocean Observatories

The development of sustained ocean observatories provides an excellent opportunity for long-term passive acoustic studies of fishes. LEO-15 is a long-term ocean observatory located off the coast of New Jersey in 15 m water depth. Because the

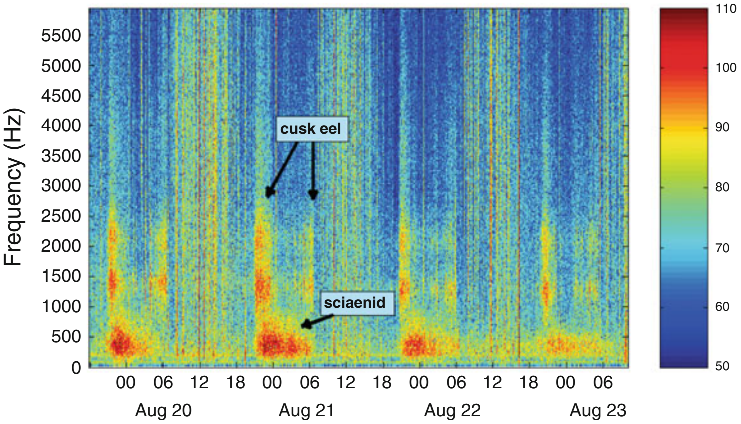

Fig. 12.4 LEO-15 ocean observatory recordings. Data are shown as a composite spectrogram. Low-frequency sounds between 100 and 600 Hz from dusk through midnight are from sciaenids (weakfish and Atlantic croaker). High-frequency sounds between 1000 and 2500 Hz are from crepuscular cusk-eel sound production. From Mann and Grothues (2009)

ocean observatory is hard-wired to shore, it is relatively straightforward to capture acoustic recordings onshore. A hydrophone at LEO-15 documented nightly occurrence of sound production by cusk eels, which produce a relatively high-frequency sound (Mann et al. 1997), as well as sciaenids (croakers and drum). A composite spectrogram of 4 days of recording reveals two nightly peaks in sound production by cusk eels, one at dusk and a lower-level one at dawn (Fig. 12.4). Sciaenids produced sounds during the late afternoon and night.

The main advantage of ocean observatories is that they are also being used to record physical and chemical properties of the ocean. At LEO-15 there were brief periods of cold-water intrusion that were negatively correlated with fish sound production rates (Fig. 12.5). These data show the utility of having simultaneous oceanographic measurements that can be used to help explain variability in fish sound production. Of course, the decrease in sound level could be due to the fish ceasing to produce sound, or moving to another area. A study combining active acoustic measurement of fish movement combined with passive acoustics could answer this question.

12.2.4 Hydrophone Arrays

The use of hydrophone arrays has been important in cetacean studies where whales can be localized and tracked over large ranges. Comparatively little research using hydrophone arrays has been done with fishes. Rountree and Juanes (2010) recorded sound production by cusk using a remotely operated vehicle (ROV) outfitted with three hydrophones. Mann and Jarvis (2004) localized a suspected deep-sea fish sound in the Tongue of the Ocean, Bahamas using four hydrophones from the AUTEC test

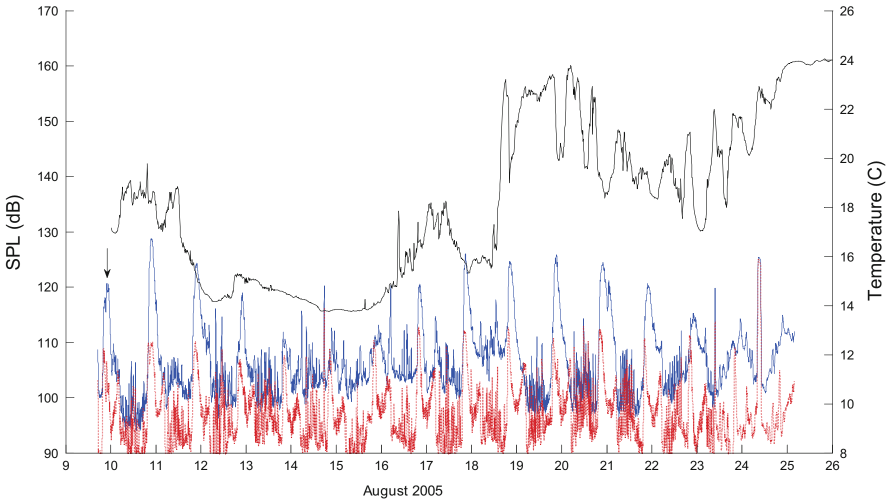

Fig. 12.5 LEO-15 ocean observatory time series of water temperature (*black*) and sciaenid band sound pressure levels (200–300 Hz; *blue*) and cusk-eel sound levels (800–1200 Hz; *red*). Sound levels decreased with drops in water temperature. The sound level plot was smoothed with an 11-point moving average to reduce noise spikes from boat traffic. Date tick marks are at midnight. From Mann and Grothues (2009)

range. The sound was a stereotypical pulsed, low-frequency (800–1000 Hz) sound, which was localized to midwater (548–696 m) where the bottom was 1620 m depth.

A 5-channel hydrophone array was used to localize black drum sound production to study individual behavior and measure source level (Locascio and Mann 2011a). Because black drum produced sounds repeatedly, it was possible to localize and track each sound from a presumptive individual calling black drum, which swam in loops as it called (Fig. 12.6). From the localization data and estimates of signal loss associated with sound propagation, black drum were found to produce sounds with a source level of 165 dB re 1 μPa, which falls more into the range of intensity documented for marine mammals than fishes (Locascio and Mann 2011a).

There is a need to further develop the use of hydrophone arrays to study fish behavior and estimate sound source levels. One interesting result of the black drum study was that the estimated source level was close to the highest level sounds recorded on passive acoustic recorders (Fig. 12.6). One challenge with many chorusing fishes, such as croakers, is that many individuals produce overlapping sounds making the identification and quantification of individual sound producers difficult.

12.2.5 Autonomous Gliders

Autonomous gliders are a relatively new technology for studying oceanography over large time and space scales. Gliders such as the Slocum glider (Teledyne Webb research) are buoyancy-driven, electric autonomous underwater vehicles approximately 2 m

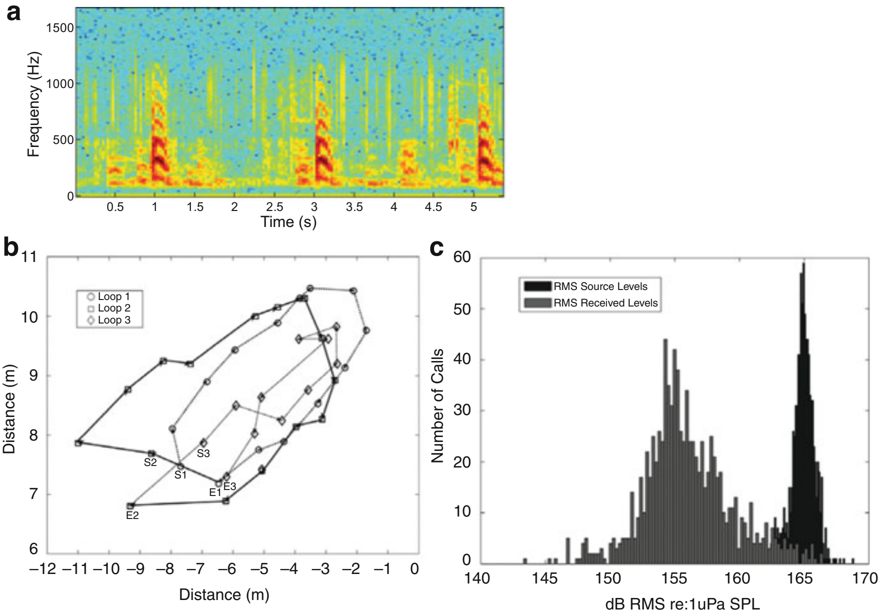

Fig. 12.6 (**a**) Spectrogram of black drum sound production, which appears as a harmonic sound with a fundamental frequency around 100 Hz. The calls appear to be repeated about every 2 s, and lower level calls from other individual black drum can be seen in the background. (**b**) Localization of a calling black drum shows that it swims in loop approximately 10 m long as it calls. (**c**) Histogram of received levels of black drum sounds and source levels based on localization show that the highest received levels are similar to the source level estimates. From Locascio and Mann (2011a, b)

in length and shaped like a winged torpedo (Webb et al. 2001; Schofield et al. 2007). Forward propulsion in the glider is created by varying the vehicle buoyancy allowing to glider to traverse over 600 km using a single set of alkaline batteries. As the glider ascends and descends the water column, on-board environmental sensors measure temperature, salinity, surface currents, fluorescence, and apparent and inherent optical properties (Schofield et al. 2007). In addition to this suite of sensors, hydrophones have recently been integrated into gliders to detect and map fish sounds (Wall et al. 2012). The absence of a drive motor and propellers minimizes mechanical noise produced by the glider making this platform particularly adept for acoustic studies compared to some ROVs (Rountree and Juanes 2010).

Hydrophone-integrated gliders have been deployed in the eastern Gulf of Mexico since 2009. Missions are usually 1–2 weeks in length and cover a range of depths up to 1000 m. Throughout the 15 missions conducted between April 2009 and April 2011, 25,760 acoustic files were recorded over various glider tracks. Glider missions were run during all months except May, August, November, and December, and acoustic data were collected during all hours of the day. All gliders deployed were successfully retrieved providing a high return rate compared to stationary acoustic recorders deployed in the same area (Dudzinski et al. 2011).

In addition to mapping the sound production of two known species (red grouper, *Epinephelus morio*, and toadfish, *Opsanus* sp.), Wall et al. (2012) described three unknown fish-related sounds recorded during a 1-week-long deployment in the eastern Gulf of Mexico (Fig. 12.7). Recording incidental biological and anthropogenic sounds during deployments is not uncommon. However, identifying the sources of each sound is challenging. A preliminary analysis of families of soniferous fishes in the Gulf of Mexico using published literature (Fish and Mowbray 1970; Hoese and Moore 1998) and unpublished sound recordings identified nearly 90 genera are likely to make sound based on anatomy. This leaves the potential sources of sound rather vast. Without corresponding video observations, the source and behavior associated with each sound, if not already documented, remains unknown.

To illustrate the richness of data collected by the glider, all of the fish sounds recorded by the glider were plotted over the course of the weeklong deployment (Fig. 12.8). The three newly discovered sounds were recorded over different geographical ranges. The 365 Hz harmonic was recorded in depths shallower than 40 m, the 300 Hz FM harmonic was recorded in depths >40 m, and the 6 kHz sound was recorded over the entire track. By looking at the location of the glider in the water column, it can be seen that the sounds could be detected over the entire water column (up to 50 m depth), and that many were produced almost exclusively at night. This diel pattern of sound production explains the apparent patchy geographic distribution of the sounds. Because the glider is moving while recording, there is a linked spatial and temporal bias in sampling.

12.2.6 Combining Fixed Autonomous Recorders and Gliders

One way to overcome the spatial and temporal bias in glider sampling, is to combine glider sampling with fixed long-term passive acoustic recorders. This has been done in the Gulf of Mexico for mapping the geographic distribution of red grouper (*Epinephelus morio*) sound production (Wall et al. 2014) (Fig. 12.9).

Manually identified red grouper calls were observed 24 h-a-day and throughout all months in which data were recorded. Most calling occurred between sunrise and sunset with peaks at dusk. Sounds were primarily generated between approximately 20 and 93 m water depth, with increased calling within known hard bottom and marine reserve areas offshore. No red grouper were detected in depths greater than 93 m (Fig. 12.9).

Acoustic data collected by hydrophone-integrated gliders provided insight into the spatial and temporal range of red grouper sound production. These data can be used as a near real-time, no-take approach to effectively monitor this species as well as numerous other soniferous fish and may aid fisheries managers in maintaining long-term population stability.

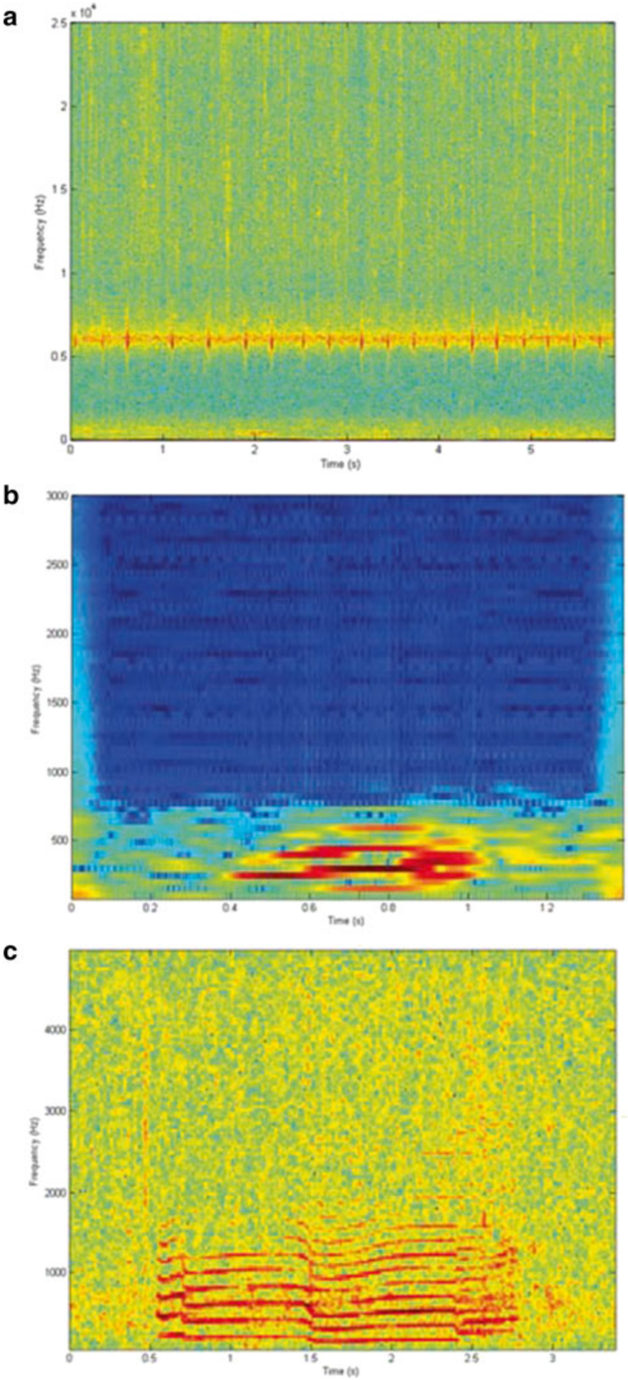

Fig. 12.7 Three unidentified sounds commonly recorded in the Gulf of Mexico from an underwater glider. (**a**) 6 kHz sound. (**b**) 365 Hz harmonic sound. (**c**) 300 Hz FM harmonic sound. From Wall et al. (2012)

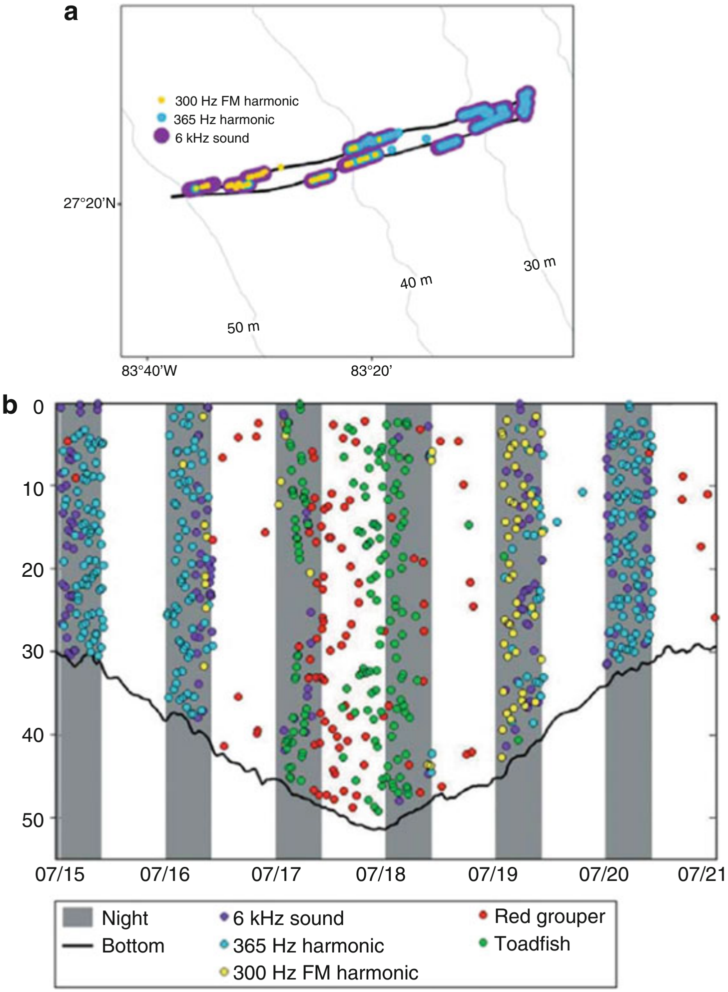

Fig. 12.8 Fish passive acoustics using an autonomous glider. (**a**) Detections of three unidentified, presumptive fish sounds along a glider transect. (**b**) Detections of five different fish sounds showing the depth of the glider and the time of detection. *Dark bands* indicate night, *light bands* indicate day. From Wall et al. (2012)

12.3 Future Research

12.3.1 Technologies to Identify Sound Producing Species and Behavior during Sound Production

Until now, identification of fish sounds has been done using fish in captivity (e.g., Fish and Mowbray 1970), penned in the wild (e.g., Aalbers 2008), and with video systems that were fixed in place (e.g., Nelson et al. 2011), diver operated (e.g.,

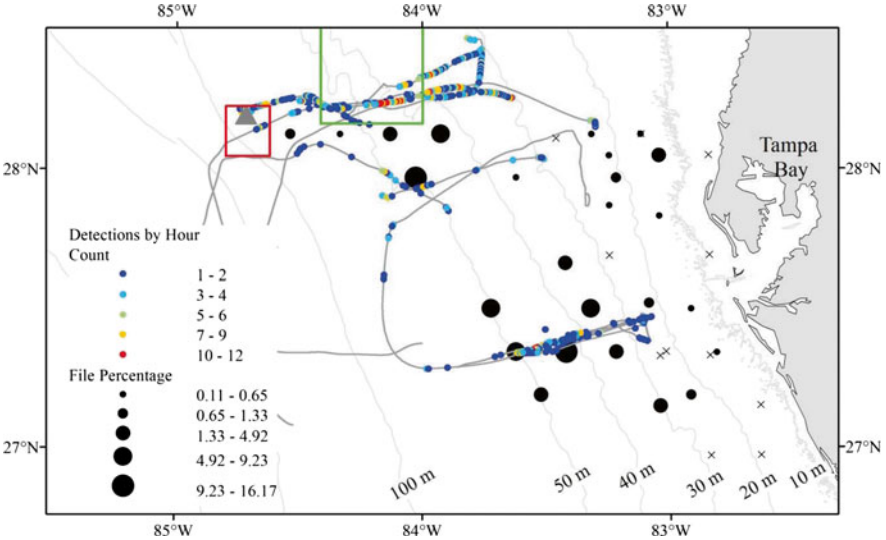

Fig. 12.9 Red grouper call detection rates from glider data (Detections by Hour) and manually analyzed stationary data (File Percentage). For glider data, *symbol color* is proportional to the number of files per hour that contain red grouper sound production. For stationary data, *symbol size* is proportional to the percent of files red grouper sound production was detected, out of the total number of files analyzed per site. Stationary recorder locations in which no red grouper calls were identified are indicated (*x*). Locations of the Steamboat Lumps recorders (*grey traingle*), the boundaries of Steamboat Lumps (*red box*), and the lower boundary of the Florida Middle Grounds (*green box*) are also shown. From Wall et al. (2014)

Lobel 1992), or controlled from an ROV (e.g., Rountree and Juanes 2010). Thus, while sounds from over 100 fish species have been recorded, this is likely only scratching the surface. One of the main findings with passive acoustics work is that we frequently encounter commonly produced sounds for which we do not know the sound source, as illustrated by the glider recordings in the Gulf of Mexico. Video approaches are time consuming, and difficult to use for fishes that produce most of their sounds at night. Captive approaches are unlikely to work for fishes located in relatively deep-water.

One solution to this problem may be to adopt technology used for tagging and monitoring sound production by marine mammals, such as the Dtag and Acousonde. Fishes are commonly tagged today with active acoustic pingers to track their location with passive receivers. It should be possible to produce an implantable miniaturized acoustic recording tag to record sound production from tagged fish. Such an approach would vastly increase our ability to record sounds from many species in many habitats and most importantly assign identity to the large number of currently unidentified sources of recorded sounds in existing and ongoing acoustic time series.

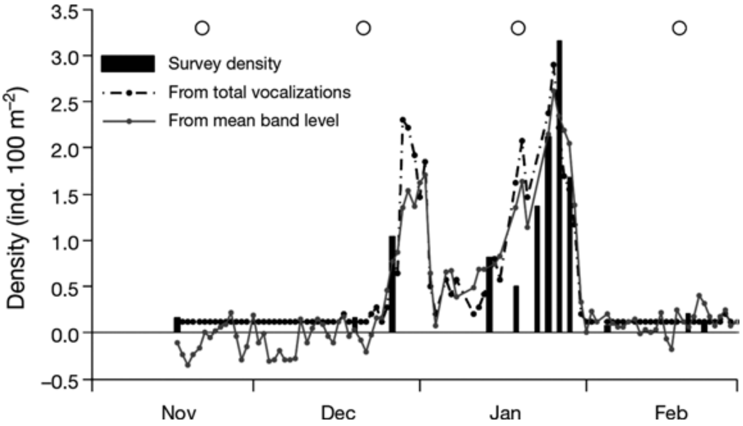

Fig. 12.10 Red hind densities (individuals 100 m^{-2}) from underwater visual census surveys (*black bars*, $n = 12$), and predicted densities from standardized total vocalizations h^{-1} (*dashed black line*) and mean band levels h^{-1} (100–200 Hz; dB re 1 μPa; *solid grey line*). *Circle*: full moon. From Rowell et al. (2012)

12.3.2 Quantification of Fish Numbers and Spawning Using Passive Acoustics

One of the major challenges of fisheries science is the estimation of the abundance, distribution, and spawning output of fishes. While active acoustic techniques have been used to quantify fish abundance, passive acoustic techniques are still not commonly used. One recent example showing how passive acoustics might be used in specialized situations comes from Rowell et al. (2012) who compared red hind densities at a spawning aggregation site and found that they were correlated to vocalization rate and total sound level (Fig. 12.10). Thus, there is a strong application of passive acoustics for monitoring spawning aggregations, which are often used to define the location of marine protected areas.

Since sound production is often associated with courtship and spawning behavior, the idea of using sounds to measure spawning output has been an attractive idea. Luczkovich et al. (1999) did find a relationship between sound production and weakfish egg production in Pamlico Sound, NC. Locascio and Mann (2012) found a good relationship of sound production with the spawning season of black drum, but little positive relationship of sound production to egg production measured on a nightly basis for black drum in a relatively small canal system. This could be due to the fact that sound production is likely dominated by males who are engaging in courtship behavior, regardless of whether females are spawning.

In some species, such as the hamletfish (Lobel 1992), white seabass (Aalbers 2008), and domino damselfish (Mann and Lobel 1998) there appear to be distinctive sounds associated with spawning. In these cases, it is expected that detection of these sounds is an indication of spawning. Additional research is needed to understand the relationship between spawning output and sound production.

12.3.3 Automated Identification of Fish Sounds

Recent developments in passive acoustic technologies have facilitated marine bioacoustics studies to effectively monitor soniferous fish over a wide range of habitat, depths, and time periods (Mann and Lobel 1995; Lobel 2002; Luczkovich et al. 2008; Van Parijs et al. 2009; Lobel et al. 2010; Locascio and Mann 2011b). As batteries become smaller and lighter and memory devices become cheaper with higher capacity (256+GB), passive acoustic monitoring (PAM) systems will be capable of recording increasingly large amounts of acoustic data. Therefore, the limit is no longer on the technology but rather on the scientist who is tasked with processing and analyzing the resulting dataset.

In the past, most acoustic analyses have been completed manually by viewing each acoustic file by eye and/or ear. This method, while often accurate, can be extremely time consuming and is subject to human error and bias not to mention is incredibly tedious. Automatic detection algorithms have become increasingly necessary and apparent in acoustic studies (e.g., Locascio and Mann 2011a; Mellinger et al. 2011; Roch et al. 2011). Automatic recognition of desired sounds or patterns is a fully or semi-automated method allowing vastly faster processing of large datasets compared to manual analysis. However, accuracy of the detection algorithm is often dependent on high signal-to-noise ratios. Therefore, data collected in noisy environments, such as areas with high boat traffic and reefs, often impede the successful application of detection algorithms. However, this aspect of efficient data management and information harvesting from long acoustic time series remains an important and difficult challenge. Software tools for managing and processing these large datasets are critical to furthering the use of passive acoustics for studying all organisms that produce sounds. We also need to require that newly identified sounds be submitted to a centralized database that is accessible to all. Some fish sounds are available from the Library of Natural Sound at Cornell and Fishbase. However, many are still stored in individual investigator's laboratories. Fish passive acoustics has great potential for helping fisheries science move towards larger scale understanding of populations and ecosystems over time. To realize this potential will require collaboration of fisheries scientists, acousticians, engineers, and modelers.

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Chapter 13
Passive Acoustic Monitoring in Benthic Marine Crustaceans: A New Research Frontier

Erica Staaterman

Abstract Passive acoustic monitoring has been used to study the soundscapes of some shallow-water coastal environments. These studies have revealed distinct patterns that depend upon the physical structure of the environment as well as the species living within it. One underrepresented group in marine bioacoustics is the benthic crustaceans, yet these animals are known to produce and detect sounds. Snapping shrimp are the most ubiquitous benthic crustacean, and their "snaps" can substantially elevate sound levels in the range of 2–15 kHz in a variety of habitats in the mid-latitudes. Clawed and spiny lobsters produce tonal vibrations and broadband "rasps," respectively, but these sounds occur more intermittently than the snapping shrimp choruses. Finally, burrow-dwelling mantis shrimp produce low-frequency rhythmic "rumbles" which tend to occur as dawn and dusk choruses. Passive acoustic monitoring of these taxa can be useful for revealing broad ecological patterns, by using some species (e.g., snapping shrimp) as ecological indicators. Acoustic measurements can reveal temporal patterns in crustacean sounds and detect species' occupancy of particular habitats. Finally, acoustic monitoring can demonstrate the temporal and frequency overlap between anthropogenic sounds and natural crustacean sounds, which can help refine research questions on potential impacts.

13.1 Introduction

Passive acoustic monitoring (PAM) is a promising new field of research, which can uncover both broad and fine-scale ecological patterns. For example, through new types of complexity indices, entire communities can be surveyed and compared acoustically (Sueur et al. 2008; Gasc et al. 2013). On the fine scale, temporal patterns in the natural acoustic behaviors of specific organisms, as well as their response

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to disturbance events, can be investigated using passive acoustics (e.g., Locascio and Mann 2005, 2008). Through acoustic recordings, investigators have found that specific benthic habitats have unique sound signatures (Radford et al. 2010; McWilliam and Hawkins 2013). Although much variation in underwater soundscapes may be due to abiotic sound sources (Wenz 1962), the contribution of the biophony to benthic soundscapes, and the site-specific differences within these environments, merits further investigation. Here we provide an overview of the research on benthic soundscapes, with a particular focus on bioacoustic studies of benthic crustaceans.

Although historically much research on ocean noise has focused on deep-water areas, several shallow-water, coastal environments have been explored acoustically, and each has revealed exciting results. For example, Radford et al. (2010) measured soundscapes off of the coast of New Zealand on a macroalgal-dominated rocky reef, a sandy bottom, and an urchin-dominated rocky reef. They found distinct acoustic signatures from all three sites, with a specific acoustic contribution from the sea urchins (Radford et al. 2008, 2010). More recently, McWilliam and Hawkins (2013) found that within an Irish Lough, a cliff site, a gravel site, and a mud site had distinct spectra, which was likely explained by a combination of different sediment characteristics and biological composition. Finally, oyster reefs and nearby soft-bottom habitats within the same estuary also showed unique sound spectra (Lillis et al. 2013). Even the sounds produced by bivalves (so-called “coughs”) have recently been identified, which may provide yet another unique sound to monitor (Di Iorio et al. 2012). These studies highlight the fact that the presence of certain benthic marine organisms can influence a marine soundscapes in several ways: by physically changing habitat structure (e.g., the presence of an oyster reef or macroalgae), and also by contributing to the unique biophony of that habitat. These descriptive studies provide valuable baseline data for marine habitats, but do not necessarily target specific sound-producers. However, because PAM allows investigators the opportunity to “spy” on their study species, it can be used to learn about natural acoustic behaviors of soniferous benthic organisms such as crustaceans.

13.2 Decapod Crustacean Sounds

While sound production in crustaceans has been documented for centuries (Wood Mason 1878), it was not until recently that investigators began to use PAM to study these species. Laboratory studies have identified various types of crustacean sounds (e.g., Hazlett and Winn 1962; Meyer-Rochow and Penrose 1976; Patek and Caldwell 2006), sound production mechanisms (e.g., Ritzmann 1973; Imafuku and Ikeda 1990; Patek 2002) and neurological receivers and sensitivity (e.g., Salmon and Horch 1976; Goodall et al. 1990). Crustaceans are indeed capable of detecting acoustic signals: sensory hairs on the exoskeleton are sensitive to substrate-borne or water-borne vibrations (Goodall et al. 1990; Tautz 1990; Budelmann 1992; Popper et al. 2001). In addition, crustaceans can detect particle motion and possibly acoustic pressure through chordotonal organs on their joints and statocyst detectors at the base of the antennae (Breithaupt and Tautz 1988; Budelmann 1992; Popper et al. 2001; Taylor and Patek 2010). Clearly these animals are acoustically active, and there is a need to better understand the behavioral functions of sounds, which can best be explored in the field.

The most ubiquitous and well-studied sounds produced by crustaceans are the characteristic "snaps" of the snapping shrimp. The acoustic behaviors and characteristics of these sounds were first described by Johnson et al. (1947). They identified that these soniferous benthic crustaceans can live in habitats ranging from eelgrass to rocky reefs to coral reefs, and are dominant in the mid-latitudes (Johnson et al. 1947). Snapping shrimp sound levels, which are strongest in the range of 2–15 kHz, are typically higher at night than during the day, with a peak during dawn and dusk (Johnson et al. 1947). Tank experiments by Hazlett and Winn (1962) attempted to determine the behavioral trigger for the alpheid shrimp's "snap," and found that it is used in a territorial context (Hazlett and Winn 1962). Some field work has attempted to count individual "snaps" as an ecological indicator tool, but the authors caution that this method may only be applicable within specific locations, rather than between sites (Watanabe et al. 2002). Because snapping shrimp are common on coral reefs, these sounds have received attention in studies on coral reef soundscapes and may indeed be correlated with certain measures of ecological health (Lammers et al. 2008; Kennedy et al. 2010; Staaterman et al. 2013). However, because snapping shrimp can also inhabit rocky reefs and even coral rubble (Enochs et al. 2011), a high level of snapping shrimp noise does not necessarily reflect a large percentage of live coral. In the future, PAM work should be combined with careful benthic surveys to better assess the relationship between snapping shrimp sounds and life on the reef.

While not as ubiquitous as snapping shrimp, lobsters, too, produce sounds. Henninger and Watson (2005) revealed the physiological mechanism responsible for the tonal, low-frequency vibrations produced by clawed lobsters, but did not determine the behavioral significance (Henninger and Watson III, 2005). Sound production in several species of spiny lobsters has been well studied; these lobsters produce a broadband "rasp" through a stick-and-slip mechanism (Patek 2002). To determine the behavioral context of rasps in California spiny lobsters, Staaterman et al. (2009) presented *Panulirus interruptus* individuals with different model aggressors and noticed that they only responded acoustically after they had been physically contacted, suggesting that the "rasp" serves as an antipredator startle signal (Staaterman et al. 2009). The use of passive acoustic monitoring in this environment would allow researchers to understand natural predator–prey interactions by recording the occurrence of these antipredator sounds. Furthermore, sounds that are produced as a byproduct of lobster movement, especially during their active nocturnal foraging period, may be evident through long-term recordings and could be used to monitor the presence or absence of this species. Mulligan and Fischer (1977) found that the sister species, the Caribbean spiny lobster *P. argus*, produces three types of sounds: "flutter," "popping," and "rasp," depending on the level of arousal (Mulligan and Fischer 1977). Hazlett and Winn (1962) examined natural diel variation in *P. argus* sounds through passive recordings on a reef in Bermuda

(Hazlett and Winn 1962). They found that more sounds were produced at night, but acknowledged the limitations of their conclusions due to low replication. They were only able to make three recordings, spread across 2 years and two different months, presumably due to technical limitations (Hazlett and Winn 1962). This is precisely the type of experimental question that can be revisited with passive acoustic monitoring, now that tools are available for longer-term recordings.

13.3 Stomatopod Crustacean Sounds

In addition to decapod crustaceans, stomatopod crustaceans are known to produce sounds as well. The mantis shrimp strike produces a sound that is similar to the snapping shrimp “snap,” but is a by-product of feeding and aggressive behaviors (Hazlett and Winn 1962; Caldwell 1979; Patek and Caldwell 2005). In addition to the strike sound, at least one species of mantis shrimp, *Hemisquilla californiensis*, is known to produce a sound that is not associated with strike behavior: a low-frequency “rumble,” first recorded in tanks by Patek and Caldwell (2006). The authors recorded sounds from males while held in tanks, and through dissections they deduced that rumbles are produced by a pair of muscles under the carapace.

When a species’ sounds have already been characterized in a lab setting, passive acoustic monitoring is the logical next step for understanding its acoustic ecology. A follow-up study by Staaterman et al. (2011) explored the temporal patterns of sound production in the California mantis shrimp through PAM. The investigators deployed an autonomous recording unit in the habitat of *H. californiensis*, near a mantis shrimp burrow, for 8 days during the mating season. They found that there were distinct daily patterns in mantis shrimp acoustic activity (Table 13.1). During crepuscular periods, the rumbles were loud and highly rhythmic. Multiple mantis shrimp were often audible during these times, creating a “mantis shrimp chorus.” The authors noted that these acoustic patterns matched known patterns of physical activity—mantis shrimp are most active during crepuscular periods, typically seen foraging or guarding the entrance to their burrows (Basch and Engle 1989). Because the recordings were made during the mating season, they hypothesized that the rumbles could be used by males to attract females or to defend their burrows. This chorusing behavior is analogous to observations in many terrestrial animals (Bradbury and Vehrencamp 1998). During the nighttime, the authors recorded sounds that resembled mantis shrimp rumbles but were quieter and less rhythmic (Table 13.1) (Staaterman et al. 2011). They suggested that these sounds could have been produced while mantis shrimp were deep inside their burrows, further from the hydrophone. Recording the sounds of *H. californiensis* during an 8-day period allowed the investigators to discern daily acoustic patterns and match them to previously published behavioral observations (Basch and Engle 1989), and to propose hypotheses about the function of the rumbles. These ideas would not have been possible without the ability to listen continuously to the mantis shrimp habitat.

Table 13.1 Daily patterns in the acoustic activity of the California mantis shrimp (*Hemisquilla californiensis*) were consistent with published data on behavioral activity and burrow openings (fifth column in table below corresponds to data from Fig. 13.3 in Basch and Engle (1989), $n = 13$ individuals)

Time of day	Approximate hours	Acoustic activity observed	Number of days observed	Percentage of burrows open
Morning Crepuscular period	~06:30–08:30 h	Loud, rhythmic rumbles	8 out of 8 days	50 % of burrows open
Mid-morning	~9:30–11:30 h	Loud, rhythmic rumbles	6 out of 8 days	Not documented
Mid-day	~11:30–01:30 h	No rumbling	6 out of 7 days	15 % of burrows open
Evening crepuscular period	~17:00–19:30 h	Loud, rhythmic rumbles	7 out of 8 days	50–70 % of burrows open
Night	~20:00–05:30 h	Quiet, sporadic, lower frequency rumbles	8 out of 8 days	0 % of burrows open

Sounds were recorded for almost 8 continuous days, but one midday period was missed. Table reproduced from Staaterman et al. (2011)

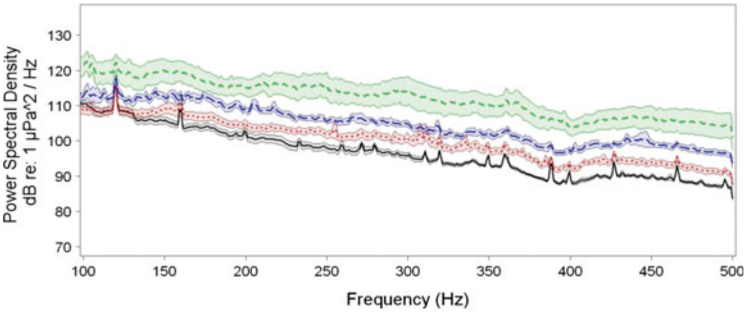

Fig. 13.1 The average of sound levels from different times of day, recorded at Catalina Island, CA, demonstrated that midday periods were significantly louder than the other times of day due to vessel traffic. Power spectral density (± standard error, dB re: 1 µPa^2 Hz^{-1}) is shown as a function of frequency (Hz) for each 1-h period. *Green*: 12:00–13:00 h; *blue*: 18:00–19:00 h; *red*: 06:00–07:00 h; *black*: 00:00–01:00 h. Peaks at 120 and 160 Hz were created by the perpetual "hum" from the autonomous recording unit (Staaterman et al. 2011 and unpublished data)

In further examination of the data, the same authors also measured variation in daily noise levels across the mantis shrimp bandwidth, to examine the prevalence of boat noise (Staaterman et al. 2012 and unpublished data). They examined 1-h sound files for representative times of day: 0:00–1:00 h, 6:00–7:00 h, 12:00–13:00 h, and 18:00–19:00 h and found that midday periods were significantly louder than the others, primarily due to boat traffic (Fig. 13.1).

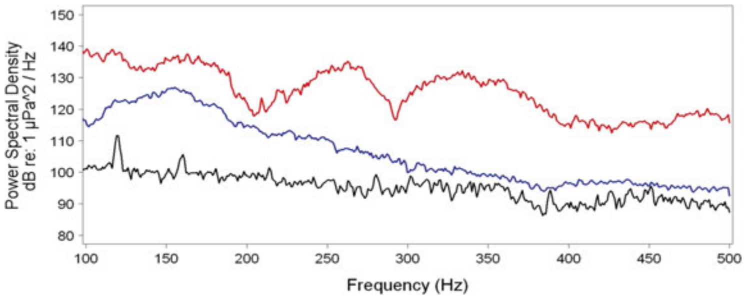

Fig. 13.2 Vessel noise (*red line*) power spectral density measurements (dB re: 1 µPa^2 Hz^{-1}) were significantly greater than mantis shrimp rumbles (*blue line*) and background noise (*black line*) across all frequencies (Hz). Peaks at 120 and 160 Hz were created by the perpetual "hum" from the autonomous recording unit's hard drive (Staaterman et al. 2011 and unpublished data)

They also measured the intensity level of each of these sources (Staaterman et al., unpublished data), and found that each source was distinct in frequency distribution and intensity characteristics (Fig. 13.2), particularly in the 100–250 Hz frequency band, which is the communication bandwidth of the mantis shrimp. On average, the contribution of vessel noise was 12 dB greater than that from mantis shrimp rumbles and 30 dB greater than the background noise (Fig. 13.2).

Finally, 24 hour spectrograms revealed that noise from boat traffic was frequent, especially during the daytime hours (Fig. 13.3, Staaterman et al., unpublished data). Boat noise was significantly louder than mantis shrimp rumbles and is clearly capable of masking these sounds (Figs. 13.2 and 13.3). This is one example of how PAM can be used to examine patterns, and potential overlap, between biological and anthropogenic sound sources within one acoustic habitat.

Although the use of PAM has been limited thus far for benthic crustaceans, this method holds great promise for this extremely diverse taxonomic group. In fact, PAM may be most useful for benthic animals such as burrowing shrimp or crabs, since they are relatively sedentary. For animals that are most active at night, such as spiny lobsters, active acoustic experiments in the field are extremely difficult. But passive acoustic monitoring may be able to reveal not only their movement patterns, but also feeding activity and predator–prey interactions. Finally, the deployment of acoustic recorders at multiple locations within and between habitats may help scientists to understand the spatial distribution of acoustically active crustaceans. Considering how little we know about the acoustic ecology of crustaceans, this type of research will inevitably be novel and exciting, a frontier waiting to be explored.

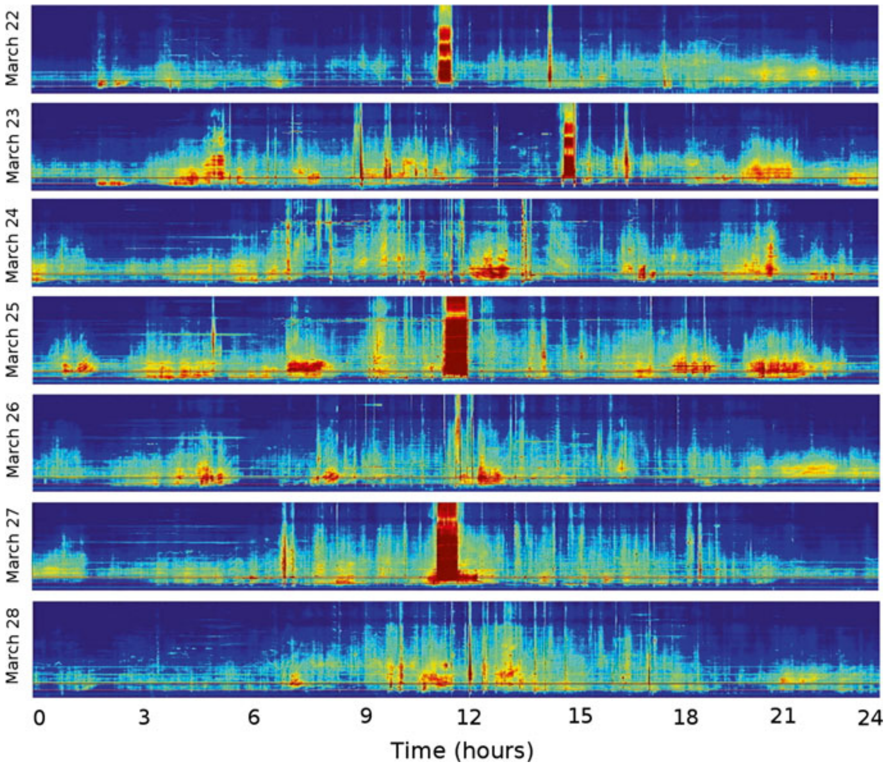

Fig. 13.3 Twenty-four hour spectrograms (0–500 Hz on *y*-axis, color scale: relative dB) from Catalina Island, CA, in March 2009 illustrate temporal patterns in the acoustic habitat of the California mantis shrimp. Note the frequent and high intensity broadband *vertical lines*, especially during daylight hours, which represent vessel noise. The *horizontal lines* were a result of the unit's hard drive (Staaterman et al. 2011 and unpublished data)

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Chapter 14
A Multiplatform Ultrasonic Event Recorder for Tagging, Towing, and Stationed Monitoring of Odontocetes

Tomonari Akamatsu

Abstract A simple and easy to handle acoustic event recorder (A-tag) has been developed and applied to monitor the echolocation behaviour, distribution, and long-term presence of odontocetes. A-tag stores peak intensity of a biosonar pulse as well as the sound source direction calculated by the time difference of sound arrival by stereo hydrophone. "A-tag" was developed as a biologging system to observe acoustic sensing behaviour of dolphins and porpoises in the wild. Results showed the free-ranging finless porpoises scan ahead by their sonar in advance before swimming silently. The inspection distance reached several tens meters that provide long enough 'safety margin' for the animal before facing real risks or rewards. The frequent sound production of dolphins and porpoises was confirmed by the acoustic tagging that is helpful for passive acoustic monitoring of odontocetes. A-tag was modified for towed and fixed operation. Towed-type A-tag has been widely used for acoustic line transect to observe distribution of odontocetes. Number of individuals were observed by counting independent sound sources recorded by the stereo hydrophone. Acoustic capture-recapture model provides detection probability of A-tag that is useful to estimate total population size in the monitored area. Fixed-type A-tag has been applied for a long-term monitoring of presence and swimming direction of odontocetes. Combining with sound production rate observed by the acoustic biologging, density estimation of animals is feasible using stationed monitoring data. Patient and continuous recording of echolocation sounds by the fixed A-tag provided various types of underwater behaviour and movement of odontocetes. Now the acoustic devices made the observation of dolphins and porpoises automatic like oceanographic observation devices.

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14.1 Overview of Acoustic Tag (A-tag)

The use of a narrow focused beam gives odontocetes excellent target discrimination. Once the animals focus on a target, the size and distance of the target and its shape (Harley et al. 2003) and structure (Au 1993) can be discriminated. The sonar behaviour of large-toothed whales (Miller et al. 2004; Madsen et al. 2005; Zimmer et al. 2005; Johnson et al. 2006, 2008; Tyack et al. 2006; Ward et al. 2008) and small porpoises (Akamatsu et al. 2005a) has been investigated using electronic tagging technology. These studies showed frequent use of biosonar sounds, which is useful for the reliable detection of odontocetes using passive acoustical monitoring (PAM) systems. Sound production of individual animal is the acoustical cue, which can be detected by a passive acoustical monitoring system. The detection probability can be calculated by the cue production rate (Marques et al. 2009; Kimura et al. 2010).

Monitoring of sound production contributes a quantitative survey of abundance using passive acoustic methods. To do this research, a small ultrasound recorder that can be attached to the animal is needed. The A-tag (stands for Acoustic tag) was designed for deployment on small odontocetes to record biosonar pulse events (Fig. 14.1). A-tag does not record the waveform of the sound; rather, it records the peak sound pressure of each biosonar click and the time difference of the arrival of the sound at two hydrophones (Akamatsu et al. 2005b). The event recording architecture

Fig. 14.1 Two finless porpoises (*Neophocaena asiaeorientalis*) with A-tag. These animals are ready to be released in a seminatural reserve, an oxbow lake of the Yangtze River in China. The whole system, including an A-tag, a suction cup, and a VHF transmitter were affixed to float material so that it floated after spontaneous detachment from the animal body after approximately 24 h. A VHF radio transmitter with an antenna was used for the retrieval operation. Recorded data in the flash memory of the A-tag were downloaded after the retrieval

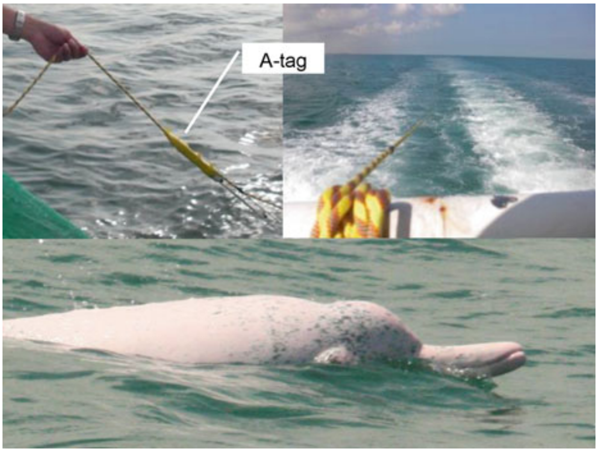


Fig. 14.2 A simple acoustic transect using towing-type A-tag off western Taiwan, targeting the Indo-Pacific humpback dolphin (*Sousa chinensis*). The towed-type A-tag was fixed on a rope and towed behind a boat. High-pass filter prevent contamination of most of the low-frequency noise during towing

makes A-tag small and robust. While only 21 mm in diameter and 112 mm in length, it runs 30 h continuously, with the primary constraint being battery capacity using CR2 lithium battery.

Although A-tag was originally designed as an animal-borne system, it has been used as a passive acoustic monitoring system towed from a ship or deployed under a buoy as well. Using the same core circuit, A-tag can be used in several acoustic monitoring applications, such as tagging, towing, and stationary platforms. Its small size makes it easy to handle. For the acoustic transect survey, A-tag was fixed on a rope and towed from a ship (Fig. 14.2). This is a completely stand-alone system and does not require a cable connection to the ship, an external power supply, or a personal computer to record the signals. Two commercially available UM-1 batteries housed in an optional case enable A-tag to operate continuously for 30 days for the stationary deployment. The recorded datasets are small and in CSV (comma-separated value) format, allowing simple analysis of sequential data that can be handled using conventional worksheet software such as Igor Pro (WaveMetrics, USA).

Stereo recording of A-tag is one of the unique features of this system. A high sampling frequency of 3.7 MHz was employed to measure the time difference of sound arrival between two hydrophones. Even using a short baseline of 10 cm between two hydrophones, A-tag calculates the time difference with a resolution of 271 ns. The sound source direction is a key for discriminating the recorded sounds of tagged animals from those of other individuals in the area. This feature was also be used to count the number of independent sound sources, which usually corresponded to the number of animals present. In this article, we describe the A-tag specifications and findings of the applications.

14.2 Specifications

14.2.1 Hardware

The miniature acoustic data logger, A-tag, consists of two ultrasonic hydrophones (MHP 140ST; Marine Micro Technology, Saitama, Japan) with a passive band-pass filter (−3 dB with a 55–235 kHz range), a high-gain amplifier (+60 dB), a CPU (PIC18F6620; Microchip, Detroit, MI, USA), flash memory (128 MB), and a commercially available lithium battery (CR2). All electronics were housed in an aluminum case that is pressure-resistant to a depth of 200 m (Fig. 14.3). A-tag stores the sound pressure data and the time-arrival difference between the two hydrophones every 0.5 ms. To save memory, A-tag records sound pressure only above a preset detection threshold level (134 dB peak-to-peak re 1 μPa) (Fig. 14.4).

The time difference of arrival is measured separately from sound pressure. A pulse above the preset threshold level triggers the counter to measure delay time between the two hydrophones at 271 ns resolution. The baseline length of the two hydrophones is 105 mm, which corresponds to the maximum time difference of 70 μs in water. Given the 271-ns resolution, the time-arrival difference is digitized within ±258 counts. Upon detection of the first pulse within each 0.5-ms period, the high-speed counter (271-ns resolution) measures the time difference until the pulse is detected at the other hydrophone. After 0.5 ms, the sound intensity at the primary hydrophone and the time-arrival difference are stored.

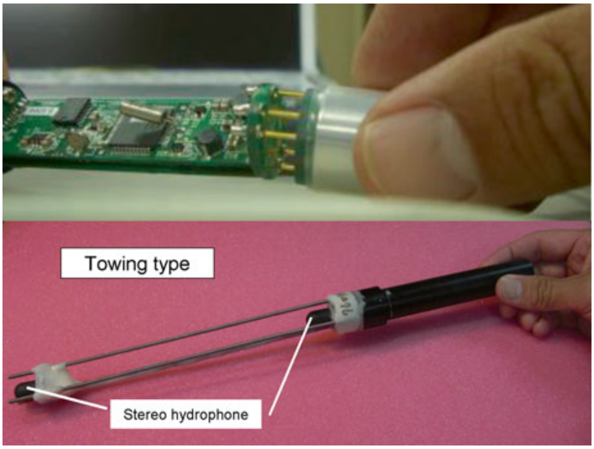


Fig. 14.3 The small electronic circuit of A-tag including preamplifier, high-pass filter, peak hold circuit, time difference counter, CPU, flash memory, and a battery case. The signal processing firmware is updatable. All electronics are housed in a pressure resistant cylinder. The white stuff is a plastic to support hydrophones and extension codes

14.2.2 Multiplatform System

The locations of A-tag's two hydrophones can be adjusted for specific purposes of observations. For the tagging purposes, two hydrophones were affixed to the front and the sides of the float material (Figs. 15.1 and 15.4). The sensitive torso side of the hydrophones pointed to the sound source of biosonar signals below the blowhole of the animal. The baseline distance between the two hydrophones was set at 10 cm to determine whether the sound came from tagged animals or from other animals. Attachment was made dorsally behind the melon and blowhole to avoid any disturbance to the dolphin's biosonar activity. Even from the dorsal side of the animal, the off-axis beam of the tagged animal could be recorded (Akamatsu et al. 2005c.

The towing-type A-tag was designed to minimize drag force (Fig. 14.3 and 15.5). This shape was conveniently attached to a rope using electrical tape (Fig. 14.2). The acoustically measured direction of the phonating porpoise in relation to the towed A-tag is shown as a dotted line in the upper right inset of Fig. 14.5. The change in orientation of the porpoise from a positive to a negative angle indicates that the animal passed by the A-tag in the bow-to-stern direction. A single trace of the sound source direction corresponds to one animal, and the number of animals passing

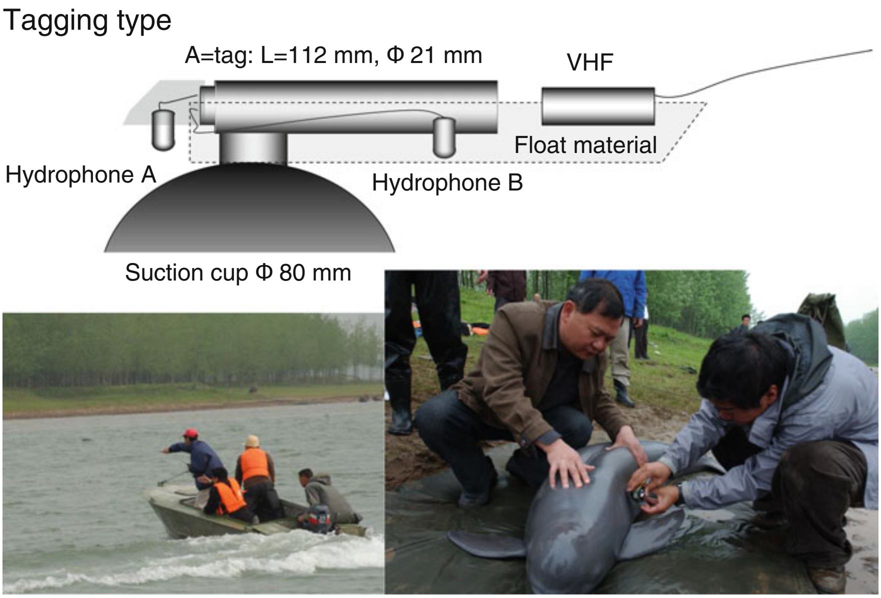


Fig. 14.4 Tagging-type A-tag. After the capture of finless porpoises in the seminatural reserve in China (*left*), an A-tag with a VHF transmitter was carefully attached to the skin on the dorsal side of the animal (*right*). After spontaneous detachment from the animal, the A-tag was retrieved using radio transmission

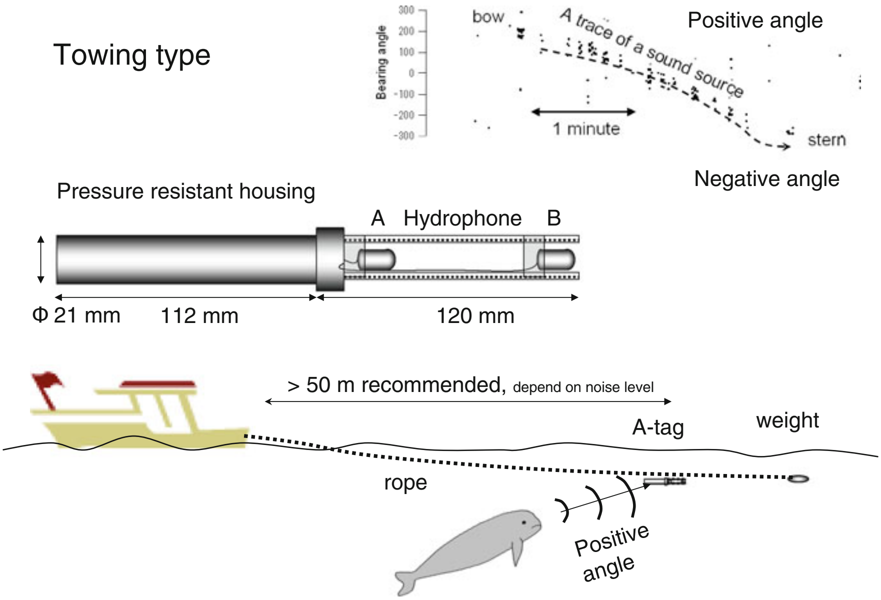


Fig. 14.5 Towing-type A-tag. Depending on the animal's location relative to the towed A-tag, positive or negative time differences correspond to the direction of an animal on the bow or stern side of the A-tag. The bearing angle indicates that an animal passed by

within the detection range (approximately 300 m maximum) of the acoustic system was counted. To prevent counting the same animal twice, boat speed was set at 5 m/s, which finless porpoises are not able to catch up for a long time. For stable deployment, a small weight at the tail of the towed apparatus prevented rope vibrations. Noise from the towing boat, particularly propeller cavitation could mask the recording. Although the built in band-pass filter eliminates the low-frequency component, additional rope to separate the A-tag from the towing boat is helpful. In addition, an iron bar or a bamboo rod was affixed to the side of the boat to offset the tow rope from the propeller wake.

The fixed-type A-tag is suitable for long-term monitoring of numbers and swimming directions of dolphins and porpoises (Fig. 14.6). When securely attached to a breakwater or seabed in a narrow strait, the T-shaped system identified the directional movement of phonating animals such as inshore-offshore or tidal current directions. If buoy deployment was preferred, a straight-type A-tag was moored on a rope (Fig. 14.6). In this vertical setting, the elevation angle of the sound source was used to count the animals. Unlike the towing system, passive acoustic monitoring (PAM) in a fixed position makes the total number of animals in the observation range difficult to determine; double counting of single animals is unavoidable. Because of the limited observation range of a PAM system, the fixed system is adequate for long-term monitoring but is not appropriate to measure the population size when the number of monitoring stations is limited except to measure the density of the presented animals (Kimura et al. 2010).

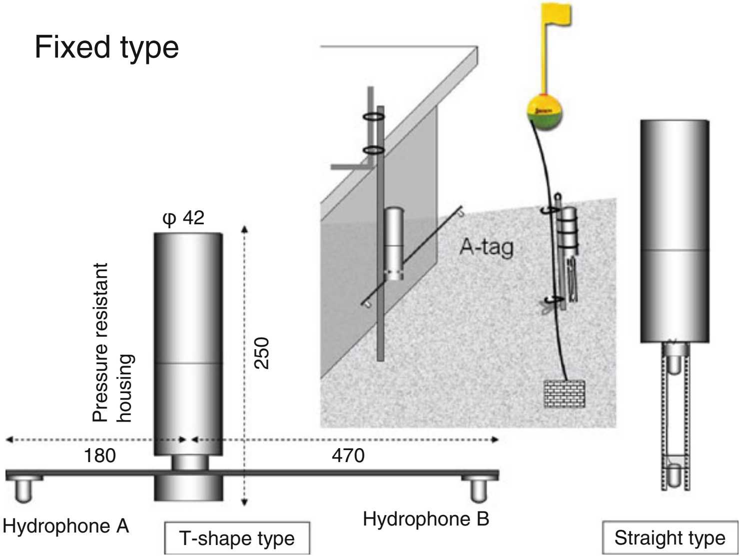


Fig. 14.6 Fixed-type A-tag. The T-shaped type of A-tag is suitable when a rigid platform is available, such as a breakwater or double-anchored buoy. The straight type is suitable for buoy and rope mooring, which do not allow to fix the direction. The A-tag records not only the presence of the phonating animals but also the swimming of their movement and the minimum number of animals in the vicinity

System setup of and data download from the A-tag were identical for all types of deployments because the same type of core circuit was used. For setting up and downloading, an interface box for the A-tag, RS232 to USB converter, and a PC were the same. The start times were selected in a calendar/delay hours. An interval recording function was available to extend observation period. When the unit was deployed beside a ship that used an echo sounder, a filter to exclude a specific direction range was selected. The low-noise preamplifier of A-tag system is a key technique for the successful application. A handling manual, specifications and analysis programs are available on Internet http://atag.web.fc2.com/.

14.3 Findings

14.3.1 Porpoises Scan Ahead

Free-ranging finless porpoises used sonar to scan the area ahead of them before swimming forward silently. This inspection distance reached several tens of meters, providing a "safety margin" for the animal as it approached danger or prey. Once the porpoise detected potential prey, it focused sonar on the target during its approach (Akamatsu et al. 2005a).

Fig. 14.7 Capture operation of finless porpoises in the seminatural reserve, Hubei, China

Nine finless porpoises were captured in the reserve. Eighteen fishing boats drove finless porpoises from the upper end of the oxbow to the lower end (Fig. 14.7). A net approximately 1 km long was used to divide the oxbow transversely. A round, fine-mesh net was used to encircle the animals. In the final stage, fishermen wearing life jackets dove into the water and captured the animals individually. In the meantime, 18 boats surrounded the seine net, and more than 50 fishermen carefully watched each section of the net to avoid entangling the animals. The water depth was less than 1 m, which allowed the fishermen to handle the animals safely.

A-tags and behavior tags were deployed on finless porpoises. The behavior tags (PD2GT, Little Leonardo, Tokyo, Japan) had dimensions similar to those of the A-tags; they recorded swimming speed, dive depth, and roll-and-pitch angles of the animals' movement. Swimming speed was used to calculate the swimming distance. The combination of these two tags, therefore, logged phonation and body movement simultaneously (Fig. 14.8).

The finless porpoises observed in this study produced sonar signals frequently, every 5.1 s on average, suggesting that finless porpoises strongly rely on their acoustic sensory systems for navigation, safe travel, and capturing prey. The distance inspected by echolocation was approximately proportional to the sound interval (called interclick interval) because dolphins and porpoises produce sound after receiving the echo from a target (Turl and Penner 1989). They wait for the echo before producing the next click. Therefore, the interclick interval should be longer than the time it takes the sound to travel to the target and back to the animal. Interclick intervals were measured by the A-tags.

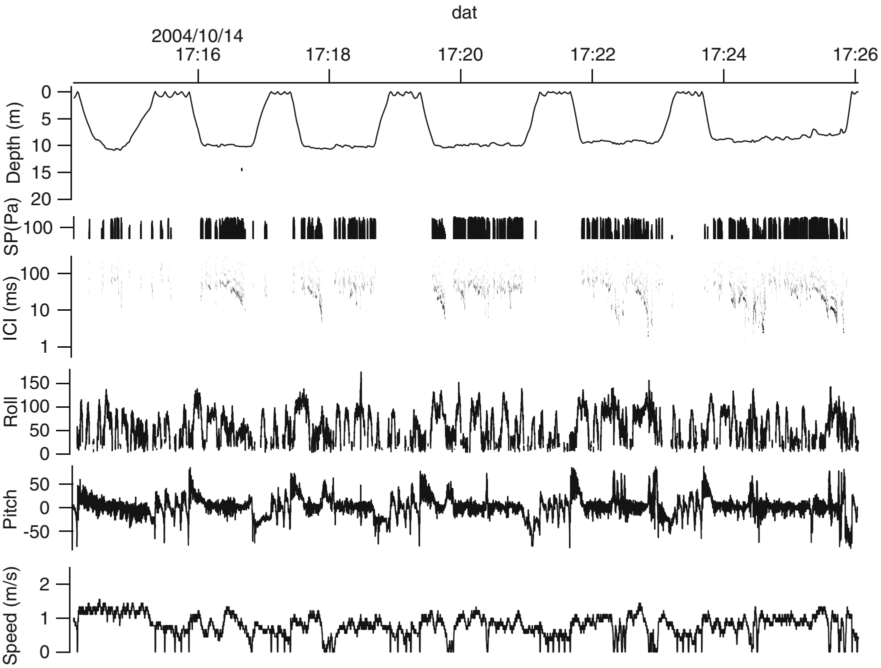


Fig. 14.8 Phonation and the body movement of a finless porpoise could be observed using the tagging method. Sound pressure (SP) and interclick interval (ICI) were recorded by the A-tag. Depth, roll angle, pitch angle, and speed were recorded by the behaviour tag. Note that echolocation occasionally stopped for example at 17:18 and 17:20

The finless porpoises sometimes stopped echolocation for short period (Fig. 14.8). During this interval, the porpoises were acoustically "blind." Visual senses were not effective because of the turbidity of the water in the Yangtze River. Even during silence, they continued swimming at a rate of approximately 1 m/s. The distance the dolphins swam during silence and the distance they inspected acoustically before the silent swimming were compared; the sensing distance was almost always longer than the silent swimming distance (Fig. 14.9). When moving through a visually limiting environment, acoustic inspection of the area ahead is essential for these animals. This strategy offers substantial advantages both in terms of risk avoidance and prey capture. As shown in Fig. 14.10, finless porpoises inspected the areas in front of them for a sufficient period of time before they swam into them silently. The porpoises seemed to maintain a large safety margin in their sonar range when inspecting the area ahead of them relative to the distance they swam silently.

A porpoise is acutely aware of the distance to a prey target that is outside its visible range. When a porpoise located prey, it reduced the interclick interval according to its distance to the target (Fig. 14.11). This is called the biosonar approach phase. The distance traveled during the approach phase and the change in distance scanned were similar (Fig. 14.12), suggesting that the porpoise recognized a remote target

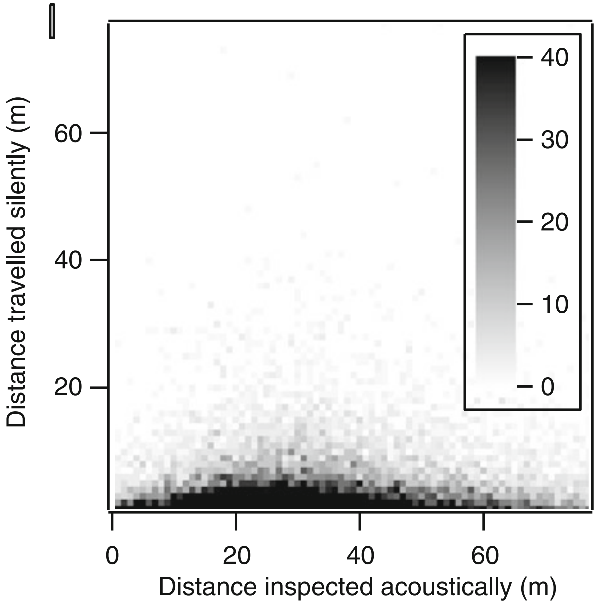


Fig. 14.9 Distance inspected acoustically was almost always longer than the distance travelled silently, according to the analysis of 49,470 click trains produced by eight finless porpoises

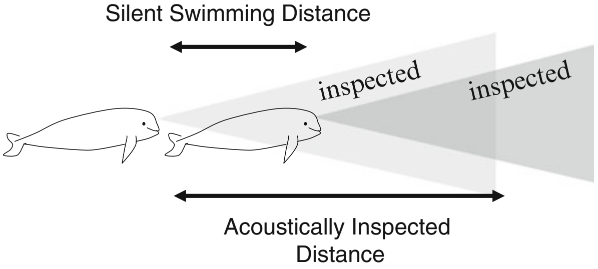


Fig. 14.10 The porpoise acoustically scanned the area in advance of its approach. Before swimming out of the inspected area, it produced sonar sounds again to survey the area in front of it

and focused its sonar on the prey while approaching. Porpoise find prey acoustically at a distance of 30 m; they can then shorten the detection intervals to maintain contact with the target while they approach.

14.3.2 Scanning Sonar of Rolling Porpoises

Dolphins and porpoises use narrow ultrasonic beams for echolocation (Au 1993). The beam width of bottlenose dolphin sonar is 10° (Au 1993), and that of the harbour porpoise is 16° (Au et al. 1999). An acoustic lens and reflectors (Cranford et al. 1996;

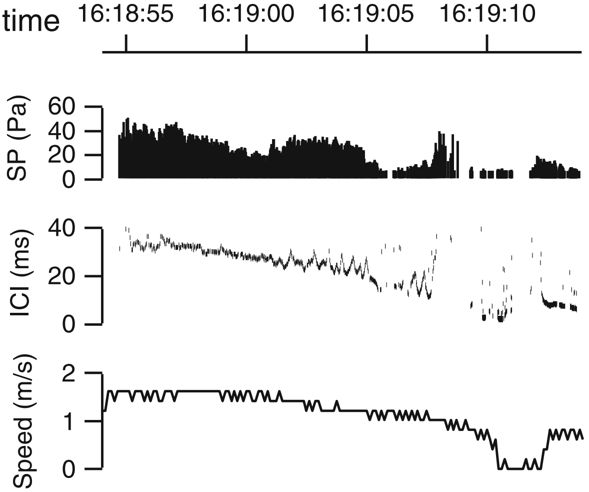


Fig. 14.11 Approach phase of the porpoise's sonar. The porpoise reduced the interclick intervals (ICI) from 30 ms to less than 10 ms while swimming. The change in the sensing distance could be calculated from the change in the interclick intervals. The outgoing sound pressure (SP) was simultaneously reduced. At the end of the approach phase, swimming speed was zero, meaning that the animal had turned around and that its speed relative to the water suddenly dropped. The approach phase, therefore, is likely used for prey capture

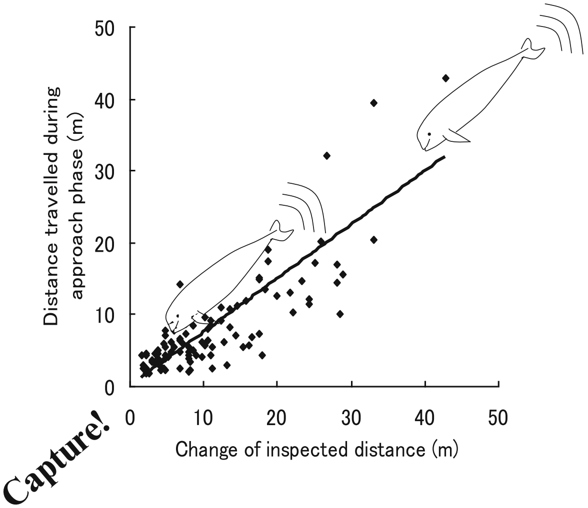


Fig. 14.12 Changes in the inspected distance and the distance travelled during the approach phase were compared. Good agreement among the data suggests that the porpoise was aware of the distance and that it locked onto the target during approach

Aroyan et al. 1992) focus the ultrasonic beam on a target, such as a prey item. The use of a narrowly focused beam gives odontocetes excellent target discrimination. Once the animals focus on a target, the size and distance from the target, its shape (Harley et al. 2003), and structure (Au 1993) can be discriminated.

A different strategy is needed to find prey within a vast volume in which vision is limited. For example, Ghose and Moss (2003) and Surlykke et al. (2009) demonstrated that the flying bat (*Eptesicus fuscus*) first scans the space around it with a sonar beam and then centres the beam axis on an insect. Scanning sonar is commonly used in ocean fishery surveys. The axis of a narrow multibeam fan is electronically operated to achieve fine spatial resolution and a wide scanning area (Trenkel et al. 2008). Although the off-axis source level of sonar signals of porpoises is effective for fish detection across a short distance, a strong on-axis beam is most useful for long-range sensing. For echolocating animals, beam-axis scanning by changing the orientation of the head and body are possible methods of enlarging the search area.

Using these data-retrieval methods, we found that body rolling by finless porpoises was combined with extensive search efforts (Fig. 14.13). The roll angle could be calculated from the dorsoventral acceleration of the behavior tag on the animal (Akamatsu et al. 2010a). The number of sound production of sonar signals increased when the porpoises frequently changed roll angles. In contrast, the porpoises

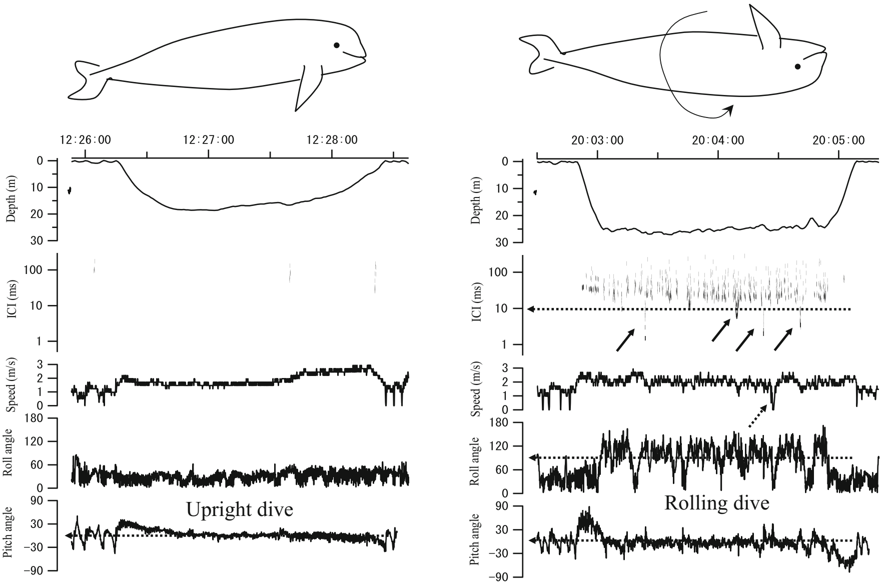


Fig. 14.13 Two different types of dives were recognized in the finless porpoise: upright and rolling. During the upright dive, the animal kept its dorsal side up and did not phonate much. During the rolling dive, the porpoise produced sonar signals extensively. Some of the sonar signals have short interclick intervals, indicated by *arrows*, suggesting short-range target detections. Short-range sonar occasionally associated with a speed drop, which indicates the turning around movement

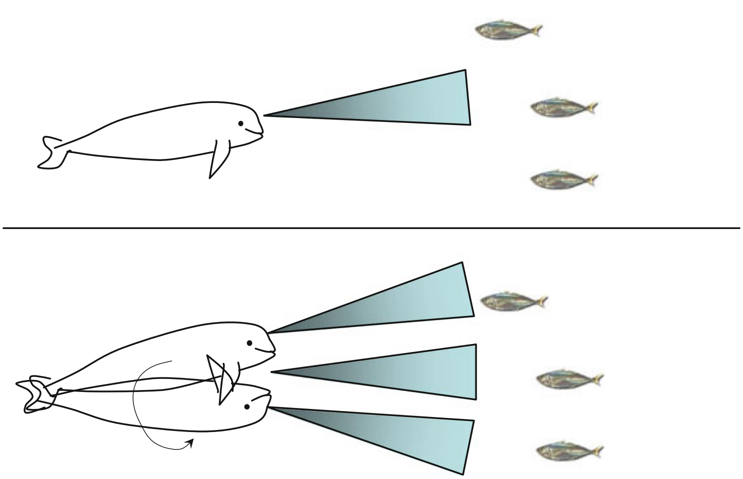


Fig. 14.14 By rolling the body while using sonar, the porpoise has a greater probability of locating prey

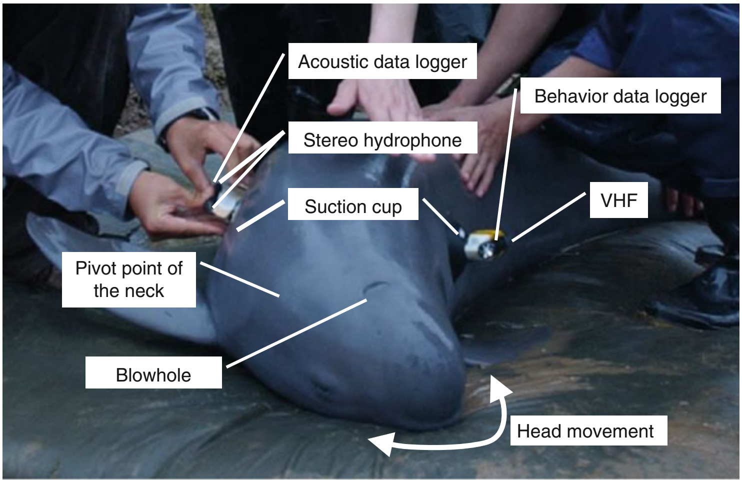


Fig. 14.15 Head movement during swimming could be observed using a stereo acoustic tag. The time difference in arrival of sound between two hydrophones changed relative to the position of the sound source below the blowhole

employed their sonar less during upright dives. Rolling dives comprised 31 % of the total dive time of the 15 animals. Rolling behavior might enlarge the search area of the porpoise by changing the beam axis of its sonar (Fig. 14.14).

In finless porpoises, the joints of the cervical vertebrae are flexible, allowing the animals to turn their necks at an angle to their longitudinal body axis (Fig. 14.15). This allows another form of beam scanning. Head movement was measured using

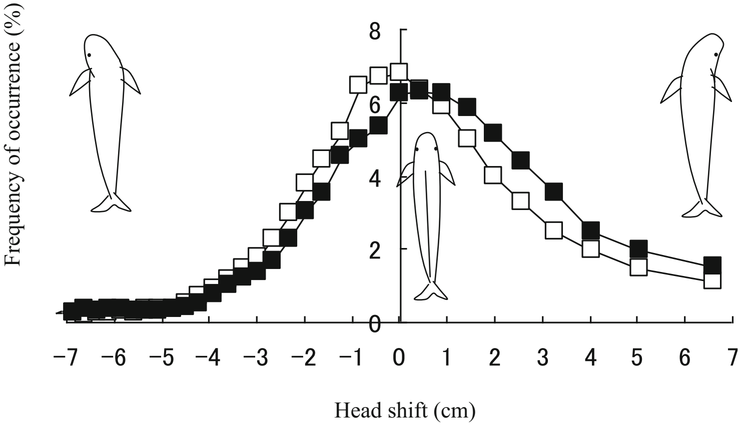


Fig. 14.16 Head shift occurred in both uplight dives (*white squares*) and rolling dives (*black squares*). Head shift might be used for instant assessment, similar to a visual glance in any direction

the A-tag data. The time difference of the arrival of the sound at the two hydrophones changed according to the relative position of the sound source below the blowhole to the A-tag. As indicated in Fig. 14.16, head movement occurred not only during rolling dives but also during upright dives. The distribution of head movements during both types of dives was similar.

Head movements were quicker than body movements when the beam axis was changing; body rolling took several seconds. During both rolling and upright dives, head movements might assist in making instant assessments of the arbitral direction targeting of any obstacles nearby. This conclusion coincides with our observations of the same pattern of head movement among different dive types.

14.3.3 Acoustic Transect

Acoustic tagging experiments revealed that porpoises produce sonar sound very frequently. This is helpful for passive acoustic monitoring because many acoustic cues can be received in a short time.

In 2006, an international team performed a survey to locate the extremely endangered river dolphin baiji (*Lipotes vexillifer*) from Yichang to Shangai, an approximately 1700-km stretch of the Yangtze River, which was the historical habitat of baiji (Fig. 14.17). After a 42-day round trip, efforts to make visual and acoustical survey failed; no baiji were observed (Turvey et al. 2007). Baiji are now considered to be functionally extinct.

At the same time, the team surveyed Yangtze finless porpoises as well (Zhao et al. 2008). Acoustic detections and visual observations of porpoises were compared (Akamatsu et al. 2008a). Two research vessels towed A-tags, which were used to

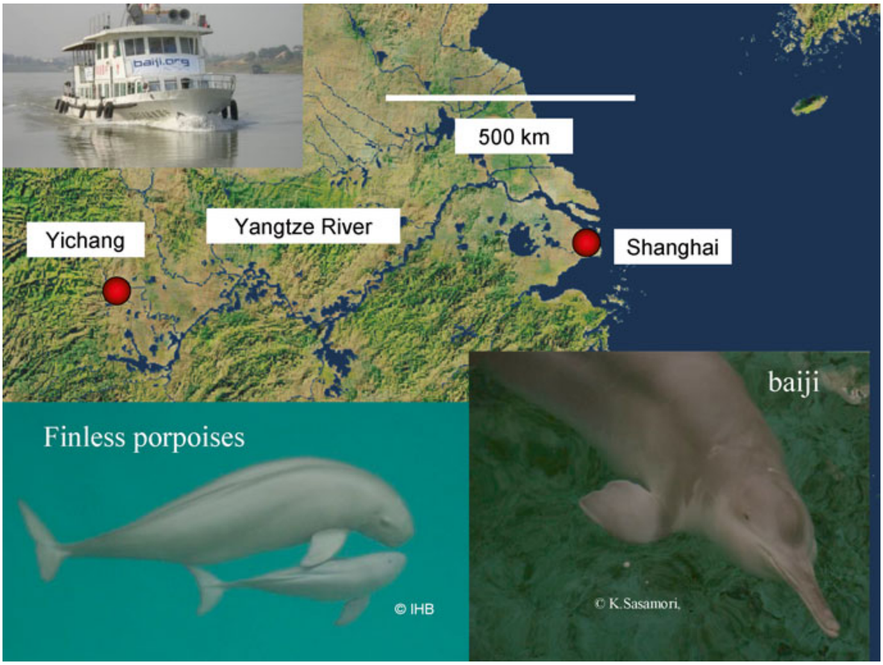


Fig. 14.17 Acoustic monitoring and visual observation were used to survey freshwater dolphins from Yichang to Shanghai in 2006. Despite extensive effort, no baiji were found; an approximately 50 % decline in the population of finless porpoises was suggested

store the intensity and sound source direction of the high-frequency sonar signals produced by finless porpoises at ranges up to 300 m on each side of each vessel. The formation of simple stereo beams allowed the separation of distinct biosonar sound sources, which allowed the researchers to count the porpoises by their vocalizations (Fig. 14.18).

In total, 204 porpoises were acoustically detected from one vessel, and 199 were detected from the other vessel in the same section of the Yangtze River. Visually, 163 and 162 porpoises were detected from two vessels within 300 m of the vessels' paths, respectively. As shown in Fig. 14.19, acoustic and visual detections were matched well (Zao et al. 2013). High- and low-density areas were clearly shown. However, the data revealed that the existing five high-priority porpoise conservation sites contain few or no surviving porpoises sections. They proposed modified priority sections for effective conservation.

Some of the animals were detected by both acoustic and visual methods, while many single animals were missed by visual observation (Fig. 14.20). The Yangtze finless porpoise has no dorsal fin, and the population is known to be small. In the turbid water of the Yangtze River, visual detection of this animal was difficult. On the other hand, acoustic detection of finless porpoises using ultrasonic sonar signals was effective because of their frequent sound production. In addition, acoustic observation is an ideal independent observation technique compared to visual observation.

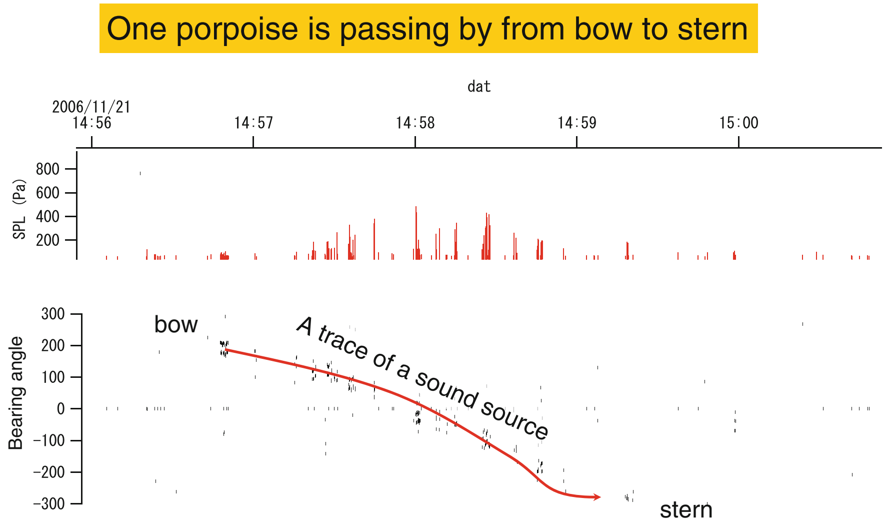


Fig. 14.18 A trace of a sound source corresponds to an animal was used to count the phonating animals. Frequent sound production by porpoises was measured using PAM

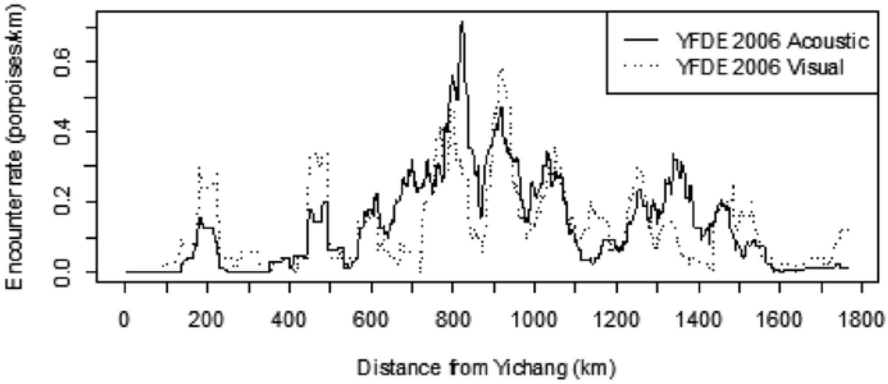


Fig. 14.19 Encounter rate of finless porpoises by visual and acoustic observation in the Yangtze river, China. Both detections agreed well

The detection probability had been calculated using two independent sets of visual observation data from the same area. However, double visual observation, especially on the same boat, is difficult since the primary observer team could cue the independent observers. In contrast, acoustic detection was completely independent from visual detection; acoustic detection was automatic, and no human effort was needed while the A-tag was towed behind the vessels. The calculated detection probability using the acoustic method was always higher than that of visual detection for each vessel (Richman et al. 2014). Recently, Kimura et al. (2014) proposed acoustic

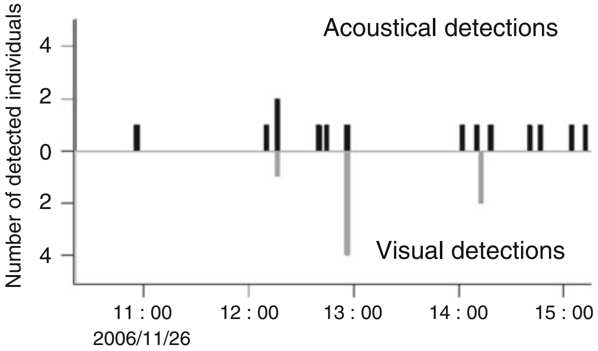


Fig. 14.20 Comparison of the time of detection and the group size between acoustical monitoring and visual observation. Many single animals were detected acoustically without a corresponding visual observation

capture-recapture method without using visual means to calculate detection probability. This enables the estimation of population size of odontocetes including undetectied individuals. The use of simple, relatively inexpensive acoustic monitoring systems should enhance population surveys of free-ranging, echo-locating odontocetes.

14.3.4 Tide, Light, Prey, and Porpoises

For the sustainable management of wildlife, habitat fragmentation should be avoided because it causes the genetic isolation of each fragmented group. Fragmentation of the populations of this species has been suggested recently. A major portion of the Inland Sea-Hibiki Nada population of finless porpoises (number 3 of Fig. 14.21) may be located at the west end of the Seto Inland Sea and in the Sea of Japan. These areas are connected by the Kanmon Strait. Reports of sightings in the strait have been quite limited. Our question was whether the population was or was not fragmented at the Kanmon Strait. We used the fixed-type A-tag for PAM to monitor the presence of finless porpoises in this major international shipping lane from March 2005 to March 2006 (Fig. 14.21).

During 75 days of effective observation, 37 porpoises were detected acoustically. On average, one individual was detected every 2 days (Akamatsu et al. 2008b). Most of the finless porpoises appeared at night, and no porpoises were observed from 12:00 to 18:00 h (Fig. 14.22a). In addition, shipping traffic could be counted using the same acoustic data (Fig. 14.23). Shipping traffic observed using the same acoustic system showed trends opposite to that of finless porpoises during the daytime (Fig. 14.22b). The tidal current did not affect the presence of the animals (up to 5.2 knots), as shown in Fig. 14.21c; however, porpoises swam along the direction of the current. Finless porpoises appeared to be isolated and used relatively long-range sonar during the observations, suggesting that the porpoises were passing through the Kanmon Strait rather than searching for prey.

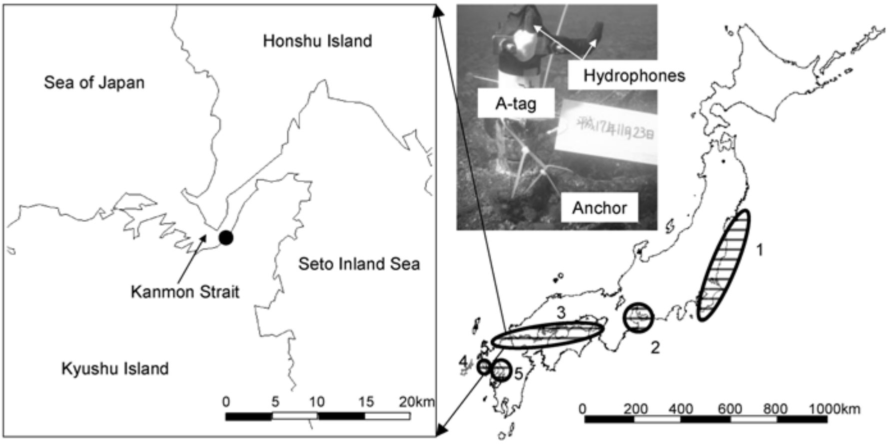


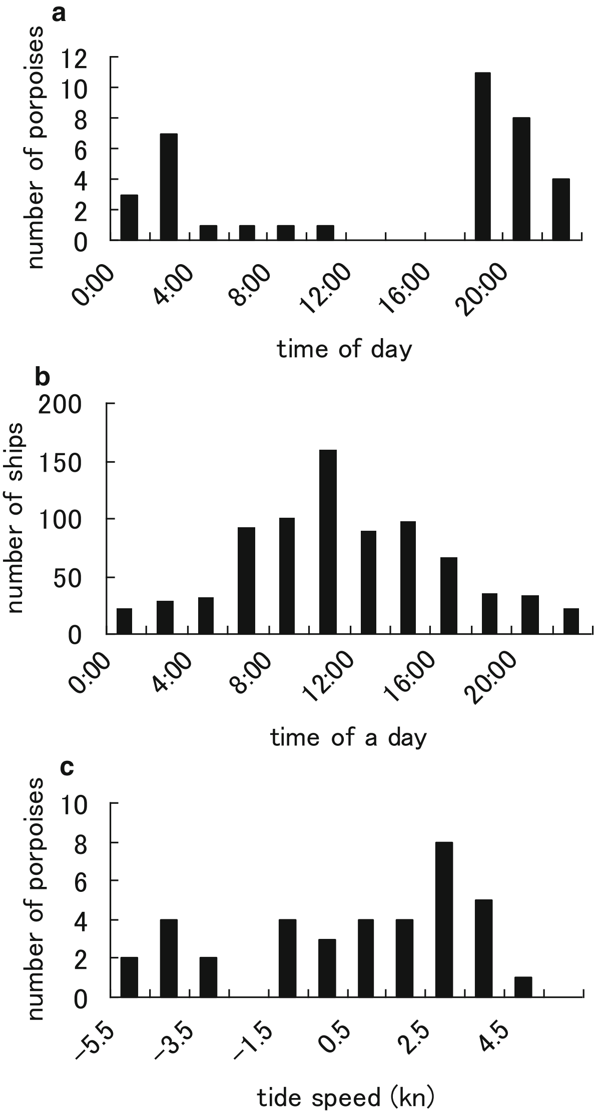
Fig. 14.21 A study site of the fixed-type A-tag and the distribution of five populations of finless porpoises in Japanese waters. The third population may be divided into east and west sides at Kanmon Strait

In western Taiwan, presence of humpback dolphins were strongly affected by the tidal phase that was revealed by fixed acoustic observation during 268 days (Lin et al. 2013). Using the time dependent change of the sound source bearing angles, circling movements of animals were idnetified. It was considered to be the hunting behavior of epipelagic fish and the observed number of this behavior changed significantly over the four tidal phases.

Wang et al. (2014) indicated that solitary finless porpoises in the Yangtze River were frequently present and feeding in the port areas. Diel patterns were evident involving biosonar behavior as well as fish presence and boat traffic. Fish density was idependently monitored by an echosounder. The frequencies of the click trains and buzzes were significantly lower during the day than in the evening and at night, which suggests that porpoises in this region are primarily engaged in crepuscular and nocturnal foraging.

Another example of prey and predator relationship was found in in the Istanbul Strait (Bosphorus) where three cetacean species, namely the harbour porpoise (*Phocoena phocoena*), the common dolphin (*Delphinus delphis*), and the bottlenose dolphin (*Tursiops truncatus*) were observed. Dede et al. (2014) deployed A-tag in the strait from July 2009 to September 2010. Nocturnal presence pattern was prominent in March and April. In the meantime, the cetaceans were concentrated in the specific direction from the fixed monitoring system and produced short-range sonar frequently. It is well known that pelagic fish such as sprat and bluefish start their migration from the Aegean Sea to the Black Sea in spring. This study suggests that the cetaceans use the middle part of the Strait for feeding on the pelagic fish in spring when the fish migration has just started. In this study area, family identification of Delphinidae and Phocoenidae is proposed (Kameyama et al. 2014) based on

Fig. 14.22 (**a**) Presence of finless porpoises in Kanmon Strait; (**b**) number of acoustically detected ships; and (**c**) the number of detected porpoises according to the tide speed



the comparison of the intensity ratios of two band frequencies (130 and 70 kHz). Even in the presence of mixed species group at the same time, quantitative calculation of mixed ratio was possible.

Seasonal presence pattern of finless porpoise were strongly correlated with the water temperature and fish catch in the Hario Strait, Nagasaki, Japan (Akamatsu et al. 2010b). A small population of finless porpoises approximately 300 individuals habituates in Omura Bay, which connects to East China Sea through the Hario Strait. Until autumn, anchovy recource is abundant in the Omura bay, which is confirmed by the fisheries data (Fig. 14.24). However, the anchovy move to East China

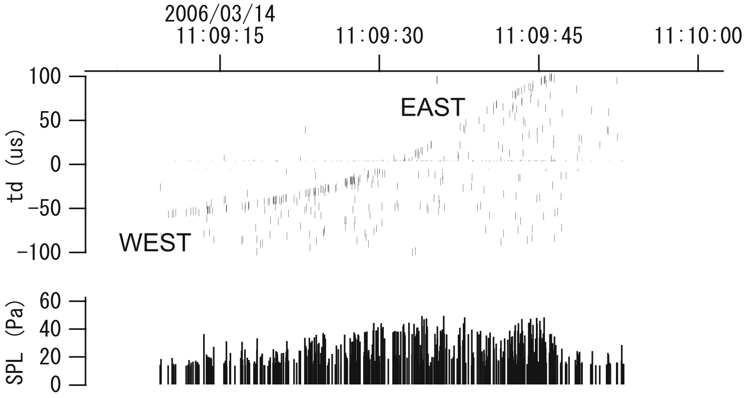


Fig. 14.23 A ship's noise signal detected by A-tag. The ship moved from west to east. These signals were recorded almost continuously, and their sound pressure changed randomly, unlike biosonar signals

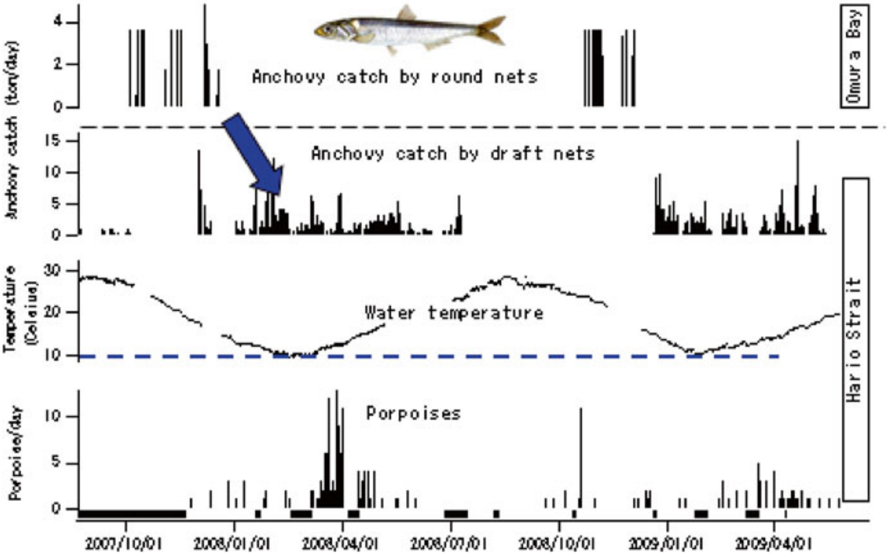


Fig. 14.24 Seasonal change in fisheries capture, water temperature, and number of porpoises detected. The total catch of Japanese anchovy per day inside Omura Bay (*top*) and the Hario Strait (*second row*) showed seasonal highlights. Negative *black bars* indicate the period without passive acoustic monitoring of porpoises due to system maintenance

Sea when the water temperature dropped close to 10 °C in winter. The migrating anchovy was caught in the straight by fishermen. This suggests that the prey availability in the Omura bay is low in winter time. Porpoises seemed to be waiting the returning anchovy into the bay when the water temperature recovers in spring

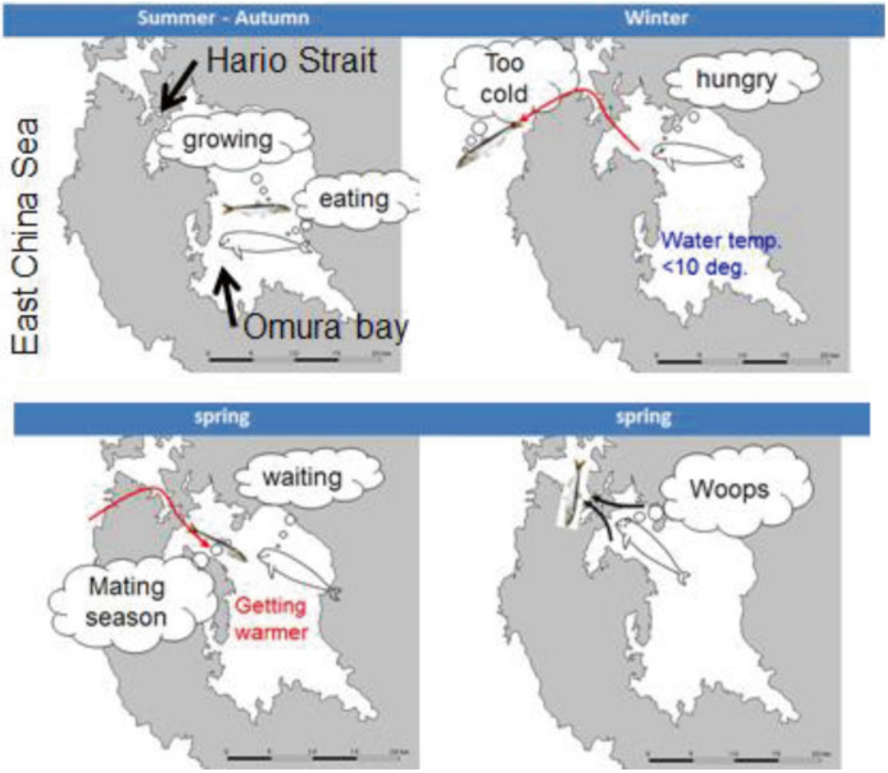


Fig. 14.25 Finless porpoises could wait anchovy returning in spring when the prey migrates through the Hario Strait for reproduction

(Fig. 14.25). The current in the strait is 8.5 knot at most. Waiting and foraging porpoises could be sucked in the strait in March and early April and detected by the fixed acoustic sensor.

We need to note that the fixed acoustic observation could underestimate the group size of odontocetes. For a dense group, resolution of bearing angle using an array of hydrophone is not enough (Kimura et al. 2009). However, the acoustic monitoring method had the advantage of high detection probability. Fixed PAM is especially effective for low-density condition of animals such as endangered species.

14.4 Summary

The miniature stereo acoustic data logger, A-tag, recorded the biosonar behavior of porpoises. Porpoises were observed to cautiously scan their forward paths. For targeting prey, they used an approach phase in which they locked their sonar on their prey. Porpoises frequently rolled their bodies, possibly to enlarge their search volume, and appeared to employ scanning sonar while diving to capture prey. The frequent sound production of porpoises confirmed by acoustic tagging was useful whether towed or fixed PAM A-tag systems were used. The sound source direction measured by A-tag was useful for counting animals. The detection performance of acoustic monitoring was better than visual observation for single animals. Animal movement was also observed in very low-density areas.

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Chapter 15
Signal Processing

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Abstract We examine some methods commonly used for analyzing marine bioacoustic recordings. Filtering techniques are used to prevent aliasing, to remove certain types of noise, to flatten the spectrum of ocean noise before recording, and so on. Filter design necessarily requires making choices that affect trade-offs among various desirable filter properties. Detection and classification are used for analyzing large data sets. They often start with signal conditioning, which can adjust the spectrum, standardize signal level, and remove some types of noise. They proceed by calculating numerical acoustic features and using them to decide whether a given sound is present (detection) or to choose which of several categories a vocalization belongs to (classification). A variety of methods for detection and classification are briefly described, with the choice depending both on the nature of the sound(s) and the noise as well as on the task to be solved. Detectors operate in the time domain or on a time–frequency representation, with different ones appropriate for different call types. Classifiers are characterized as either generative or discriminative, as parametric or nonparametric, and as supervised or non-supervised. Performance of detection and classification can be evaluated in several ways, including receiver operating characteristic curves and precision/recall statistics. Localization of calling animals is usually performed using time differences of arrival of sounds at several hydrophones; a variety of methods are available, with the best choice depending on the characteristics of the sound and the acoustic environment. The most accurate localization methods use acoustic propagation modeling to estimate travel times. Several software packages are reviewed for filtering, detection, classification, and localization.

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15.1 Introduction

Marine animal sounds are captured using the systems covered in the preceding chapters of this book and ones similar to them. These systems use hydrophones to capture a sound signal—a representation of the sound pressure over time—and either make it available in real time or store it for later analysis. Analysis of biological and anthropogenic sounds has the potential to provide the kinds of information used in the previous chapters in this book—census information (presence/absence or counts), habitat usage, insights into behavior, and the effect of human activities on marine life. This chapter provides an introduction to the *signal processing* needed to accomplish these tasks. Throughout the chapter, it is the authors' intention to provide a qualitative description of common signal processing techniques along with references as to guide the reader interested in acquiring in-depth knowledge. The type of signal processing needed depends on the type of result desired. For instance, assessing the possibility of physiological harm to an animal (temporary or permanent deafness, tissue damage, etc.) requires knowing the sound spectrum received by the animal over time. This in turn may require signal processing techniques to localize the animal from its calls and to measure the sound spectrum over time. To study a species' distribution or movement, one can automatically detect, and sometimes localize, vocalizations from individuals of that species.

Here we review some of the most common signal processing tasks employed in marine bioacoustics. We assume that the reader is familiar with Fourier transforms and their properties, at least at a conceptual level. First is a section on filtering, which is commonly used in data acquisition, resampling of signals, and flattening of spectral responses. Following that is a description of automatic call detection and classification, reviewing the strengths and weaknesses of the more widely used methods, and then a discussion of localization techniques and applications. Final sections cover software widely used for marine bioacoustics as well as future directions for research.

15.2 Filtering

Filtering is commonly used in marine bioacoustics to alter the spectrum of a sound signal. A filter receives a sound signal as input, alters it in some manner, and emits the altered signal. For instance, a *low-pass filter* allows lower frequencies to pass through unimpeded but stops higher frequencies (Fig. 15.1). The frequency regions where sound is allowed through the filter is known as the pass band and frequencies that are attenuated are within the stop band. The point of transition between a pass band and a stop band is referred to as the cutoff frequency, or sometimes the break frequency or corner frequency. Conversely, a *high-pass filter* allows the high frequencies to pass through and stops the lower ones. A *band-pass filter* passes through only a selected range or band of frequencies, blocking frequencies above and below that range; it has two corner frequencies, one pass band, and two stop bands.

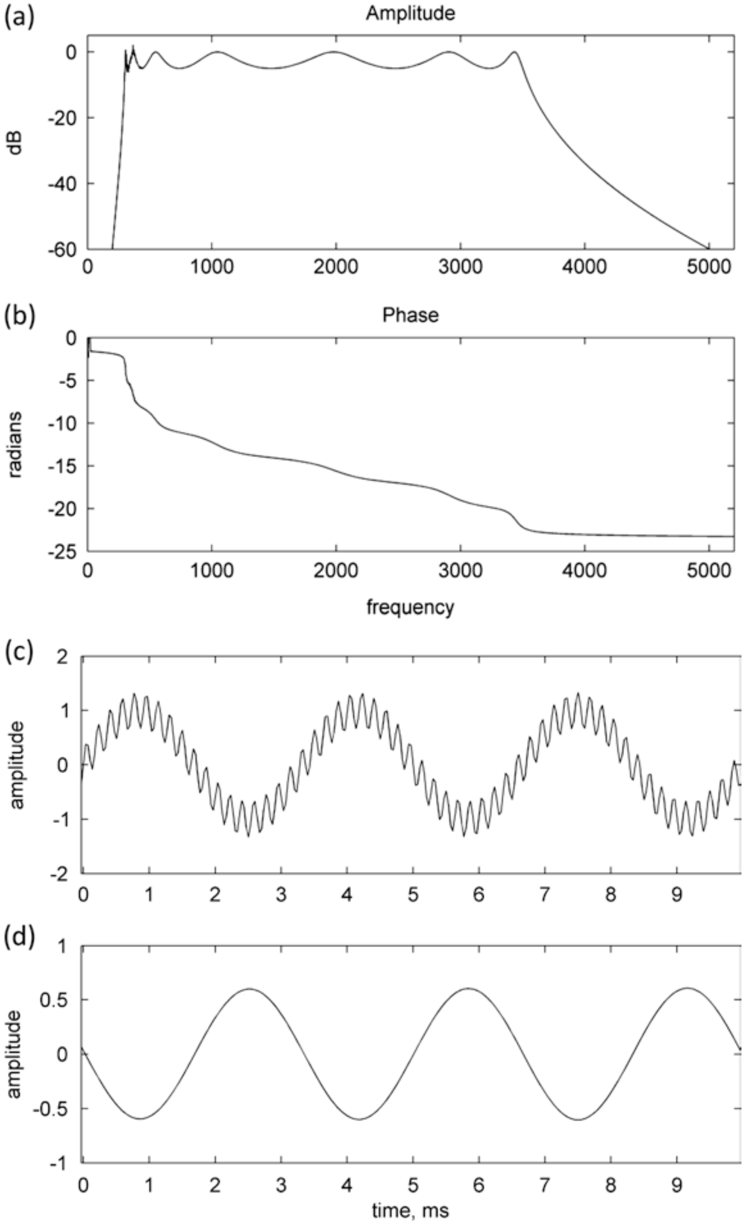


Fig. 15.1 Filter frequency response in (**a**) amplitude and (**b**) phase showing the pass band (300–3500 Hz) and stop bands (<50 and >5100 Hz). Note the ripple in the amplitude pass band, as well as the imperfect linearity of the phase in the pass band; a perfectly linear filter would have a *straight line* in this region. The phase in the stop bands is highly nonlinear, but this is relatively unimportant since there is very little signal energy at these frequencies. This is a 7th-order Chebyshev Type I IIR filter. (**c**) A signal with sinusoidal components at 300 and 5500 Hz, and (**d**) the same signal after filtering with this filter. The 5500 Hz component is removed, as it is in the stop band. Note that the phase of the 300 Hz signal is shifted by $-\pi$ radians (180°) as predicted by the phase plot (**b**) at 300 Hz

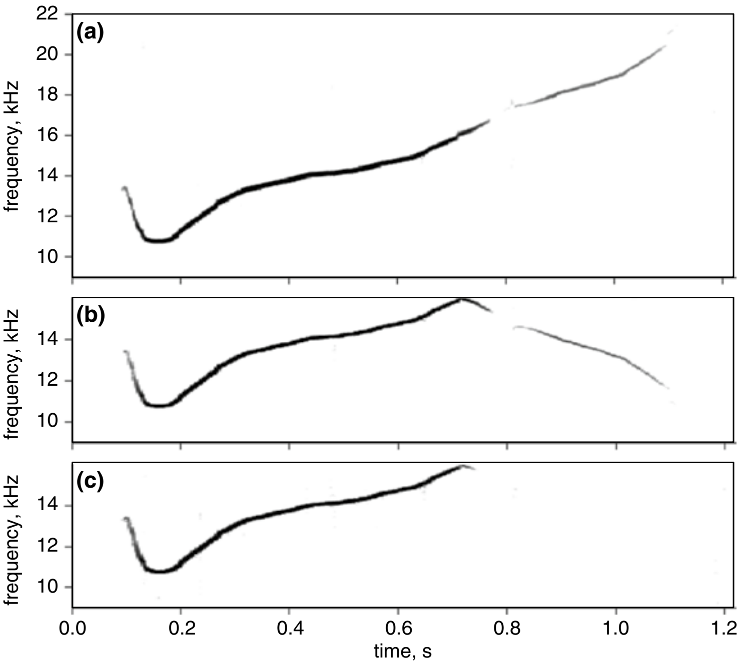


Fig. 15.2 Spectrograms showing an example of aliasing of a common dolphin whistle. (**a**) The whistle with a sample rate sufficiently high to capture it in its entirety. (**b**) The sound improperly resampled without low-pass filtering. At the Nyquist frequency of 16 kHz, the whistle appears to "reflect" to lower, incorrect frequencies. (**c**) The sound properly resampled, using filtering before resampling with a low-pass cutoff of 16 kHz. The *top part* of the dolphin whistle above the Nyquist frequency is absent, as it must be at this sample rate, and no longer appears at the wrong frequency

The most common use for filtering is to prevent aliasing. Aliasing occurs when sounds are present above the Nyquist frequency, which is defined as half the sampling rate. When such sounds are represented as a digital signal, they are indistinguishable from sounds below the Nyquist frequency—in other words, they appear *aliased* to that lower frequency (Fig. 15.2). Sound-playback equipment will play them as the lower frequency. To prevent this frequency shift, every digital acquisition system—every system for converting analog signals into digital samples—has an analog anti-alias low-pass filter to remove sounds above the Nyquist frequency.

Anti-alias low-pass filtering is also necessary when resampling a digital signal to a new sampling rate: Because the Nyquist frequency for the new sampling rate is different from that of the old rate, all sounds at frequencies above the new Nyquist rate must be removed from the signal before it is resampled at the new rate. To down-sample a signal to $1/k$ of its current sampling rate r, then, one must apply a low pass filter with a cutoff frequency of $r/(2k)$, then down-sample by selecting every kth sample of the filtered signal. To up-sample a signal to k times its current sampling rate r, one must insert $k-1$ zeroes after every sample to obtain a signal with the desired sampling rate of *kr*, then apply a low-pass filter to the new signal with a cutoff frequency of *r*/2.

Another relatively common use of filters is to flatten the spectral response of hardware devices. A hydrophone, for instance, may capture some frequencies well but attenuate others somewhat. To correct this spectral shaping, a filter can be designed with the inverse of the hydrophone's spectral response, thus restoring the original spectrum of the sound signal.

Different filters have different properties, and it is helpful to understand the tradeoffs between these properties in choosing a type of filter.

- The most prominent property is the *frequency response* of a filter, which specifies how much gain or attenuation the filter causes at each frequency between 0 Hz and the Nyquist frequency. Often one desires a filter with a "rectangular" frequency response, such that all frequencies in the pass band have gain 1 (0 dB) and all other frequencies have gain 0 ($-\infty$ dB). Unfortunately, this is mathematically impossible for a finite filter, and all realizable filters are only an approximation to this ideal filter. Common ways in which a filter misses the ideal are (a) having *ripple* in the pass-band, such that the gain oscillates above and below 1; (b) having *transition region(s)* of some bandwidth in which the gain goes from 1 to nearly 0 or vice versa; often one wants this transition region to occupy only a narrow band of frequencies; (c) having the gain in the stop band be some number of decibels below the gain in the pass band, rather than the ideal gain of 0; attenuation of 60 dB in the stop band is often used to remove unwanted frequencies. Examples of these shortfalls can be seen in Fig. 15.1a. Generally speaking, all of these properties improve with increasing order of the filter (see below).
- A related value is the *phase response*, which specifies (in degrees or radians) how much each frequency is delayed as it passes through the filter. Identical delay across frequencies is also called *linear phase response*, since a constant delay time is the same as a phase change that increases linearly with frequency. Having a constant time delay can be important when detecting calls using templates, when analyzing call characteristics, or in any other application for which the shape of the call is important.
- The *order* (length) of the filter, usually denoted by N. The frequency response generally improves with increasing order, but at a price: The *computational cost* of a filter, which is important for real-time applications, is proportional to N. This is discussed in more detail below.
- The *response time* of a filter refers to the time it takes for a given sound on input to appear (filtered) at the output. Response time is also called *group delay*. For most filters, response time is also proportional to N, and for many filters it is equal to $N/2$ sample periods. Response time for some filters (IIR filters, described below) can vary with frequency.
- *Stability* is a factor for some filters. An unstable filter can, with certain inputs, have an output that increases toward infinity.

Generally speaking, one can improve the frequency and phase responses—make the pass band have less ripple, make the transition region narrower, or decrease the gain in the stop band—by increasing the order of the filter. The drawback is that the computational cost rises, and usually the response time does as well.

An important distinction in digital filters is whether they are *infinite impulse response* (IIR) or *finite impulse response* (FIR). These are also called *recursive* and *non-recursive* filters, respectively. An IIR filter reuses one or more of its previous output values in computing the next output value (hence the name recursive), while an FIR filter does not. Because IIR filters have this feedback, they can be unstable. A more complete discussion of stability is available elsewhere (Oppenheim and Schafer 2009), but suffice it to say that one can test a digital filter for stability by providing it an impulse—a signal whose samples are all zero-valued except for a single 1 value—and checking whether the filter's output decays to 0 over time.

A digital filter consists essentially of two length $N+1$ vectors of filter coefficients, traditionally called $\vec{A}$ and $\vec{B}$, where N is the order of the filter. Many methods for designing digital filters are available, including IIR filter design methods known as Chebyshev types I and II, elliptical, Butterworth, and Bessel, and FIR methods called the window method and the frequency-sampling method. A more complete discussion of all these methods is available elsewhere (Oppenheim and Schafer 2009), but one can judge a given filter by examining its frequency and phase responses (Fig. 15.1) and considering its order.

The filter coefficients are used to implement the filter. In simplest form, a filter is implemented with

$$y[n] = (1/a_0)\begin{pmatrix} b_0 x[n] + b_1 x[n-1] + b_2 x[n-2] + \ldots \\ \qquad\qquad -a_1 y[n-1] - a_2 y[n-1] - \ldots \end{pmatrix} \tag{15.1}$$

where $x[n]$ is the input signal, $y[n]$ is the output signal, n is a time index (with smaller values in the past), and a_i and b_i are the filter coefficient vectors. When implementing a filter to operate on successive blocks of input data, care must be taken to preserve the data from the end of one block for the start of the next block to prevent a discontinuity in the output signals. For FIR filters, one must preserve the last N inputs $x[n]$; for IIR filters, one must preserve both these inputs and also the last N outputs $y[n]$. Equivalently, it is possible to apply FIR filters by preserving only the input samples: If the block length is m samples, with $m \gg N$, one can filter each block and then ignore the first N and last N samples of the result, keeping only the middle $m-2N$ samples. (Thus the start of each input block must be $m-2N$ samples after the start of the previous block in the input sample stream.) FIR filtering can also be implemented using a discrete Fourier transform (DFT) to perform the convolution represented by Eq. (15.1). This is computationally more efficient, sometimes dramatically so, for filters whose order is more than a handful of samples. and can be combined with FIR block processing as described above. See Oppenheim and Schafer (2009) for information on performing convolution using a DFT.

For an FIR filter, all A coefficients in Eq. (15.1) after a_0 are zero; a_0 is often 1, so it can be ignored as well. The computational cost of an FIR filter of order N is thus half that of an IIR filter of the same order. Also, because the filter's output depends on only the inputs x and not the outputs y, the filter is inherently stable; once the most recent $N+1$ inputs in an impulse signal are all zero, the output of the FIR filter is necessarily zero as well. FIR filters can be (and usually are) designed to be symmetric, with the left half of the coefficients a mirror image of the right half, which implies that they have constant time delay, or linear phase (Oppenheim and Schafer 2009). The drawback of FIR filters is that they tend to have much higher order, and hence much higher computational cost and longer response time, for a given frequency response. For instance, an FIR low-pass filter of order 110 has approximately the same transition band width—i.e., its frequency response falls off just as fast above the cutoff frequency—as an IIR Chebyshev Type I filter of order 10. Although the computational cost of the FIR filter is half that of an equal-order IIR filter, this FIR filter still has 5.5 times the computational cost and response time of the comparable IIR filter.

Digital filters can be designed using several popularly available packages (such as in the Signal Processing Toolbox in MATLAB™), or via websites that allow one to enter the desired filter characteristics and then return the filter coefficient vectors. The packages also contain methods that implement Eq. (15.1)—that apply the filter to a block of input samples $x(n)$ and return the output samples $y(n)$, with provisions for preserving the filter's state between the end of one block and the start of the next. These routines are usually highly optimized to run quickly, using a DFT and employing multiple processors when possible. So if they are available, by all means use them.

15.3 Detection and Classification

Many applications of marine bioacoustics involve large-scale data sets—data sets collected from many hydrophones, or over long time periods, or both. Analyzing such data sets usually requires automated methods to find any animal vocalizations of interest. This process may be broken down into the separate steps of *detection*—finding potential sounds of interest in the recorded signal—and *classification*, assigning these sounds to categories. Detection methods usually operate on a continuous signal, making decisions at each time step about whether a sound of interest is present or not, while classification methods operate on short, discrete chunks of sound, typically ones roughly the duration of the calls under investigation, to assign them to one of several categories. Despite these differences, there is no firm distinction between detection and classification, and many techniques do some of both. Even a detection method as simple as finding any transient sound typically operates in a specific frequency band and with transients of a certain duration, characteristics that cause it to have some selectivity for—some classification of—the sounds it detects. Classification techniques are sometimes used in a two-way decision to choose whether a sound is of a desired call type or not, a task that is very much like detection. In addition, some techniques, like the template-matching methods discussed below, combine detection and classification into one step. Also, for the common case in which detection is followed by classification, the sounds found by the detector and thus presented to the classifier are very much dependent on the characteristics of the detector, and training and testing of the two methods is closely intertwined. This section reviews some of the issues that arise in using detection and classification methods, and succeeding sections examine some of the widely used methods.

Detection and classification methods typically use one or more *features* of a sound to make decisions. A feature, also known as a *measurement*, *statistic*, or *observation*, is simply a quantity derived (extracted) from the sound by some algorithm. Examples include minimum frequency, duration, amplitude modulation, and entropy (e.g., Erbe and King 2008). There can be multiple algorithms for a given type of measurement; for instance, measuring duration is not simple for sounds that fade in amplitude at the end, and it can be done in several ways. Fristrup (1992) developed noise-robust methods for estimating features of animal sounds. Detection and classification systems often use several features calculated from each sound, in which case the features are grouped into a *feature vector* containing all of the desired values. (Confusingly, the feature *vector* is sometimes referred to as the feature or observation itself.) An *N*-element feature vector, corresponding to one call, or portion thereof, defines a single point in an *N*-dimensional space, and the implicit or explicit goal of many classifiers is to group as a single class those points that are near each other in this space. Using multiple feature vectors to represent a call is common when there is some form of evolution over time of the signal. An example of this can be seen in Deecke and Janik's (2006) work with dolphin whistles where measurements of the signal were produced every 10 ms.

Decision criteria. Detection and classification tasks use a *decision criterion* to decide the class, if any, to which a segment of audio belongs. Fig. 15.3a shows an

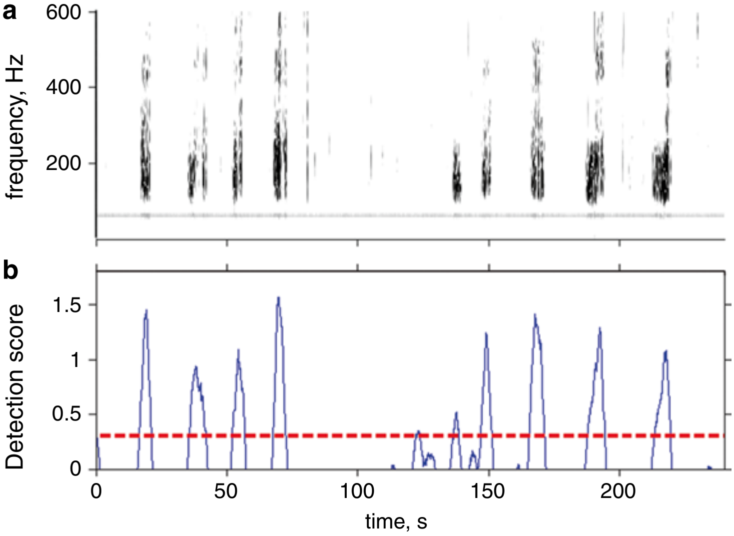


Fig. 15.3 Spectrogram and detection function for harbor seal "roar" vocalizations. Whenever the function exceeds the dashed-line threshold, a detection is registered

example of a *detection function* for harbor seal "roar" vocalizations computed from an audio signal. The decision criterion—a threshold in this case—is used to decide when to label the signal as having harbor seal sounds, or equivalently to trigger a *detection*. In this example, the decision criterion is used merely to decide the presence or absence of the desired sound. But in other contexts, decision functions may select from among several possible results, such as several types of calls. In such multi-way decisions, the decision criteria are correspondingly more complex, involving perhaps bounded $N-1$ dimensional hyperplanes in the N-dimensional space of features (Fig. 15.7b below).

Tradeoff in choice of threshold. Use of a threshold, or any two-way decision criterion, requires a numerical choice of that threshold, a choice that affects detector performance and involves a tradeoff. The tradeoff is between *wrong detections*, also known as *false positives, false alarms*, or *Type I errors*, and *missed calls*, also known as *false negatives* or *Type II errors* (Table 15.1). A higher threshold will result in fewer detections, reducing the probability of wrong detections but also raising the probability of missed calls, and vice versa for a lower threshold. The choice of threshold depends on the goal of the automatic detection. Some situations require detecting every call; this may be necessary when searching for an endangered species such as a right whale, or in real-time monitoring to ensure that no marine mammals are present in an area before doing something potentially harmful (e.g., blasting for construction of a harbor). In this case, a relatively low threshold is needed, with further checking of detections, either manually or with a classifier, to weed out the wrong detections. Other situations, like estimating population or population density, may require detecting only those calls that are relatively loud, but doing so as reliably as possible, with few false positives. For these situations, a relatively high threshold is needed. The section on performance measurement below discusses the setting of thresholds, including quantitative assessment of thresholds.

Table 15.1 Terminology use in describing detections

	Detected	Not detected
Desired vocalization	a	b
Anything else	c	d

The left side of the table indicates the truth about a set of calls—whether or not a given sound really is the desired call—while the top of the table indicates whether a given method detects the sound. The letters a, b, c, and d indicate the number of sounds of each type that occur

a = correct detection, true positive
b = false negative, Type error, II error, or miss
c = false positive, Type I error, or wrong detection
d = correct non-detection, true negative

False positive rate $= \frac{\&\$\$\$;}{a+c}$

False negative rate $= \frac{b}{a+b}$

Precision $= \frac{a}{a+c}$

Recall $= \frac{a}{a+b}$

Note that it almost never makes sense to speak of detecting or classifying *all* calls of the target species. Other than for captive-animal recordings, animals may be at widely varying distances from the hydrophone(s), with varying levels of interfering noise. A nearby loud call may be clear, but a sufficiently distant one is faint relative to background noise—i.e., it has a relatively low signal-to-noise ratio (SNR). In recordings made in the wild, there are always low-SNR calls at the limit of detectability and identifiability. This is true regardless of the detection and classification method used, including manual scanning.

Degree of automation. A closely related issue is the degree of automation needed. A fully automatic system is easy to use but probably unreliable. That is, it may require no supervision, but then no one notices if the detector/classifier makes wrong detections or misses calls—occurrences that are particularly likely if interfering noise in the background changes. At the other extreme is manual scanning—that is, a person manually checks all recordings by examining spectrograms or listening to the calls. This process is quite labor-intensive but is nevertheless useful when high confidence is required, as in the case of clearing an area of marine mammals before some potentially harmful action.

Most applications of automatic detection/classification fall somewhere between these two extremes. One popular technique is to check some subset of the detection/classification results to find the fraction that are wrong, then use this fraction to estimate the number of wrong detections in the full data set. In doing this, one must take care to examine separately those time periods when the fraction of wrong detections is likely to be different. This can happen either when the expected number of calls varies—which can happen because of migration or other movement, seasonal or diurnal changes in calling behavior, etc.—or when the background noise varies and thus alters the likelihood of a wrong detection—which can happen due to the appearance of interfering species' calls, changes in physical noise due to wind, waves, ice, etc., or changes in anthropogenic noise, like an increase or decrease in vessel noise. Another popular analysis method is to use automatic detection to find potential calls, then check *all* detections to determine which are correct. This can be useful when searching for a rare or endangered species, and can be combined with sampling of some time periods when no calls are detected to determine whether missed calls are an issue.

Desired level of specificity. How narrow a category of sounds must be detected? Different applications of automatic detection/classification will have different answers to this question, and will require different detection methods. At the most general level, one may wish to detect all possible marine organisms, as for a study that examines possible ecological and trophic interactions. At less general levels, to comply with the marine-mammal protection laws, one may wish to detect all marine mammal sounds present. One may wish to detect a certain taxonomic group—for example, detect all members of the family Ziphiidae (beaked whales). One may wish to classify sounds of a certain group defined acoustically, such as mid-frequency whistlers including dolphins, pilot whales, *Berardius* beaked whales, etc. One may wish to detect threatened and endangered species, either to study them or to avoid possible harm to them. One may wish to detect a certain species, a certain call type, or at the most extreme level of specificity, calls of a certain individual.

These different levels of specificity require different approaches to detection and classification. For instance, finding sounds of all marine organisms requires a very general detection and classification system, such as a simple transient detector plus perhaps a classifier to remove known interfering sounds. A very specific task, like finding whistles of a certain single species of dolphin, may require a very specialized system: detecting all whistles in a certain frequency range, then measuring features of the whistles and using a classifier on the feature set to distinguish species. Finding clicks of odontocetes, a task at an intermediate level of specificity, can be done using detection of sounds that occur across a wide band of frequencies, plus further tests on the duration of these wide-band sounds.

Difficulty of detection or classification. The difficulty of a given detection task depends on several factors. One is the *call stereotypy*—that is, the degree to which different calls from the same or different individuals resemble one another. Highly stereotyped calls like blue whale “B calls” are relatively simple to detect and classify, and are amenable to the template-matching methods discussed below, while the highly variable units of humpback or bowhead whale songs are comparatively difficult (Fig. 15.4). Some call types may include both stereotyped and variable components, in which case it may be feasible to detect and classify only the stereotyped portion.

The type of call can also affect the choice of detection method and the difficulty of detecting and classifying it. For instance, click sounds of echolocating cetaceans require different detection techniques than the whistles of dolphins: Clicks can be detected using the simple time-domain methods discussed below, while whistles usually require a more complex frequency contour tracking method.

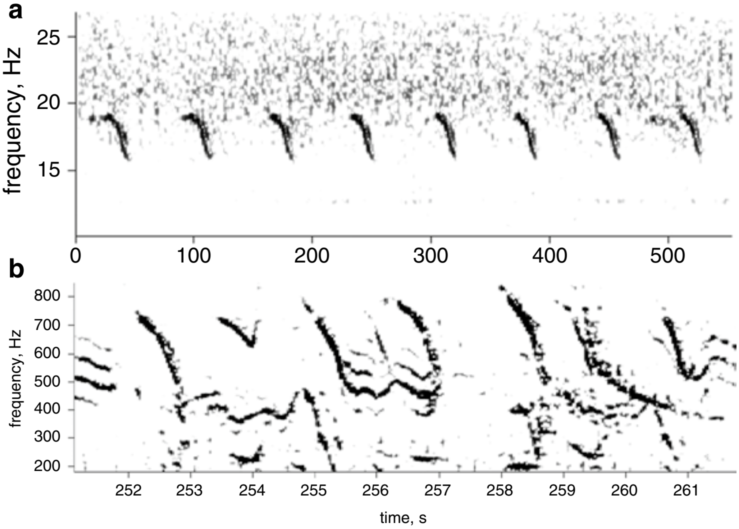


Fig. 15.4 (**a**) Highly stereotyped vocalizations of Atlantic blue whales. (**b**) Highly variable song units of bowhead whales

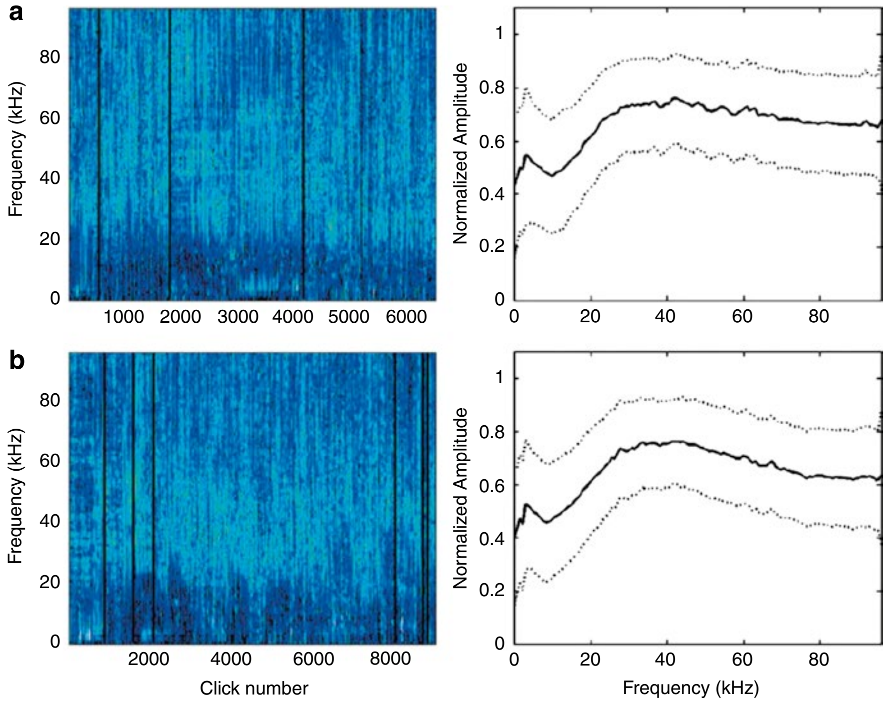


Fig. 15.5 Spectra of the clicks short-beaked common dolphins and common bottlenose dolphins. Spectra of individual clicks are plotted on the *left* with lighter tone denoting higher energy. (Note these are not continuous spectrograms, but rather compiled spectra of just clicks.) Averaged spectra are shown on the *right* by *solid lines* with *dotted lines* showing ±1 standard deviation. Their similarity makes separation of these two species difficult. Reprinted with permission from Soldevilla, M.S., E.E. Henderson, G.S. Campbell, S.M. Wiggins, J.A. Hildebrand, and M.A. Roch. 2008. Classification of Risso's and Pacific white-sided dolphins using spectral properties of echolocation clicks. J. Acoust. Soc. Am. 124: 609–624. Copyright 2008, Acoustical Society of America

Interfering sounds have a large effect on the difficulty of detection and classification. Masking by wide-spectrum background noise reduces the SNR of all calls, making detection and classification more difficult. Interference from other sounds in the environment can be even more of a problem, particularly when it has characteristics similar to the calls of interest. Most often similar sounds come from other species; cases in point are the vocal similarity of right and humpback whales (Mellinger et al. 2004), and the similarity between the clicks of common bottlenose dolphins (*Tursiops truncatus*) and short-beaked common dolphins (*Delphinus delphis*; Soldevilla et al. 2008), as shown in Fig. 15.5. Interference can also be nonbiological in origin. Indeed, in polar regions, the sound of ice cracking and rubbing has extreme variety, and is capable, for short time periods, of mimicking sounds of many different marine organisms. The general message here is *know your noise*. Noise, and its variation over time and space, have a large effect on the performance of detection and classification systems.

15.3.1 Conditioning

Signal conditioning refers to pre-processing a signal, or some representation of a signal such as a spectrogram, to prepare it for detection and classification. Some types of conditioning known as *normalization* are done to make an input signal more uniform, so that later stages of analysis have the behavior one might expect. For instance, a simple form of signal conditioning is to use automatic gain control to make an audio signal have a desired average sound level. Typically this involves calculating the moving average level (using some averaging time constant t_a), then dividing the signal by this average and perhaps multiplying by a constant to achieve the desired average level. The time constant t_a used in averaging should be chosen bearing in mind the call type to be detected or classified; using too small a t_a can make the averaging process silence the desired calls, while too large a one can make it fail to reduce background noise quickly, perhaps leading to poor performance at detection and classification. One rule of thumb is to use a time constant such that a new loud sound is reduced to half its original level in a period 3–5 times the duration of the desired call type.

Signal conditioning is also performed on spectrograms and other time–frequency representations. Often this is done for removing noise, or *de-noising*. One way to do this uses the same long-term averaging described above, but operates in each frequency bin independently. This technique, known as *pre-whitening* or *spectrum flattening*, has the benefit of removing long-duration, constant-frequency sounds such as vessel propeller noise and motor sounds (Mellinger et al. 2004). Another technique uses a wavelet transform to effect the de-noising (Kovesi 1999; Gur and Niezrecki 2007). Other forms of conditioning that are applied to spectrograms include image processing filters for various purposes. One type smooths edges in the image, so that frequency contours are easier to detect; it has been employed to detect right whale calls (Gillespie 2004). Other examples of image processing filters include the opening and closing operators which join areas that are almost connected and smooth away rough edges respectively. These have been used in the recognition of both baleen (Mathias et al. 2008) and odontocete (Mallawaarachchi et al. 2008) tonal calls.

15.4 Detection Methods

The most widely used detection methods are reviewed here; a similar review of classification methods follows. We use *input signal* to mean the sound signal in which we wish to find calls of interest, *detection function* to mean a function of time that reflects our belief that the desired sound is present at any given time, and *threshold* to mean the level above which the detection function must rise to indicate a detection. The most straightforward detection methods operate in the time domain, i.e., using the time series signal itself rather than another representation like a spectrum or spectrogram, and we review them here first.

Matched filtering is a template-matching method in the time domain. It consists essentially of cross-correlation of a fixed template, the *kernel*, with the input signal. The kernel is normally a copy of the call of interest, either a very clear recording or a synthesized version of the signal. The reason for needing a very clear version is that any noise in the kernel adds to noise in the detection function, increasing its error rate. Matched filtering has a long history in detection theory, having been used to detect radar reflections during World War II; it is the optimum linear filter for detecting a known sound in the presence of white Gaussian noise. “Known” in this context means that the waveform (time series) of the target sound is known exactly. Although animal calls are never “known” in this sense, as there is always some variation from one animal sound to the next, matched filtering is still useful for detecting highly stereotyped calls. It has, for instance, been used for detecting the B calls of blue whales (Stafford et al. 1998) and for discriminating the clicks of individual sperm whales (Gillespie and Leaper 1996). Matched filtering works less well when there is variation between calls, or when the background noise is not white—as when the sound contains significant vessel noise. Urazghildiiev and Clark (2006) present a method for detecting right whale calls by matching many possible templates in parallel.

Band-limited energy summation consists of simply using the level of the input signal within a fixed frequency band as the detection function. The waveform is bandpass-filtered to leave only the desired portion of the spectrum, so that sounds in this band result in increases in amplitude of the detection function (the filtered signal), and a threshold is applied to the result. This method is fairly general, in that it detects *any* sounds within the desired frequency band (though further processing of the detection function can be performed, as explained below, to restrict which suprathreshold events are considered detections). It has been used most often for detecting echolocation clicks of odontocetes, as for example for detection of sperm whale clicks (Gillespie 1997; Mellinger et al. 2004). Variants of this method have been developed for discriminating the desired clicks from those of other species present. Energy ratios between a band of interest and a neighboring band where energy is not expected (Au et al. 1999) have been used. A method known as the Energy Ratio Mapping Algorithm (ERMA) optimizes the selected frequency bands to distinguish the target species’ clicks from expected clicks of other species in a survey area. The two corresponding bandpass filters are both applied to the input signal in parallel, and the ratio of these filters’ output in combination with a Teager–Kaiser energy operator is used as the detection function (Klinck and Mellinger 2011).

A large class of detection methods is based on time–frequency representations of the input signal such as the spectrogram. Other time–frequency representations are sometimes used or suggested, including wavelets and the Wigner–Ville distribution, though spectrograms remain by far the most widely used in bioacoustics. Qian and Chen (1999) provide an overview of these other representations. Wavelets have been used two ways: Directly, in that the wavelet coefficients provide the input feature vector to a classification system, and indirectly, in that the features are derived from the wavelet coefficients. Conversion of a signal to a time–frequency representation can make it simpler to detect sounds with particular time–frequency characteristics, including manual detection, and also makes it simple to apply conditioning techniques to equalize or "whiten" the long-term spectrum of the signal (Mellinger et al. 2004). This has the effect of reducing the effect of long-duration noise sources such as vessel sounds, wind and wave noise.

The Hilbert–Huang transform has been used to detect and analyze cetacean sounds. This transform, similar in spirit to a wavelet analysis, consists of decomposition of the signal into a "mode function," which is calculated from envelopes of the successive maxima and minima of the waveform, and the residual that is left after subtracting the mode function from the original signal. The decomposition is then repeated on the residual using a different, orthogonal mode function, and the whole process is iterated until the residual becomes sufficiently small. The result is a set of mode functions that describe the original signal. Adam has had success using this technique to analyze sperm whale clicks (Adam 2006a, b) and to track killer whale whistles (Adam 2006b, 2008).

The simplest of time–frequency methods is similar to band-limited energy detection: The detection function is simply the sum of spectrum values in a given frequency band—i.e., in the appropriate bins of the spectrum. This method has the same advantages and disadvantages as the similar method in the time domain discussed above, except that noise removal via spectrogram conditioning is possible.

Many animal sounds are composed of frequency contours—narrowband tonal sounds that change frequency over time. Such sounds include whistles of many odontocetes, moans of mysticetes, and trills of some phocid seals. Such sounds are typically detected using methods that find a peak in the spectrogram frame (spectrum) at the start of the contour, then track that peak over time in successive frames. If the peak is sufficiently high above background noise and persists for a sufficient duration, a detection is registered. Methods employing these ideas have been used to analyze whistles of bottlenose dolphins (Buck and Tyack 1993) as well as moans of baleen whales (Mellinger et al. 2011). The advantage of these methods is that they detect frequency contours of all shapes and sizes within a specified frequency band; this is also their disadvantage, because if there are interfering frequency contours in this band, the methods typically detect them as well.

A number of other tonal detection methods are based on processing spectrogram energy. Gillespie (2004) presented another method for detection of frequency contours based on edge-detection techniques from the field of image processing. The spectrogram is smoothed to eliminate speckle, and the outlines of sounds are found using an edge-detection algorithm. If the contour is longer than a specified minimum duration, it is then subjected to further analysis to determine whether it is from the desired target species. Several groups have used Bayesian filtering, where the spectral peaks observed during the detection process are used to update a posterior distribution of where the next peak in a tonal might occur, and a statistic of the distribution (e.g., the mean) is used as a point estimate. This was first reported by Mallawaarachchi et al. (2008) and White and Hadley (2008) with Kalman and particle filters respectively. Roch et al. (2011b) showed that more advanced particle filters could perform well in complex auditory scenes with many animals producing calls simultaneously. Their work also considered delaying decisions about crossing whistles until groups of intersecting whistles were entirely detected, permitting information from both sides of the crossing to be used. Finally, Kirshenbaum and Roch (2013) applied image-processing based ridge detection algorithms.

Spectrogram correlation is a template-matching method in the time–frequency domain. As with matched filtering, it involves cross-correlation of a kernel with the input signal, only this time the input signal is represented as a spectrogram. The kernel can either be synthesized or generated from a recording; synthetic kernel generation methods generally include mechanisms to detect the calls of interest while rejecting interfering calls that occur simultaneously. Spectrogram correlation has the advantages and disadvantages of template-based methods: the method permits high specificity with respect to call type, but detection performance declines when calls vary too much from the template. The method generally allows for more variation in calls than matched filtering does, and Mellinger and Clark (2000) present a method for handling variation in the timing of successive parts of calls. Spectrogram correlation has been used principally for detecting stereotyped calls of baleen whales, including blue whales (Mellinger and Clark 1997), right whales (Munger et al. 2005; Urazghildiiev et al. 2009), and sei whales (Baumgartner et al. 2008). While many baleen whale calls are highly stereotyped, some call characteristics have been shown to experience drift over time. An example of this is blue whale B calls in the Northeast Pacific, whose dominant frequency has been shown to decline by nearly a third over a period of over 40 years (McDonald et al. 2009). This has led some researchers (e.g., Oleson et al. 2007) to develop kernels specific to certain time periods.

Another spectral method uses phase information to detect echolocation clicks. Kandia and Stylianou (2006, 2008) show that the position of a delayed unit impulse can be predicted by the group delay (negative derivative of the signal's phase spectrum), and the average over frequency for the group delay function similarly predicts the delay of rapidly decaying functions such as an echolocation click. They propose a method to estimate the slope of the group delay and use sets of sliding windows to detect when an echolocation click is at the origin of a window. Negative phase slopes are indicative of an impulsive sound far from the start of the frame. As the window slides, a negative-to-positive zero crossing of slope indicates that an echolocation click is at the origin. This method is robust to high levels of background noise and is relatively nonspecific, detecting all short-duration impulsive sounds such as odontocete echolocation clicks.

Finally, the detection can be based on the entropy estimated from spectrogram frames. These methods estimate a statistic called the Shannon information entropy that measures the amount of information in the signal. Portions of an input signal having marine mammal calls contain more information, and so the entropy statistic over time can be used as a detection function. This method is very general, detecting a wide variety of cetacean and pinniped sounds (Erbe and King 2008). This generality is both its strength and its weakness; it would be most useful for detecting the presence of any marine mammal, but not useful for detecting a certain species or call type. Entropy methods have also been use to analyze the information content of humpback whale songs (Suzuki et al. 2006; Miksis-Olds et al. 2008).

While most of the detectors described so far operate in the time–frequency domain, detectors for both tonal and impulsive calls can operate on time-domain signals. For a tonal signal $x[n]$, its instantaneous frequency can be estimated from an analytic signal $y[n]=x[n]+jH(x[n])$ where H denotes the Hilbert transform and $j=\sqrt{-1}$. The instantaneous frequency is defined as

$$f_i(t)=\frac{1}{2\pi}\frac{\mathrm{d}\phi(t)}{\mathrm{d}t}$$

where $\phi(t)$ is the phase of the analytic signal $y[n]$. This can be interpreted as the mean of the changing spectrum at time t (see Boashash 1992 for a thorough discussion of instantaneous frequency), and the goal of the time domain detectors discussed here is to track how instantaneous frequency evolves over time. Ioana et al. (2010) modeled the instantaneous frequency by analyzing short segments in which the instantaneous frequency could be modeled by a series of piecewise polynomials. An alternate process proposed by Johansson and White (2011) tracked tonal calls by optimizing a set of notch filters over time. The filter parameters follow the instantaneous frequency and permit recovery of the whistle. The developments in this area are interesting and merit further investigation; however at the time of this writing, there remain significant challenges in dealing with complex and noisy data sets.

The Teager energy operator (Kaiser 1990) is a short-time energy estimation method used in the bioacoustics community for detecting brief calls such as echolocation clicks. Proposed by Teager and developed by Kaiser, it is sometimes referred to as the Teager–Kaiser energy operator and estimates energy based on three samples. The energy is based on the energy required to *generate* simple harmonic motion in a mass-spring model. The operator estimates the energy needed to excite such a system, which is proportional to the square of the amplitude and frequency of the measured signal. Kaiser showed that for a variety of non-harmonic human speech signals, the Teager energy operator still gave very good indications of where energy was present. Kandia and Stylianou (2006) were the first to propose using the Teager energy operator to detect echolocation clicks of sperm whales. Due to the broadband nature of odontocete echolocation clicks whose peak frequencies are typically in quieter portions of the spectrum, the high frequencies tend to result in strong rises of Teager energy (Fig. 15.6). Kandia and Stylianou showed that the skewness of the Teager energy distribution could be used to efficiently determine whether or not an echolocation click existed over a given window. When clicks were present, an energy growing algorithm permitted the recovery of clicks. Echolocation clicks violate the assumptions of the model (non-harmonic signal, and the estimation error increases greatly when the frequency is greater than 1/8th of the sampling rate), yet Kandia and Stylianou showed empirically that the Teager energy was effective for detecting echolocation clicks.

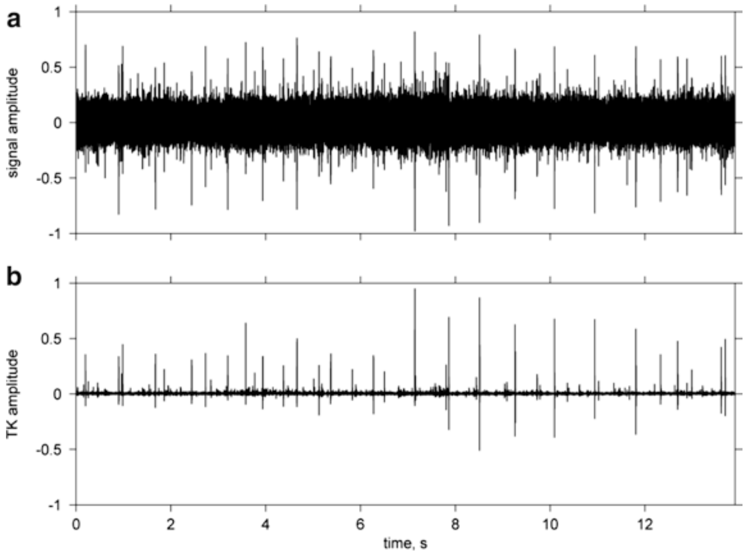


Fig. 15.6 (**a**) An acoustic signal containing sperm whale clicks. (**b**) The result of applying the Teager–Kaiser operator to this signal. Note that the clicks stand out much more above background levels here than in the acoustic signal

15.4.1 Detection Function Processing

The methods mentioned above produce a detection function, which must then be analyzed to find discrete *detection events*—times when detections, and hopefully calls, occur. The simplest way to do this is simply to register a detection event whenever the detection function surpasses the threshold, but a number of refinements to this method are often helpful.

Multipath rejection. Marine bioacoustic sounds often reach a hydrophone by multiple paths—echoes off the sea surface or floor, multiple refractive paths within the water column, or some combination of these. Usually one desires to ignore these multiple arrivals and register only one detection event per call produced by the animal. A simple means to do this is to have a short *refractory period* after a detection event, such that no further detections are possible within this period. The length of this period depends on the geometry of the multiple paths between source (the animal) and receiver (hydrophone). This rejection method is effective, but it runs the risk of rejecting other calls, perhaps from nearby conspecifics, that happen to arrive during the refractory period. To avoid this, one can reject other calls within the refractory period if the absolute value of the normalized cross-correlation of the first arrival and a later arrival is above certain amount; this is usually effective because multipath arrivals of a call are typically (though not always!) highly similar in structure. The absolute value operation is needed because of the sign change (phase inversion) that happens to acoustic pressure waves when they reflect off the water's surface.

Jitter rejection. The detection function typically contains a significant amount of jitter—variation on a very short time scale. This jitter can cause the detection function to cross the detection threshold several times while rising above or falling below that threshold in the long run, possibly triggering multiple detections. Two approaches to handling this are effective. One is to *smooth* the detection function—to take an average, or perhaps a weighted average, of every group of n samples. Here n is essentially a time constant that determines the time scale over which smoothing occurs. Heuristically, it has been found to work well to use a time constant roughly equal to or less than the duration of calls to be detected, depending on the detection method used. Smoothing lowers the height of detection function peaks, which presumably occur when a call is present, so it is necessary to adjust the detection threshold when using it; fortunately, it also tends to reduce the height of the detection function when calls are *not* present as well, so non-calls are still rejected. The other method for handling jitter is to register a detection event only for a local peak in the detection function—i.e., when the detection function is larger than all other values within a neighborhood of a certain duration. As above, the duration should be approximately the duration of the call to be detected.

Enhancing energy localization. The Teager energy operator has been used by several groups for detecting echolocation clicks of odontocetes (e.g., Roch et al. 2008) and with varying modifications, such as signal preconditioning with high-pass filtering (e.g., Bénard and Glotin 2010; Gervaise et al. 2010; Soldevilla et al. 2008). The technique has also been applied to the output of detection algorithms (Klinck and Mellinger 2011) to find regions of high short-time energy.

Adaptive threshold. The threshold need not be constant. It can be beneficial to calculate a long-term average of the detection function and adjust the threshold height to it. This is especially helpful in two cases for which the variance of the detection function changes over time. First, the performance of time-domain methods can suffer because of a change in background noise; this essentially raises the height of peaks in the detection function, including unwanted peaks due to noise or interfering sounds. Second, even spectrogram-based methods that pre-whiten the background noise can have increased variance in the detection function as a result of heightened noise, and these changes in variance can again trigger false detections. Having the detection threshold change in response to changes in the variance of the detection function (Gillespie 1997) helps solve both of these problems.

Detecting regular calls. Bioacoustic sounds that occur at regular intervals can be detected by methods that are sensitive to regularly occurring peaks in the detection function. One way to do this is by taking successive frames of the detection function—successive fixed-size sequences of samples of it—and computing the autocorrelation of each frame. Peaks in the autocorrelation between the times (lags) corresponding to known call intervals then indicate regularly occurring calls. This method has been effective at detecting regular sounds that are too faint to detect directly in the spectrogram. Many cetaceans use regularly occurring vocalizations at some point in their life cycle; this method has been used on songs of fin whales (Mellinger et al. 1994), pulse trains from minke whales (Mellinger and Clark 1997), and clicks from sperm whales (Mellinger et al. 2004).

15.4.2 Classification

After deciding what to classify and selecting an appropriate feature set, one must decide what method will be used for classification. One of the most important lessons for those wishing to classify data is that there is no one best method for classification. In fact, the aptly named "No free lunch" theorem (Duda et al. 2001) shows that this is the case. Consequently, it can sometimes be useful to try multiple classification techniques on the same data set. That said, no classifier will help when there is a poor feature set, and selecting good features is one of the most critical steps in developing an effective system. Formally, the task of a classifier is to assign a label to a set of features derived from phenomena that one wishes to classify.

Classification systems can be broadly divided into generative and discriminative techniques. *Generative classifiers* learn how features associated with each class are distributed and decide the class label for a new instance (animal call) based on some measurement of similarity to the training distribution. In contrast, the designers of *discriminative classifiers* do not concern themselves with how features are distributed, but rather how to separate classes. Figure 15.7 shows a sample of features derived from echolocation clicks of Risso's dolphins and Pacific white-sided dolphins. These two species are readily distinguishable acoustically (Soldevilla et al. 2008) and one can see a very good separation in even the first two cepstral feature vectors here. The left plot shows an example of a simple Gaussian classifier, where the shapes of the two multivariate Gaussian distributions have been estimated to maximize their fit to each species' training data. Likelihood contours are plotted about the means of the two distributions. To use such a classifier for a call, one calculates the feature vector(s) for the call and determines which distribution would have the highest likelihood for that vector(s). In contrast, the right plot shows a line perpendicular to the separating hyperplane resulting from linear discriminant analysis. Test vectors are also projected onto the line, and classified based upon where they lie on that line. The boundary is roughly the midpoint between the means of the projected training vectors.

Classifiers can be thought of as producing a static partitioning of the feature space. Figure 15.8 shows the partitioning for a subset of a two-dimensional feature space in a three-class species identification problem. This example was produced with two-dimensional click features and a generative classifier.

Discriminative methods have the advantage that they attempt to optimize the classification decision, and many have argued that these techniques are in general more appropriate for classification. A caveat to this is that the training data must adequately characterize the separation boundary. As an example, if one were to build a "detector" for Risso's dolphins using only the toy data sets of Fig. 15.7 (not recommended), *all* other species would have to fall on the correct side of the boundary. In contrast, a generative model could set a threshold such that anything sufficiently distant from the training distribution would be rejected.

In addition to considering classifiers as generative or discriminative, one must also consider whether or not the goal of the classifier to is to learn known categories

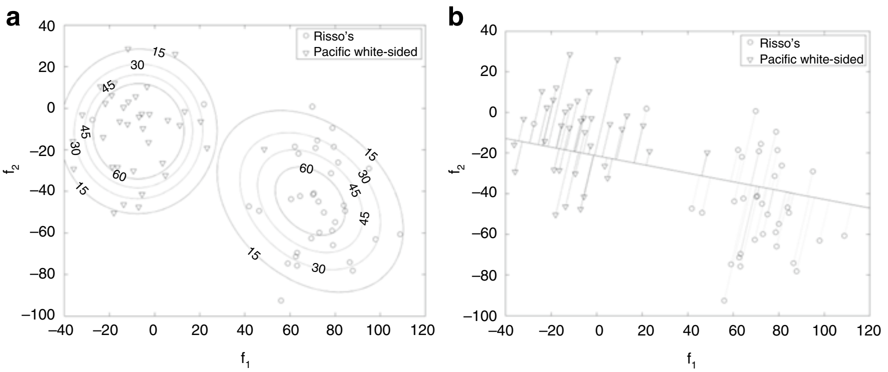


Fig. 15.7 Comparison of two classifiers trained on echolocation click features from Risso's and Pacific white-sided dolphins. (**a**) The generative classifier on the *left* models the click features as a Gaussian distribution for each species. *Contour lines* show likelihood values scaled by 10^5 for readability. (**b**) The discriminative classifier on the *right* shows projection onto a *line* selected by linear discriminant analysis

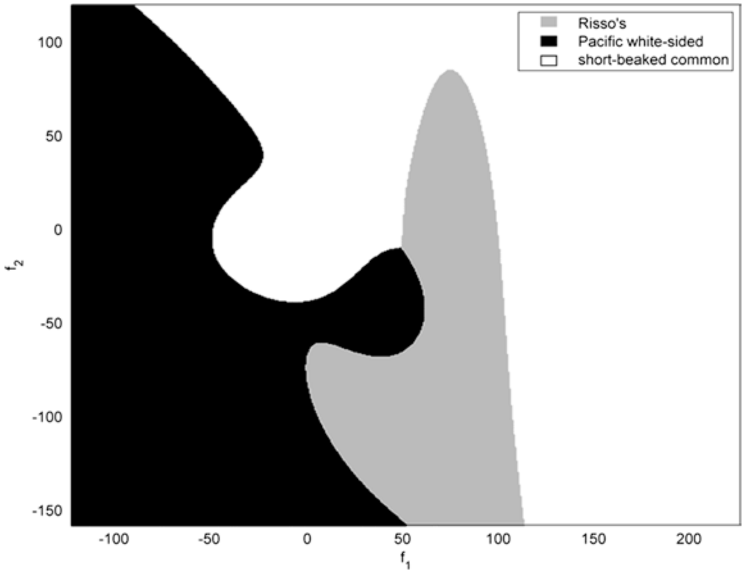


Fig. 15.8 A three-class species identification problem for Risso's, Pacific white-sided, and short-beaked common dolphins showing that classifiers induce a partitioning of the feature space. As in the previous figure, a classifier was trained from two-dimensional feature data derived from echolocation clicks. This example introduces a third species and uses data from several sightings. A two-mixture Gaussian mixture model (described later in this chapter) was trained for each species. Rather than plotting training vectors as in Fig. 15.7, this plot shows the species that would be selected for any test vector within the range of the plot. Decisions are made by selecting the species associated with the model with the highest likelihood

or to discover categories on its own. When the class labels are provided in the training process, the classifier is called a *supervised* learner. *Unsupervised* learners determine groups based solely on properties of the data, and it is up to the human analyst to determine if the groups carry any significance.

Both the Gaussian classifier and linear discriminant analysis are examples of models used for classification. In both cases, the training data is used to determine parameters for an algorithm that distinguishes between different types of feature vectors. In the Gaussian classifier, maximum likelihood estimation could be used to show that the Gaussian distribution which maximizes the probability of each class's training data is the sample mean and covariance. In the case of linear discriminant analysis, the hyperplane is chosen so as to maximize the separation between points of the different classes when they are projected onto a separating line. Fitting a classifier depends upon the type of classifier, but generally it involves maximizing (or equivalently minimizing) some statistic of the training data. After fitting, the model's performance is evaluated (see details later in this chapter). In most cases, the eventual goal is to have enough confidence in the classifier's decisions to apply it to field data where the result is not known. Except in the case of simple problems, no classifier will have perfect performance, and one needs to understand the classifier's performance to use it effectively in a bioacoustic study.

15.4.3 What Is the Right Type of Classifier?

Selection of an appropriate classifier for a call depends upon numerous issues. The analyst must consider the characteristics of the calls to be classified (e.g., is it a long frequency-modulated call such as a moan or whistle that varies over time or a short echolocation click?), whether the goal is classification or understanding what features are important for classification. Finally, the analyst must consider how much expertise they or others have working with available software packages or developing them on their own.

From a theoretical perspective, classification errors are composed of several different components. The Bayes error (also called Bayes rate) is the classification error that would occur with an optimum classifier for a given feature space and distribution of features. Unfortunately, real-world classifiers do not typically achieve the Bayes rate, which assumes that one knows the exact distributions of the classes being modeled and that features are measured without error. There are many factors that can corrupt feature vectors, including ambient noise, propagation effects such as dispersion and echoes, measurement error, and a host of other factors that serve to distort the feature vectors associated with the call being measured. Error above the Bayes rate is composed of two components, bias and variance. The *bias* is a result of structure imposed by the type of classifier used. Manning et al. (2008) give the example of classifying data that is separated by a nonlinear boundary. Using a family of classifiers capable only of linear separation would be likely to produce a high bias, as they would not be able to construct the appropriate nonlinear boundaries between classes. In contrast, *variance* is related to how sensitive the classifier is to variation in a training set. A classifier that produces very different results when given slightly different training data exhibits high variance.

The number of parameters in a model, or its order, is related to bias and variance (Hastie et al. 2001). When the model order is low, the bias tends to be high. As the order is increased, bias decreases and the error rate on the training set (but not necessarily on an independent test set) will decrease. Unfortunately, as one achieves a better and better fit of the training data set, one learns the idiosyncrasies of that particular data set rather than characteristics of the population from which the sample was drawn. This *overfitting*, or *overtraining*, of the training data results in a high variance and a poor error rate when given different data to classify. This is known as the bias-variance tradeoff and in general the search for an appropriate classifier is an attempt to find the model that optimizes the balance between the two types of controllable error.

Many classifiers are designed to discriminate between only two classes. While this may appear to be limiting, it does not pose serious challenges. To solve multiclass problems with two-class classifiers, one typically trains one classifier per class, with each one learning one of the categories (e.g., blue whale D call) versus all other categories. To classify a new call, it is evaluated by each classifier, and the one with the best response is selected.

In the next several sections, several types of classifiers are discussed. They can broadly be divided into parametric and nonparametric classifiers. While all classifiers have parameters, such as thresholds, *parametric* classifiers attempt to fit parameterized statistical distributions such as Gaussian distributions. A *nonparametric* classifier, in contrast, has no assumptions about an underlying distribution for the data. The tour concludes with a brief overview of unsupervised learning. Throughout this discussion, the goal is to provide the reader with an intuitive feel as to how each classifier functions as opposed to the complete understanding that one would require to implement the method. The discussion is far from exhaustive and should not in any way be considered a complete account of machine learning techniques. There are several excellent books on machine learning and the interested reader is referred to Duda et al. (2001), Hastie et al. (2001, 2009), and Mitchell (1997).

15.4.4 Nonparametric Classifiers

For highly stereotyped calls, there are a number of simple but effective methods that are based on template matching. The central concept for template-matching classifiers is that the call is not expected to vary significantly from the examples, or templates, to which they are to be matched. The previously discussed matched filters and spectrogram correlation methods can both be seen as examples of nonparametric classifiers. A limitation of both of these methods is the inability to account for changes in time variability in a signal. A method of permitting nonlinear variation in the timing of call production is the use of dynamic time warping, a technique used in early speech recognition systems (Rabiner and Juang 1993). In dynamic time warping, one aligns feature vectors from a template call to those of a test call. The method uses a dynamic programming algorithm to efficiently find optimal pairings between the feature vectors of the template and test call. This permits nonlinear alignment, or speeding up and/or slowing down portions of the call. Dynamic time warping has been used for recognizing signature whistles of bottlenose dolphins (Buck and Tyack 1993) adapted to model timing between piece-wise spectrogram correlation of components of bowhead whale song (Mellinger and Clark 2000), killer whale calls (Brown and Miller 2007), and used as part of a system to cluster delphinid whistles (Deecke and Janik 2006; see discussion of unsupervised methods below).

A final type of template method is nearest neighbor search. This technique accounts for variability in a template by allowing many examples of templates, each stored with a class label. When an acoustic sample is presented to be classified, a similarity metric is used to determine which *k* templates best match the sample (Duda et al. 2001). It is up to the practitioner to choose an appropriate value of *k*. The class labels of these *k* "neighbors" are examined, and a majority vote is used to decide to which class the sample belongs. While such a technique would seem to be computationally expensive, considerable effort has gone into computational methods to perform this task in a reasonable time even when there are a large number of examples. The well known *k*-means algorithm (Mitchell 1997), also called vector quantization, can be thought of as an approximative variation of nearest neighbor search. Training data are clustered and clusters are labeled according to the most frequently occurring class in the cluster. Instead of searching for the *k* nearest neighbors, cluster means represent the data, and a search is made for the closest cluster mean, resulting in significantly reduced search time.

As mentioned above, linear discriminant analysis can be used to find separating hyperplanes, and many more sophisticated methods uses trees or networks of linear discriminant classifiers. While linear discriminant analysis cannot model complex partitions of the feature space, choosing the right features can make them quite effective. A particularly elegant example of this can be found in the work of Gillespie et al. (2013), where the authors split whistles into segments and extracted simple features from the segments (e.g., mean, slope, curvature) and generated distributions of these statistics based on samples from many segmented whistles. Statistics of these distributions were computed and used as feature vectors that were classified by linear discriminant analysis.

Decision tree classifiers use a series of questions about feature values, such as "Is the center frequency of an echolocation click within a certain range?" The first question forms the root of the tree, with subsequent questions fanning out like the branches of the tree. Much like the popular children's game of 20 questions where a player attempts to determine of whom or what their opponent is thinking using yes or no questions, these systems partition the feature space into rectangular regions, or hypercubes. Each hypercube is either labeled by a class or further subdivided by another question. Decision trees can be seen as a form of rule-based system, and when a human's knowledge and intuition is used to construct the rules we refer to this as an expert system. Madhusudhana et al. (2009) developed such a system for the classification of B and D calls produced by blue whales (*Balaenoptera musculus*). Unfortunately, the rules used by humans are not always easy to quantify nor can they be generalized easily when new classifiers are desired.

Alternative forms of decision trees determine which questions to ask automatically. The systems examine the possible rules that could be used to split the dataset at each point and then select the rule that best separates the data set. An impurity measure is used to evaluate the quality of each potential split. Several impurity metrics are commonly used, but the general idea is to determine if the proposed split results in improvements to the classification error or to an information theory metric such as cross-entropy (Hastie et al. 2003). This process is repeated recursively on each split until the nodes contain only a single class or some metric is met. Tree classifiers frequently overfit the data. Consequently, a critical step for most tree-classifiers is to prune some of the lower level splits after the tree has been trained. Perhaps the two best known tree classifiers are classification and regression trees (usually referred to by the acronym CART), and the C 4.5/C 5.0 algorithms (Hastie et al. 2001). CART has been applied to the task of determining which species of odontocete has produced a set of whistles by Oswald et al. (2007). Tree based classifiers offer the advantage over other types of classifiers that it is typically easier to understand how the algorithm made its decision.

There are a large number of classifiers that are covered under the name of "neural networks," or connectionist networks as they are sometimes called. One of the most popular of these in the bioacoustics community is the back-propagation neural network, which consists of interconnected nodes called perceptrons. Each node is capable of separating the data linearly, but when they are combined, the network is capable of performing nonlinear separations of data (Lippmann 1989). As shown in Fig. 15.9, the components of an input feature vector $\vec{f} = \left[f_0, f_1, \ldots, f_n\right]'$ are fed to an input layer of perceptrons.

Each node in the input layer projects the feature vector onto a line (similar to linear discriminant analysis). The results of these classifications are distributed to

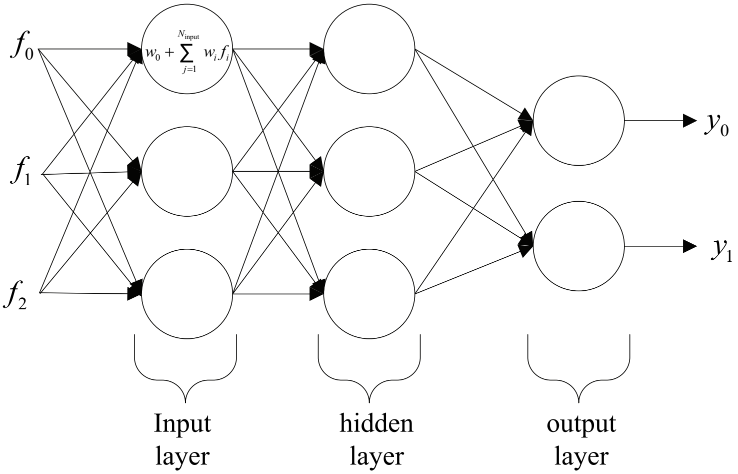


Fig. 15.9 A feedforward neural network with one hidden layer. Each component of the feature vector $\vec{f}$ to be classified is presented to the input nodes of the classifier. The results are propagated through the network and the output vector $\vec{y}$ contains the classification result

the nodes of a hidden layer where the process is repeated using the previous layer's output as input. In principle, multiple hidden layers are possible, but typically only one is used. With enough nodes and training data, a single hidden layer can model any input–output relation, though the number of nodes needed might be large and presents a risk of increasing the variance (overtraining). The hidden layer delivers values to the output layer whose outputs are used in the classification decision. In the earlier example of distinguishing echolocation clicks of Risso's dolphins from those of Pacific white-sided dolphins, one could train the network to output a value close to 1 on y_0 when the decision is that the click was produced by a Risso's dolphin and a value close to 1 on y_1 otherwise (Fig. 15.9).

Training is an iterative process, where the node parameters are adjusted at each iteration to make the output agree with the class of the training samples. A parameter called the learning rate controls how aggressively the node parameters are updated. When the learning rate is high, nodes are adjusted by large magnitudes, but large adjustments may skip over a good parameter set. Lower learning rates increase the number of iterations required but are less likely to "overshoot" a good set of node parameters. A common strategy is to start with a large learning rate and to decrease it over time. Due to the ready availability of software and generally good performance, neural networks have been used extensively for cetacean bioacoustics. Examples of this method used on various cetacean discrimination tasks include Deecke et al. (1999), Houser et al. (1999), and Potter et al. (1994).

A final form of nonparametric classifier is Vapnik's support vector machine (Burges 1998; Cristianini and Shawe-Taylor 2000). Support vector machines (SVMs) are linear classifiers which have the potential to separate nonlinear data by projecting them into a higher dimension where linear separation is possible. The separating hyperplane is chosen by minimizing an empirical risk function under a 0–1 loss rule. The result of this is that the hyperplane is selected so as to maximize the distance between points of different classes. To account for cases where the training data is not linearly separable in the higher dimension, a user settable penalty parameter is introduced that increases the value of the optimization function when points fall on the wrong side of the hyperplane. When using a support vector machine, one must also decide what kernel to use. Kernel functions provide weight, or support, for a local neighborhood about a point, and common choices for kernels (Hastie et al. 2001) include polynomial, radial (Gaussian) basis, and neural network (sigmoid) functions. Kernels typically have parameters, and the SVM's performance will thus be a function of the penalty, kernel function, and kernel parameters. Support vector machines have been used to distinguish odontocete species by their echolocation clicks (Jarvis et al. 2008; Roch et al. 2008).

15.4.5 Parametric Classifiers

Parametric classifiers attempt to model the *posterior distribution* of a class ω (e.g., species, group call type) given a feature vector x as evidence: $P(\omega|x)$. Decisions are made using the Bayes decision rule, which selects the class ω from the set of all possible classes Ω that has the highest posterior likelihood:

$$\arg\max_{\omega\in\Omega} P(\omega \mid x).$$

When the posterior distribution is accurate (this is rarely the case), this decision rule minimizes misclassification error. Direct estimation of $P(\omega|x)$ is difficult, but Bayes rule can be used to rewrite this probability as

$$P(\omega \mid x) = \frac{P(x \mid \omega)P(\omega)}{P(x)}.$$

$P(x|\omega)$ is referred to as the class-conditional likelihood and $P(\omega)$ is the prior probability. The *prior probability* is the probability that the next observation will come from class ω and is frequently unknown. In such cases, a *non-informative prior*, or uniform distribution, is used. The class ω is decided by using the class associated with the model that produces the highest posterior probability. As $P(x)$ is constant in the denominator above, it will not affect the maximum posterior probability and can be safely ignored, as can $P(\omega)$ when a non-informative prior is used.

It is possible to train parametric models to be discriminative classifiers. Doing so requires consideration of model parameters for different classes simultaneously. One example of this is maximum mutual information estimation, a technique that attempts to maximize the mutual information between training vectors and their associated class. When this is done, the object of training is to maximize the ratio of the correct class probability to that of a statistic of the competing models. A drawback of this technique is that parameter estimation becomes more difficult, and one typically must turn to methods such as gradient descent (Huang et al. 2001).

As a consequence of the difficulty of discriminative training, many parametric classifiers focus on maximizing the class conditional likelihood with respect to their training data. While many parametric classifiers exist, discussion will be limited to the two that are most prevalent in the bioacoustics literature: Gaussian mixture models and hidden Markov models.

Gaussian mixture models (GMMs) consist of a set of N Gaussian distributions scaled by a factor such that integration over the entire feature space still sums to one. These models are quite flexible and can model most distributions. Straightforward maximum likelihood techniques are not possible as one cannot attribute each training observation to a specific mixture. An application of the expectation–maximization algorithm (Moon 1996) permits a two-stage iterative process to create a model. In the first stage, the current model parameters are used to determine the expected associations between observations and mixtures. Using the expected values, a new maximum likelihood estimate is obtained. Convergence is guaranteed, and GMMs have been used for species identification for delphinids (Roch et al. 2007, 2011a), identification of killer whale calls (Brown and Smaragdis 2009; Shapiro et al. 2011) and in terrestrial bioacoustics for bats (Skowronski and Harris 2006).

With the exception of dynamic time warping, previously discussed classifiers are unable to exploit the temporal structure of the call. Hidden Markov models (HMMs, Rabiner 1989) provide a method to recognize calls that have similar structure but differ in the timing of the components. The fundamental concept that lets HMMs represent temporal evolution is that of a state. Each model consists of several states together with probability distributions for transitioning from one state to another. Each state models the distribution of features (frequently using a Gaussian mixture model) that occur in that state. The model learns both the state distributions and the likelihood of transitioning between states. Like the aforementioned Gaussian mixture model, information needed to compute a maximum likelihood estimator during training is not available, and the expectation–maximization algorithm is used. Both training and testing require the examination of many possible paths through the model, and dynamic programming algorithms permit this to happen in a tractable manner. These models have been used to determine group association by analyzing delphinid whistles (Datta and Sturtivant 2002), detect leopard seal calls (Klinck et al. 2008), and recognize killer whale calls (Brown and Smaragdis 2009). HMMs have been successfully applied to terrestrial bioacoustics as well (Adi et al. 2010; Clemins et al. 2005; Kéç-Kogan and Margoliash 1998).

15.4.6 Unsupervised Learning

Unsupervised learners, which typically take the form of clustering algorithms, attempt to discover the structure of data. Examples of this include Kohonen's self-organizing map, the *k*-means algorithm, Gaussian mixture models, and adaptive resonance theory networks. These may all be thought of as ways of clustering data. Kohonen's self-organizing maps cluster high-dimensional data on to a two (or at least low)-dimensional grid (Hastie et al. 2001). The *k*-means algorithm and GMMs, both mentioned above, can also be thought of as unsupervised learners when they are used to discover unlabeled clusters. One criticism of both algorithms is that they assume the number of clusters *a priori*. An alternative to this is adaptive resonance theory (ART) networks (Carpenter et al. 1991; Grossberg 1988) where clusters are constructed dynamically. ART networks consider the similarity between an input feature vector and cluster centers. If the feature vector is close enough to an existing cluster as determined by a threshold mechanism called vigilance, it is assigned to that cluster; otherwise a new cluster may be formed. Deecke and Janik (2006) have used a variation of the ART algorithm where the similarity was computed using dynamic time warping. They were able to successfully cluster signature whistles of bottlenose dolphins as well as killer whale calls.

15.4.7 Evaluating Classifier Performance

Data for a classifier should always be separated into at least training and validation sets. Due to the possibility of overfitting, classification of training data does not give a reliable indication of how well the system will perform on future data. Most classifiers have some type of tunable parameters, and it is common to set these experimentally by examining how well the system performs on a validation set. One view of parameter tuning is that it is in effect a form of training (on the validation data) and then the question arises as to whether or not the results are indicative of future field performance. As a consequence, whenever feasible, it is highly recommended to have a separate set of data called an evaluation set that is not tested until after the final models are created.

N-fold cross-validation or leave-one-out cross-validation (Duda et al. 2001) are frequently used to deal with limited amounts of data. *N*-fold cross-validation consists of dividing one's training and validation data into *N* partitions (folds). One selects most of the partitions (perhaps 60–70 %) as training data, and then uses the remaining data for validation. This process is repeated *N* times, each time moving one fold into the training data and another one out. Leave-one-out cross-validation, or jackknifing the data as it is sometimes called, refers to training a model with all training samples except one and then testing on the left out element. This process is repeated for every sample. With either method, the average error is reported.

A common extension of this is bootstrap evaluation (Hastie et al. 2001), which attempts to estimate the bias and variance of a classifier. In bootstrap evaluation, multiple random samples are drawn from the training data. For each sample, an equivalently sized training set is used by drawing with replacement (the same sample can be drawn multiple times). A classifier is constructed for each random sample, and then the mean is taken as with the previous techniques. An advantage to this method is that one can estimate the bias and variance from the error rate statistics.

If the goal is to detect a certain event such as a specific call, specific individual, or calls from a specific species, it is common to use some type of threshold to make "accept" or "reject" decisions. Varying this threshold will result in changes to the false-positive and missed-call rates. It is common to plot how these two types of error vary with respect to threshold, and receiver operating characteristic (ROC) curves are a common type of such a plot (Swets 1964). One must have a set of scores for the calls of interest, and a separate set of scores for other calls that could be mistakenly detected. Figure 15.10 shows a sample ROC curve; the horizontal axis shows the false positive (or false alarm) rate and the vertical axis shows the true positive rate. Each point on the curve shows the two types of error rate for a specific threshold, although the threshold values cannot be inferred from the plot. Given the data used to create the ROC curve, it possible to determine the threshold for a desired operating point such as 90 % true positives and 8 % false positives.

An alternative to the ROC is the detection error tradeoff (DET) curve proposed by Martin et al. (1997). The DET curve has two major differences from the ROC curve. Rather than plotting on the vertical axis the rate at which calls are detected, the rate of missed calls is plotted. Martin et al. argue that plotting error on both axes is more appropriate, and as a result of this better performance occurs on the lower left of the plot as opposed to the upper left. A second and more fundamental change is to assume that the score distributions for the calls of interest and other calls are each normally distributed. The axes are scaled to the deviates of normal distributions fitted to each type of score. When score distributions are normal, this will result in a straight line as opposed to a curve, but more importantly, the DET curve makes it easier to see the differences between classifier systems. Figure 15.11

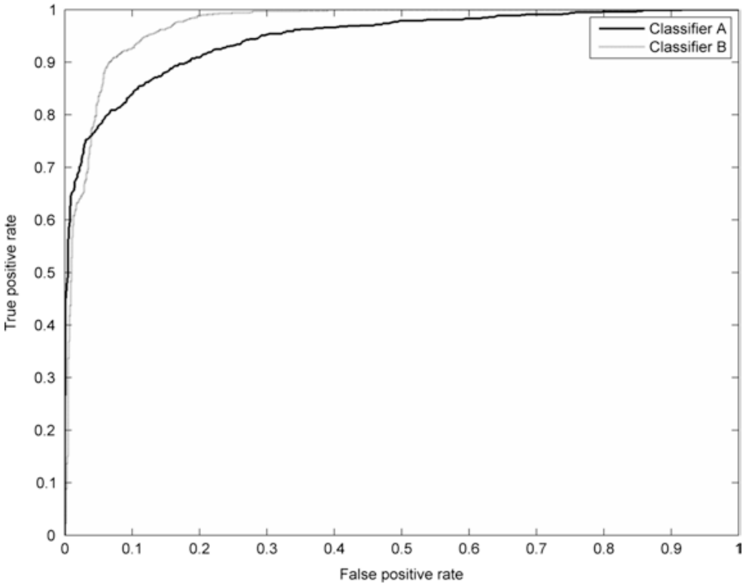


Fig. 15.10 An example of a receiver operating curve (ROC). The ROC shows the tradeoff in detection performance between correct detections and false positives as the decision threshold varies. Performance is better when the curve is closer to the *top left* of the plot. The performance of two hypothetical classifiers, where Classifier B outperforms Classifier A for most threshold values, is shown. See also Fig. 15.11

reports results for the same hypothetical classifiers shown in Fig. 15.10, but provides better separation between the curves, making it easier to compare systems. The National Institute of Standards and Technology provides software for producing DET plots in both Matlab and gnuplot (NIST 2010).

Two other performance measures widely used for evaluating detectors are precision and recall (Table 15.1). *Precision* is the fraction of all detections that are correct (true) detections. *Recall* is the fraction of all true instances that are successfully detected; it is equal to one minus the false-negative rate.

When considering any of the aforementioned techniques for acoustic data, one should be very aware that it is easier to recognize calls collected from similar environments than calls whose environments differ. As an example, one would expect better performance when the bathymetry and sea state are similar. Changes in environment can have serious impact on the feature set, and one may find that a classifier has learned a specific environment rather than species or call. This problem is not unique to bioacoustics, and has its parallels in both speech processing (Huang et al. 2001) and music identification (Downie 2008). This is illustrated in Fig. 15.12, which shows the data of Fig. 15.7 comparing the first two cepstral features of Pacific white-sided dolphin and Risso's dolphin echolocation clicks with the addition of data from a second sighting of Risso's dolphins. In spite of compensating for differences

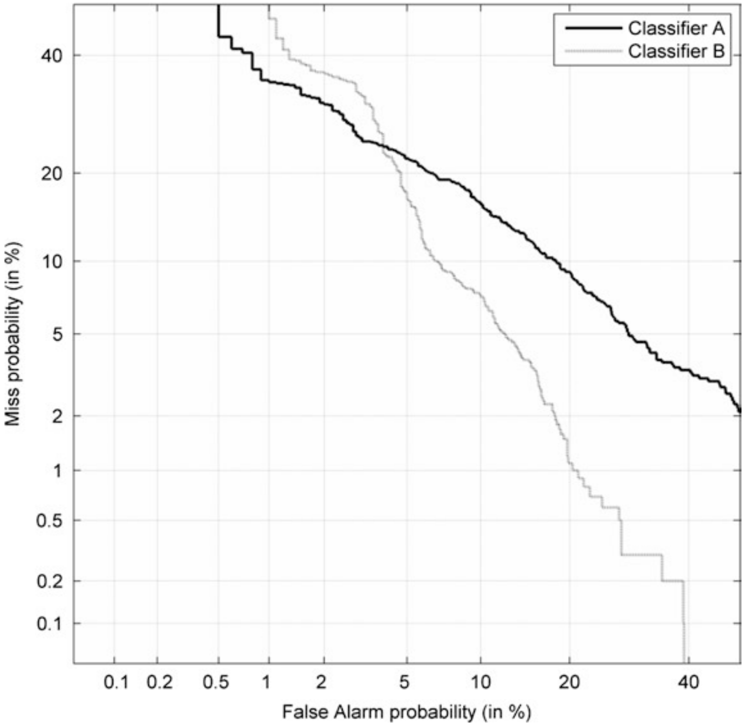


Fig. 15.11 The detection error tradeoff (DET) curve. DET curves assume that scores are distributed normally and plot normal deviates. This plot summarizes performance data for the same hypothetical classifiers shown Fig. 15.10, but highlights differences between the two classifiers

between collection systems by subtraction of the transfer function from the spectra, the distribution of the second sighting of Risso's dolphins has shifted.

As a consequence, the authors recommend that regardless of the evaluation method, all data from the same sighting should be either entirely in the training data or entirely in the test data. Splitting similar data across the train/test boundary is quite likely to improve results for the dataset being tested, but is unlikely to give one a good estimate of field performance (i.e., it will have poor generalization).

15.5 Localization

Passive acoustic localization refers to the use of acoustic signals to estimate the position of vocalizing marine life. Localization methods are useful for monitoring efforts as well as in studies of behavior, distribution, abundance, and acoustics. Various methods have been developed for different applications according to the number and configuration of hydrophones, the sound signal characteristics

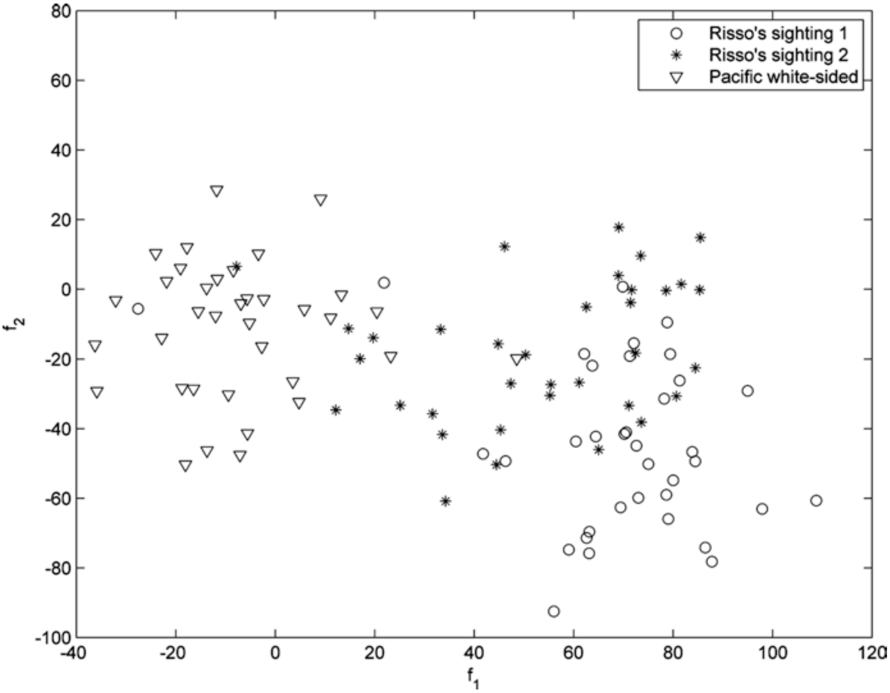


Fig. 15.12 Comparison of effects from different field collection situations. The first two cepstral features for the same dataset shown in Figure are plotted along with features from a second sighting of Risso's dolphins. Note how the distribution of Risso's dolphin features from the second sighting is less well separated from the Pacific white-sided dolphin. Shifts in features between collection situations are common and can arise from multiple sources (see text). The authors do not recommend splitting data from the same sighting when selecting training and test partitions

(duration, bandwidth, directivity, and so on), the operational requirements (such as required accuracy and precision of position estimates and computational efficiency), and the acoustic environment through which the signal propagates.

Most passive acoustic localization methods rely on travel times between the source and receivers. Unfortunately, the time at which an animal makes a call is unknown so it is not possible to measure travel time directly. Instead, most methods use the difference in arrival times between two or more receivers, since these times are independent of the time at which a call is generated. Such methods usually require a system with two or more hydrophones, called a hydrophone array. Since locations are calculated from arrival times, hydrophones must be synchronized and their positions known (often a nontrivial matter). Array processing falls into two broad categories depending on hydrophone spacing and distances over which animals are to be localized, either a compact or a widely spaced array.

This section describes localization methods descriptively; for details on related equations and calculations, the reader is referred to the references listed (which is by no means a comprehensive list). A useful overview of some localization methods, complete with equations, derivations, and Matlab™ code, is given in Zimmer (2011).

15.5.1 Compact Hydrophone Arrays

If the separation of the hydrophones is small compared to the distance of the sound source from the array, the incident sound can be approximated as a plane wave. In this case, beamforming is used to estimate the angle to the source (Johnson and Dudgeon 1993). In the simplest version, called time-domain beamforming, the arrival delay at each hydrophone is calculated for each possible arrival angle. The inverse of these delays is applied to each hydrophone signal and the resulting signals are summed. When the array is "steered" at the correct angle (by choosing the angle of the source), the delayed signals from all hydrophones coincide to give one loud combined signal; at other angles, the signals from the source interfere instead of coinciding, which results in a weaker signal. More hydrophones result in higher array gain (better signal-to-noise ratio for signals in the steered direction) and higher degrees of directionality.

A common configuration for beamforming is a linear array of hydrophones (Leaper et al. 1992; Sayigh et al. 1993; Miller and Tyack 1998). Only the angle of the source relative to array axis is obtained, which results in a cone of source position ambiguity—a 3D rotation about the axis of a line defined by the angle (Fig. 15.13). In many situations two-dimensional solutions are adequate, and the ambiguity cone is reduced to a curve (given by the intersection of the cone with a plane). This results in a left/right ambiguity for a horizontal array. Situations in which 2D solutions are adequate include when the water depth is small compared to the distance involved or when animals vocalize at predictable depths, such as near the surface. Position ambiguities

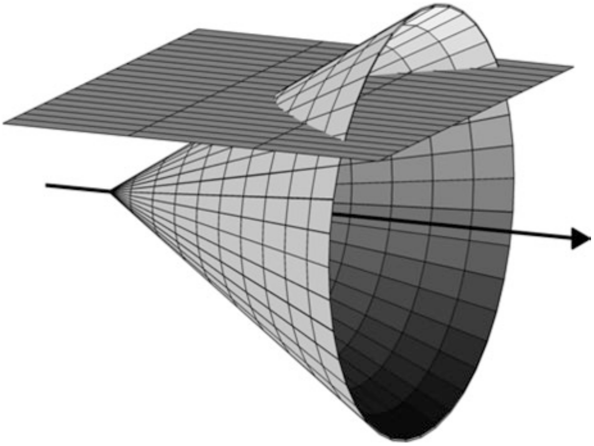


Fig. 15.13 Source position ambiguity cone for a horizontal linear array. Ambiguity can be reduced to a curve if the source depth is known by intersection with a plane corresponding to the source depth. The elements of the array lie along the horizontal axis represented by the *arrow*

can also be reduced by using more than one array (e.g., Watkins et al. 2000), provided that the spacing between arrays is wide enough to give sufficient bearing differences. Another approach uses time-motion analysis of the changes in estimated source angles as the array is towed (Leaper et al. 1992; Barlow and Taylor 2005). This method requires that vessel speed be much greater than the speed of the vocalizing animal, that the animal vocalize continuously for several minutes, and that individuals vocalizing simultaneously can be distinguished. In some cases, additional information can also be used to resolve ambiguities (for example, see multipath processing below).

Compact arrays can be built in many different configurations. For example, Clark (1980) used a compact 3-element planar array to estimate the unambiguous bearing to southern right whale calls. Compact planar arrays have also been successfully used for echolocation research (e.g., Rasmussen et al. 2002; Au et al. 2004). Planar arrays remove the bearing ambiguity of linear arrays; the ambiguity surface is the intersection of two cones, one along each axis of the array. However, without further information one cannot resolve which side of the plane a source is on. Three-dimensional arrays can resolve this array plane ambiguity (Wiggins et al. 2012; Zimmer 2013), and are becoming increasingly popular for this reason.

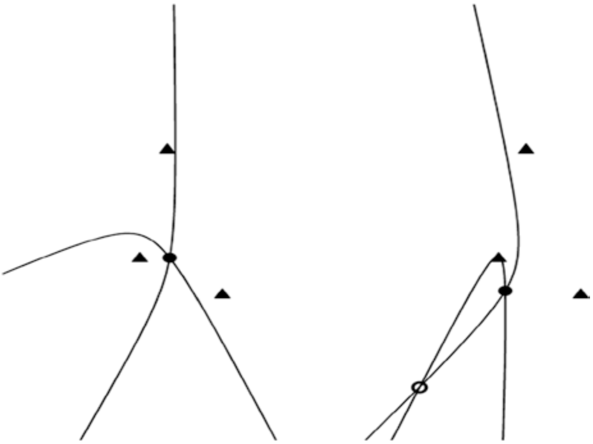
Optimally for continuous wave signals (that is, for long duration signals of single frequency and constant amplitude), hydrophone spacing must be less than half a wavelength and the largest dimension of the array, called the aperture, must be at least several wavelengths. For signals that are not continuous wave (e.g., impulsive or frequency-modulated calls), which is the case many marine mammal vocalizations, wider receiver spacing can often be used. In these cases, the receiver spacing should be close enough (usually within tens of meters) to ensure signal coherence across the receivers and beampatterns for the array should be calculated so performance is clearly understood (as shown for example in Zimmer 2011). In these cases it is often possible, and more computationally efficient, to use time-difference-of-arrival methods (see Sect. 15.5.2) with calculations simplified by the plane wave assumption.

15.5.2 Widely Spaced Hydrophone Arrays

Different methods are used when the source-receiver spacing is less than the spacing of the hydrophones, in which case the plane wave assumption is violated. The signal reaches two spatially separated receivers at different times because of different propagation path lengths from the source to the receivers. The difference in arrival time is called the time difference of arrival, or TDOA. TDOA methods are generally most accurate for sources near the center of the array, with decreasing accuracy as a source moves away from the array.

For two known receiver positions and a given TDOA, the locus of possible source locations in three dimensions is a hyperboloid. A third receiver provides another TDOA measurement, which defines a second hyperboloid (the third hydrophone actually adds two TDOAs but only one new TDOA is unique). A curve of possible source locations is defined by the intersection of these two hyperboloids. A fourth receiver defines a third hyperboloid, which intersects the curve at one or two points,

Fig. 15.14 Unambiguous 2D localization is possible with 3 hydrophones (triangles) in one case (left) but not another (right). True/false sources are shown with filled/open circles.



depending on the receiver geometry and animal position. In general, a fifth receiver is required to localize in three dimensions without ambiguity (Tyrrell 1964; Spiesberger 2001). However, for a given receiver configuration, there are usually large spatial regions for which only four receivers are sufficient for 3D localization (Spiesberger 2001). In these regions, either the source/receiver geometry results in a single point of intersection, or physical constraints (e.g., the seafloor or land) eliminate one of the source position ambiguities. On the other hand, even five hydrophones can give infinitely many possible source locations in some degenerate configurations. As discussed for compact arrays, 2D solutions are often sufficient, in which case the hyperboloids are reduced to hyperbolas and only four hydrophones are required to locate the source (and three hydrophones suffice in some regions). Figure 15.14 shows a 2D case for which three hydrophones are sufficient for one whale position but not for another.

Assuming that sound speed is spatially homogeneous, the problem of finding the point of intersection of the hyperboloids (or the closest such point if intersection is imperfect) can be expressed as a system of linear equations. For a well-defined problem (not underdetermined/overdetermined by too few/many receivers), a closed form solution to this system gives the source location (e.g., Schmidt 1972; Watkins and Schevill 1971). For overdetermined systems, a least-squares approach can be used to give the best source position (Spiesberger and Fristrup 1990; Wahlberg et al. 2001); the extra hydrophones reduce the error in the position estimate.

15.5.3 Nonhomogeneous Sound Speed

Homogeneous sound speed assumptions can result in poor location estimates when long distances or shallow water are involved (Chapman 2004). For widely spaced arrays, nonhomogeneous sound speeds can be accounted for by using nonlinear methods that incorporate differences in sound speed to construct probability density functions for source position. One approach assumes a different sound speed between the source and each of the receivers and solves the resulting nonlinear system (Spiesberger and Wahlberg 2002). Another approach, sometimes referred to as model-based tracking, allows the sound speed to vary with depth but not X-Y position (Tiemann et al. 2004; Thode 2005). A source is localized by finding the source position that gives predicted arrival times that best match the measured arrival times. Arrival time predictions are made using a sound propagation model, which in turn uses information about the environment including sound speed profiles and bathymetry.

15.5.4 Establishing Time-of-Arrival Differences

For relatively loud and/or impulsive (sharply peaked) signals in small datasets (and with very patient observers), arrival time difference can be estimated manually through visual inspection of raw or filtered waveforms or spectrograms. Since this is an extremely tedious process that can be especially difficult in noisy conditions, automated techniques to establish TDOAs are commonly used.

One way to automatically establish TDOAs is to use a "detect and associate calls" approach. A detection method (see Sect. 15.4) is used to find all calls of interest on all hydrophones. The same call (or call sequence) is associated over all hydrophones—that is, each call is associated with its arrivals on the multiple hydrophones—and arrival times of associated calls establish TDOAs. Call association can be a simple task for a single animal or when calling rates are low, such that each call is easily identified across multiple hydrophones. For more difficult cases with multiple animals with high calling rates, one option is to create histograms of TDOAs from all possible associations over a time period long enough to contain multiple calls from an individual animal. Since TDOAs vary slowly with animal movement, correctly associated calls will result in histogram peaks (e.g., Morrissey et al. 2006). Another approach separates sources before association, for example by tracking slowly varying features such as amplitude, frequency, inter-call intervals, and so on (e.g., Clark 1989). This "detect and associate" method requires that calls are sufficiently stereotyped for detection but variable enough to distinguish individual calls.

A commonly used method used for establishing TDOAs that does not require stereotyped calls is known as cross-correlation (Helstrom 1975). The TDOA estimate is the time-lag that maximizes the cross-correlation between received signals from two hydrophones. Both filtered waveforms and spectrograms of the recorded signals have been used for cross-correlation (Altes 1980; Clark et al. 1986; Spiesberger and Fristrup 1990). The cross-correlator provides gain in the signal-to-noise ratio resulting in greater ranges over which an animal can be localized. Since cross-correlation assumes that the received signal at each hydrophone is the same except for a time lag, there are cases in which it does not perform well. Such cases include highly directional call components, complicated propagation conditions, or animals that move quickly while vocalizing so that Doppler effects become important. Multiple animals can be localized by picking multiple peaks in the

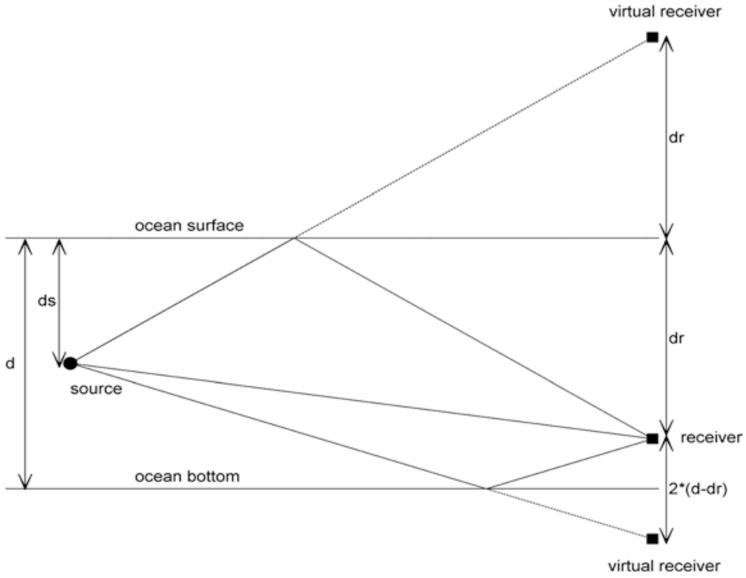


Fig. 15.15 Virtual receiver arrivals (*dotted lines*) corresponding to multipath arrivals (*solid lines*) for a flat bottom

cross-correlation function, although care is required to avoid confusion from multipath arrivals (Spiesberger 2000) and mis-association between animals (Baggenstoss 2011). Some multiple animal localization methods are designed to handle spurious/incorrect TDOAs to ease this requirement (Baggenstoss 2011; Nosal 2013).

15.5.5 Reflection Methods

In cases when multipath arrivals exist and can be separated, reflected paths can be used to help localize a sound source. To use reflections, the TDOA method can be modified by adding a virtual hydrophone that corresponds to each reflection (Fig. 15.15). The time delay between the direct-path arrival and the reflection arrival is proportional to the additional distance present in the reflection path compared to the direct path. Note that water-borne acoustic signals that reflect off the water's surface are inverted, so methods that use cross-correlation with surface reflections need to reverse the sign of the correlation result. Reflections can be used to resolve position ambiguities and improve the accuracy of estimated source positions (Wahlberg et al. 2001; Thode et al. 2002; Zimmer et al. 2003), or to localize a source with nonsynchronized hydrophones (Nosal and Frazer 2006). They can also be used to reduce the number of hydrophones needed for localization; using multipath arrivals, a single hydrophone can be used to estimate the range and depth of a calling animal (Cato 1998; Aubauer et al. 2000; Širović et al. 2007). If bathymetry varies with azimuth, an animal can be located in 3D using a single hydrophone if enough reflections can be extracted (Tiemann et al. 2007).

Reflection methods cannot be used for tonal long-duration signals in which various reflected arrivals cannot be separated. Even for short-duration signals it is not always possible to distinguish reflections. For example, very shallow vocalizations (or very shallow hydrophones) will result in direct and surface-reflected arrival times that are nearly identical. For highly directional vocalizations, such as clicks from many species of odontocetes, there might be insufficient off-axis energy to give a reflected arrival, or even a direct arrival when the reflection is strong.

15.5.6 Error Estimates

Just as important as finding source positions is understanding the errors in the estimates. Most errors in position estimate stem from uncertainty in receiver position, TDOA estimates, and sound speed. The most direct way to quantify error is to localize sources with known position. A controlled source can be used for this purpose (e.g., Watkins and Schevill 1972; Janik et al. 2000; Clark and Ellison 2000), or positions can be verified visually (Frankel et al. 1995; Noad and Cato 2007; Tiemann et al. 2006). This direct approach can be difficult to apply and generalize since resulting errors are specific to the call type, environment, and source/receiver geometry.

For practical reasons, error is usually estimated theoretically. Linear error propagation is a simple and powerful approach with much literature devoted to it (Taylor 1997; Watkins and Schevill 1971; Spiesberger and Fristrup 1990; Wahlberg et al. 2001). However, because source location is not a linear function of the model inputs, linear propagation methods can significantly overestimate error bounds and nonlinear methods can give more accurate error bounds (in addition to more accurate position estimates). For methods that construct probability density functions to localize a source, confidence regions can be defined by curves/surfaces of constant probability density (Clark and Ellison 2000; Spiesberger and Wahlberg 2002). Error can also be estimated through sensitivity studies that use a simulated source localized in perturbed environments (Tiemann et al. 2004; Thode 2005). Ideally this last approach would use a scheme such as Monte Carlo to repeat localizations for different perturbations of the environment to account for all uncertainties and their distributions.

In addition to practical issues, error is an important consideration when designing an array. Error maps can be used to optimize the hydrophone configuration and placement so that errors are minimized in the areas where sources are to be localized. For example, error analysis for a linear array reveals that angle estimates are most accurate for sources perpendicular to the array axis and the least accurate for sources in line with the array. An example of an error map for a widely spaced array is given in Fig. 15.16; sound sources within the array can be localized quite accurately, but accuracy decreases rapidly as a source moves away from the array.

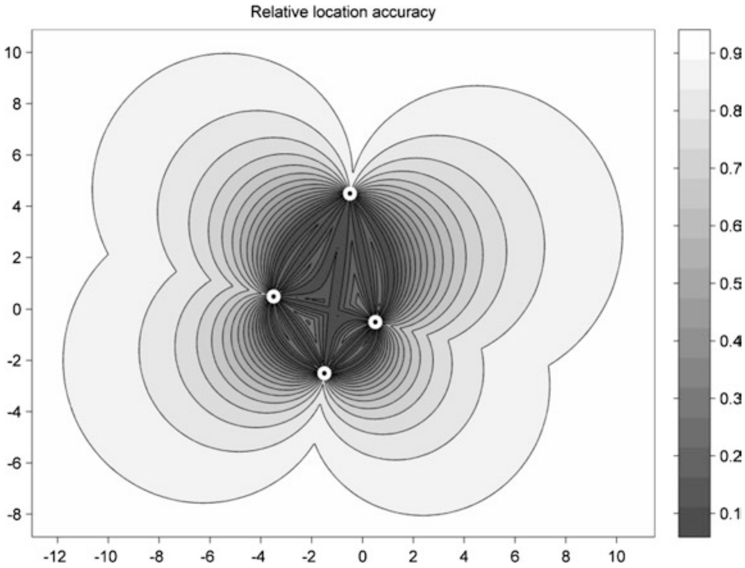


Fig. 15.16 Relative accuracy of locations calculated using the 2-D TDOA method for a given hydrophone configuration (*black dots* in *white circles*). Accuracy is good at the center of the array but falls away with distance, especially at the corners. Values represent summed location error per unit change in position

15.5.7 Other Approaches

Most localization methods rely on arrival times because they are quite robust and so can give accurate position estimates. However, other information about the position of a calling animal is available in a received signal and can be used to obtain or improve position estimates. For example, a directional hydrophone can provide a rough bearing estimate (Whitehead and Gordon 1986). If propagation effects are carefully accounted for and the call is not highly directional, differences in received levels on two or more omnidirectional sensors can be used to locate an animal (Cato 1998; Frank and Ferris 2011). Mode dispersion can also be used to estimate the range of low-frequency animal calls (McDonald and Moore 2002; Wiggins et al. 2004; Newhall et al. 2012). Matched-field processing (MFP) (Tolstoy 1993; Thode et al. 2000) finds the source position that predicts the acoustic field most similar to the measured field (note that the TDOA method can be thought of as MFP in which the only part of the field that is matched is arrival time).

Although simpler methods are often adequate, more sophisticated techniques and sensors can be used to improve localization capabilities. For example, more accurate position and error estimates can be obtained when localization is treated as a joint inversion problem for source position, receiver position, sound speed, and/or other relevant parameters (e.g., seafloor characteristics and sea state) (Tarantola 1987; Spiesberger and Fristrup 1990; Thode et al. 2000; Rideout et al. 2013).

Another promising development is in sensors (e.g., vector sensors or DIFAR buoys) that measure particle velocity in addition to pressure, allowing arrival direction to be estimated using a single sensor (McDonald 2004; Greene et al. 2004; Thode et al. 2010). Hopefully such powerful approaches will become more widely accessible as computing resources and sensors become less expensive and as efforts continue to develop improved localization methods.

15.6 Software

The availability and capability of software packages vary quickly over time, and consequently only a brief survey of available tools will be given. Discussion is divided into tools designed with bioacousticians in mind and those that are more general pattern recognition toolsets. Websites are just as transient if not more so, and if a URL given below does not function, a web search engine is likely to reveal the new site if the package still exists.

The three most common freely available software packages in marine mammal bioacoustics are Ishmael (Mellinger 2001), PAMGUARD (Gillespie et al. 2008), and XBAT (Figueroa and Robbins 2007). Available software packages for bioacoustic data analysis can be categorized into two groups: real-time and post-processing software packages. Real-time software tools allow users to record acoustic data and to run detection, classification, and localization algorithms in real time on incoming data streams. Ishmael and PAMGUARD fall into this category and are commonly used for ship-based passive acoustic surveys for which real-time capabilities are essential. XBAT is a post-processing software package developed to analyze field recordings in the lab and does not at this point provide recording capabilities.

Ishmael, PAMGUARD, and XBAT allow users to explore data in the time (waveform) and frequency (spectrogram) domains and are capable of detecting/classifying and localizing sounds of interest. All three programs are controlled via a graphical user interface which provides easy access to the main functions of the program. However, there are some significant differences in functionality of each software package elucidated in the following paragraphs which provide a brief introduction to the capabilities and goals of each package. For a more detailed description of the software packages and their modules, refer to the corresponding publications, websites, and user's manuals.

15.6.1 Ishmael (http://www.bioacoustics.us/ishmael.html)

The current version of Ishmael can be operated stand-alone on Windows™, Linux, and Macintosh platforms (the latter two under the WINE wrapper). Ishmael is capable of recording sounds and running detection and localization algorithms on incoming data streams. It handles a variety of data acquisition hardware and is well suited for real-time applications such as ship-based passive-acoustics surveys or analysis of long-term data sets from fixed hydrophones. Six detection and four localization methods are available in Ishmael. Detection methods are based on matched filtering, spectrogram correlation, energy summation, frequency contour detection (whistles and moans), the Teager–Kaiser energy operator (clicks), and characteristic repetition patterns of sounds. In recent versions of Ishmael, multiple views and multiple detectors may be run in parallel, allowing detection using multiple detection methods or parameters, or detection of multiple call types. Localization methods are based on phone-pair bearing estimation, hyperbolic position estimation, beamforming, and crossed bearings from two hydrophone pairs. Ishmael can also be operated in post-processing mode and batch run functionality allows a user to run detection algorithms over large data sets.

15.6.2 PAMGUARD (http://www.pamguard.org)

PAMGUARD is a Java™ based program which can be run on all major operating systems (Windows, Mac OS, and Linux). PAMGUARD was originally developed for ship-based passive-acoustics surveys, though it is also useful for post-processing data in files. A communications interface allows a user to access GPS data streams and to visualize ship tracks as well as locations of acoustic detections via a mapping component. PAMGUARD can interface to a wide variety of hardware to capture sound. It features five detection, one classification, and three localization methods. The available detection algorithms are based on matched filtering, spectrogram correlation, energy summation, frequency contour detection (whistles and moans), and the Teager–Kaiser energy operator (clicks); multiple instances of detectors can be run in parallel to try different detection methods and parameters, or to search for different call types. The built-in classifier can be used for real-time whistle classification. Available localization methods are phone-pair bearing estimation and hyperbolic position estimation. PAMGUARD is a modular program which can be extended by any Java™ programmer. Detailed information on how to do this can be found on the PAMGUARD website and in the user's manual.

15.6.3 XBAT (http://www.xbat.org)

XBAT (Figueroa and Robbins 2007) is a post-processing software package to analyze field recordings in the lab. In contrast to Ishmael and PAMGUARD, XBAT is not a stand-alone application: Matlab™ is necessary to be able to run the software. XBAT features an extensive input module which can handle a large selection of file formats (including compression codecs such as mp3, ogg-vorbis, and flac). The software can be configured to load many consecutive files as a file stream, which is useful to display long-term spectrograms and for visual exploration of acoustic data.

The main detection module of XBAT, based on spectrogram correlation combined with nearest-neighbor search, is easy to use. The user marks a sound of interest in the spectrogram and XBAT uses this template to search for similar sounds in the data set. The spectrogram correlation module can handle several templates at the same time, which allows a user to search for different sounds in parallel. Also templates for confounding sounds can be configured to reduce the number of false positive detections. Sounds of interest recorded on several channels can be localized by hyperbolic position estimation. XBAT is a modular software package which can be extended by any Matlab™ programmers. However this is not trivial, as there is very little documentation available on how to do this.

15.6.4 Additional Software Packages

A number of companies, institutions, and individuals offer commercially or freely available software packages designed for bioacoustic research or general scientific signal analyses. However the description of these software tools is beyond the scope of this chapter. For more information on additional software tools, please visit the "About Bioacoustics" page at http://tcabasa.org.

15.6.5 General Pattern Recognition Software

For general pattern recognition software, one can separate the types of available software into complete packages versus stand-alone libraries that offer one or more classifiers to be integrated. WEKA and the hidden Markov model toolkit (HTK) offer complete recognition systems. WEKA (Hall et al. 2009) is a graphically oriented system designed to provide an interface for classification and regression. It provides an interface for a wide variety of learning algorithms. In contrast, HTK (Young et al. 2006) was developed for speech processing and is widely used in that community. Unlike WEKA, the focus is entirely on functionality, and commands and errors can be cryptic. It implements hidden Markov models, Gaussian mixture models, and *k*-means clustering, and requires a large learning curve. Finally, the R language (R Development Core Team 2009) is an open-source language developed for statistical analysis which has a large number of classifiers as add-on packages.

Other systems provide libraries that can be linked to programming languages such as python™, Java™, and Matlab® and are candidates for practitioners with good programming skills. Examples include JBoost (a boosting library; http://jboost.sourceforge.net) and the Torch machine learning library (http://www.torch.ch and http://torch5.sourceforge.net).

15.7 Future Directions

It is the authors' opinion that the greatest gains to be made lie in the realm of feature extraction. Whether working with frequency contours or echolocation clicks, feature extraction is difficult. Most systems working with frequency contours do not attempt to account for the shape of the contour, with notable exceptions of the dynamic time warping, matched filter, and spectrogram correlation methods (Deecke and Janik 2006; Mellinger and Clark 2000). Instead, they examine statistics of the whistle such as frequency maxima and number of inflection points, which do not capture the shape. When asking researchers examining spectrograms why a specific call should be associated with a species, pod, or call type, many will reply with something along the lines of "it just *looks* that way." Features that capture this type of shape information as well as those that are capable of handling nonlinear phenomena are likely to yield advances, but an alternative and perhaps better approach is to invest more attention into how the animals are likely to *perceive* calls.

In the study of echolocation clicks, features such as zero crossings, peak values and energy band ratios, and characteristics of spectral shape such as cepstra or spectral ridge regression parameters, are all commonly used features, but they fail to account for axis variation and high frequency falloff as distance increases. While some of this can be compensated for by classifiers that learn the patterns that occur, features that are more invariant under these conditions have the potential to produce significant advances in the field. As with the discussion of frequency contours, taking inspiration from perception is also likely to be fruitful.

While improved feature extraction appears to be the most promising direction for reducing classification error, ensemble methods have been a fruitful area of research in pattern recognition and bear brief mention. The principal idea is to create multiple models for each class. Bagging (Hastie et al. 2001) attempts to reduce errors by taking N bootstrap samples (sampling with replacement the same number of vectors as in the training sample) and creating a classifier for each one. The output of these classifiers are fused to create a single decision. Boosting (Freund and Schapire 1999) uses multiple classifiers, each of which is rather weak in that by itself it might perform only slightly better than chance. Rather than taking bootstrap samples as bagging does, each training vector is assigned an initially equal weight, and a weak classifier is created. The weights are adjusted to emphasize training samples that were misclassified by the weak model, and a new classifier is created. This process is iterated, and Freund describes this process as a means of focusing on the difficult cases (Yoav Freund, pers. comm., 2010). The final decision is made based upon a weighted average of all of the classifiers. Another popular ensemble technique that has been used in marine mammal acoustics (e.g., Henderson et al. 2011; Risch et al. 2013) is random forests, where multiple decision trees are formed from bootstrapped datasets and multiple trees vote (Hastie et al. 2009).

Another major challenge for passive-acoustic monitoring systems is the analysis of very large datasets. Due to the rapid development of digital audio technology and the increasing capacity of memory devices, it has become easier than ever to produce very large long-term acoustic datasets that require considerable computation time to analyze. Parallel computing is a powerful tool to speed up the analysis of such large data sets. One approach to parallel computing uses multi-core processors (MCPs) within a single workstation. An easy way to make use of multi-core processors is to run several copies of an analysis program in parallel, with the operating systems automatically distributing the processes to all cores available. A more elegant way to benefit from a multi-core processor is to use software which can distribute computation tasks to all available cores, such as the parallel and distributed computing toolboxes for Matlab™ (Sharma and Martin 2009). A second approach to parallel computing is to use a graphics processing unit (GPU). A GPU, a collection of processors, typically handles computation for rendering computer graphics images. GPUs are powerful parallel computing devices, with hundreds or thousands of cores and many gigabytes of onboard memory. These can be used as general-purpose computers, or general purpose graphics processing units (GPGPUs). As with multi-core processors, the computations are distributed to all cores available; a Matlab toolbox for this is available. See Owens et al. (2007) for a more comprehensive description of GPGPUs.

Another approach is to use parallel computing on *clusters*—groups of computers linked to each other through a local area network (Thiruvathukal 2005). Setting up a parallel computing task on a cluster is more complex than execution on a single workstation. Data sets and a list of computation instructions are located on one or more servers within the local area network. The available processors repeatedly check the list of computation instructions for open jobs, download the respective data sets, conduct the analysis, and send the result back to the server(s). Since many data sets are transferred from server(s) to the processors, the throughput of the cluster may depend heavily on the bandwidth of the local area network. An example using a cluster to analyze bioacoustic data sets is given in Chap. 9 of this book.

A final cautionary word should be added about relying on parallel computing to achieve speed increases. Many times, the redesign of an inefficient algorithm can result in significant reductions in computing time. Most computer languages have profiling facilities that will let a user track how much time was spent in specific routines or even lines of code. Taking the time to determine where the "code bottlenecks" are and putting effort into redesign can offer significant improvements in performance that can either eliminate the need to invest time and capital in parallel architectures or at least provide even faster parallel implementations.

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