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Anthony Young

The Twenty-First Century Commercial Space Imperative

INTERNATIONAL SPACE UNIVERSITY

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Chapter 1
From Satellites to Spinoffs: A Brief History of Commercial Space Activity

In the early years of the twenty-first century, a series of unrelated events marked the tipping point in a new era of commercial space business, events that have formed a new commercial space imperative.

In June 2002, Elon Musk established Space Exploration Technologies—SpaceX, for short. He boldly announced he would pursue the construction of a new private launch vehicle to challenge the dominant Delta and Atlas rockets sending payloads to low Earth orbit.

On February 1, 2003, the space shuttle *Columbia* deorbited and began its reentry into Earth's atmosphere to its landing destination at Kennedy Space Center. The left wing leading edge of the shuttle had been damaged during ascent. Upon reentry, *Columbia* suffered structural failure and disintegration along with the loss of the entire crew. In January 2004, President George W. Bush announced the space shuttle would complete assembly of the International Space Station and then cease flight operations. The president also announced the Vision for Space Exploration that would employ new launch vehicles, new spacecraft and new human exploration goals. This set the stage for NASA to consider public-private partnerships to meet its mission needs (Fig. 1.1).

In June of that year, civilian test pilot Mike Melville flew the path-breaking SpaceShipOne to an altitude of 100 km above Earth into suborbital space. He experienced several minutes of weightlessness and then began a gentle aerodynamic reentry as the ship glided back to its departure point at the Mojave Airport. SpaceShipOne and its carrier aircraft WhiteKnightOne were the first privately funded and developed launch vehicles in history. Mike Melville became an astronaut that day.

These events and many others stemming from them indicated the United States in particular was now moving into a time of private space commerce and exploration. Many new businesses and smaller startups saw real possibilities in these developments, and this has been the basis of a new commercial space business economy—a new imperative.

Ever since the late 1950s, a well-defined commercial space launch market has existed in the United States. These private (non-governmental) launch service providers typically launched telecommunication satellites aboard Delta or Atlas rockets. Certain departments of the United States government, such as NASA, the

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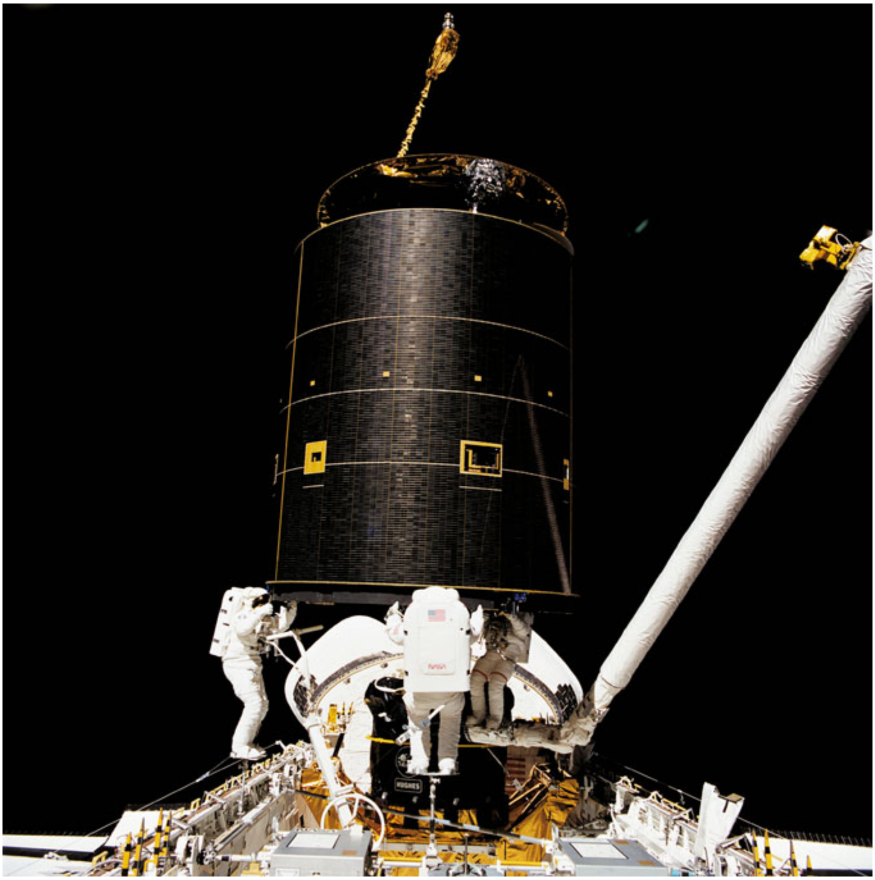

Fig. 1.1 NASA astronauts performed many commercial missions during the space shuttle era. Three astronauts are shown installing a replacement Orbus-21S motor on the Intelsat 603 satellite during mission STS-49 in March 1990 (image courtesy of NASA)

Department of Defense, the National Reconnaissance Office, and the National Oceanic and Atmospheric Administration also developed satellite payloads, which were launched to orbit using more powerful variants of the Delta and Atlas, and the Titan.

The Titan was phased out of service several years ago. The Atlas V, the latest version of the Atlas, launches predominantly government satellite payloads. The Delta II and more powerful Delta IV launch both commercial and government payloads. Both Delta and Atlas are manufactured and operated by the United Launch Alliance (ULA). These stalwarts of the launch industry are now supplemented with smaller and completely new rockets. There are now innovative air-launch services available for smaller payloads that need only to reach low-Earth orbit (Fig. 1.2).

Fig. 1.2 A United Launch Alliance Atlas V lifts off with its WorldView-3 satellite for DigitalGlobe Corporation on August 13, 2014 (image courtesy of United Launch Alliance)

Launch vehicles and services for commercial enterprises are designated private, but similar services for the U. S. government are considered public. Three prominent examples of pubic (meaning government) space programs are the Apollo program, the space shuttle program, and the International Space Station, all managed by NASA. Two examples of commercial space businesses are satellite cable television and the Global Positioning System (GPS) used in many vehicles today for travel directions.

NASA's Apollo program of manned missions to the Moon during the 1960s and early 1970s and military defense programs helped, in a broad sense, to push the technology of integrated circuits and other electronic components that contributed to the emergence of new commercial electronic products. This is a prime example of a public program resulting in private, commercial consumer products eventually being used by millions of people. The continuous re-design and improved electronics resulted in greater capabilities over a period of decades. This produced smaller, lighter and more powerful satellites and computer processing power that was instrumental in the emergence of a new commercial space business market (Fig. 1.3).

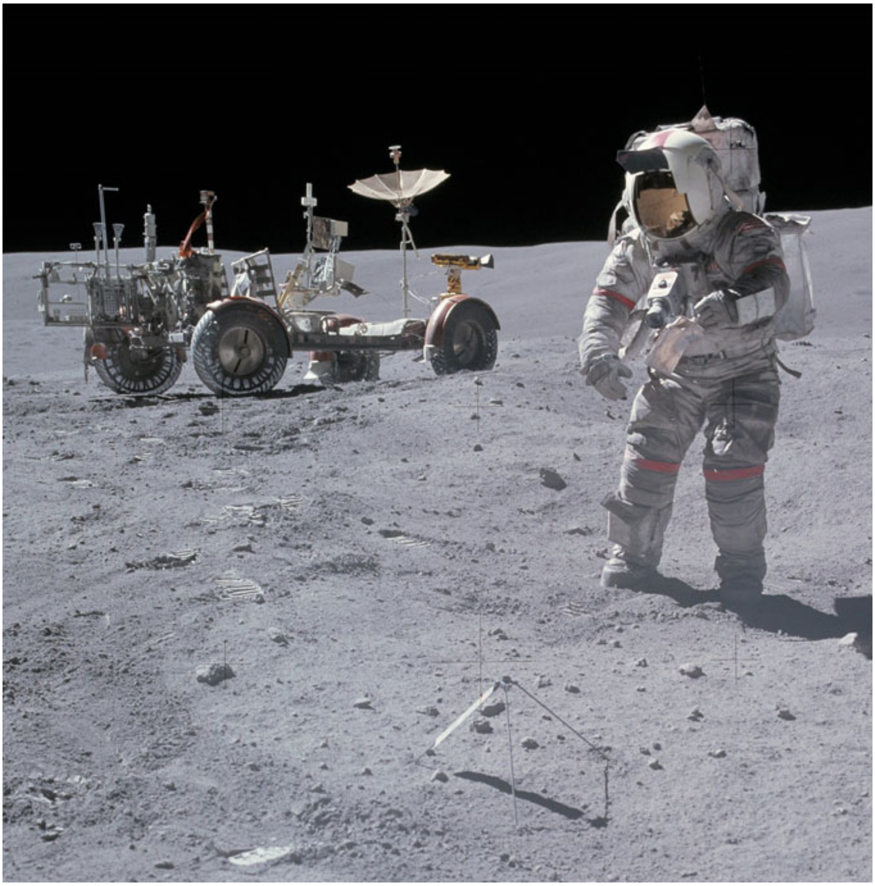

Fig. 1.3 The NASA Apollo program was an outstanding success through the support of many large and small commercial enterprises across the United States. Pictured is *Apollo 16* mission commander Capt. John Young at the Decartes region of the Moon in April 1972 (image courtesy of NASA)

Today, the telecommunications satellite industry has available an array of different vehicles to launch their commercial payloads. In the United States, there are several new launch vehicle and service providers, apart from ULA, with several launch vehicles that have significantly lowered the cost of getting commercial payloads to orbit. These are specifically covered in subsequent chapters.

Satellites: The First Commercial Space Industry

The first commercial satellite launched from the United States was Telstar, built by AT&T and launched on July 10, 1962. Once in orbit, it transmitted telephone calls, television broadcasts, and other communications. This was a watershed technological event that ushered in the "satellite era." Previously, telephone calls to Europe from the United States were accomplished by trans-Atlantic telephone cable on the ocean floor, and these would remain in operation for many years. However, a new industry grew to meet the demand of clear and secure intercontinental telephone communications using geosynchronous (GEO) orbiting satellites [1]. This is sometimes referred to as fixed-satellite service (FSS).

In 1964, the United States joined with more than a dozen other nations to establish an intergovernmental organization to coordinate the allocation of frequencies and other matters related to international telecommunications via satellites. This organization was INTELSAT. A decade and a half later, the International Maritime Organization formed INMARSAT to offer communications and emergency support services to commercial ships around the globe. INTELSAT and INMARSAT were ultimately privatized.

The U.S. Federal Communications Commission (FCC) issued the very first licenses to commercial satellite companies for U.S. telecommunications services. It was established that satellites could operate in low-Earth orbit of 160–2000 km, medium Earth orbit of 2000 to roughly 30,000 km, and geostationary orbit at roughly 36,000 km. This kind of orbit permits a satellite to orbit the Earth at a speed constant to the planet's rotation. The first satellite to achieve geostationary orbit was Syncom-3, funded by NASA and built by Hughes Space and Communications in August 1964. Geosynchronous satellites that orbit Earth are not necessarily geostationary but achieve the same location in space as viewed from Earth every 24-h period.

The American commercial satellite industry was slow to get started. The first commercial geostationary satellite was Westar I, ordered by Western Union from Hughes Space and Communications and launched aboard a NASA Delta rocket on April 13, 1974. Only nine commercial telecommunications satellites were launched and in service by 1980. As commercial markets began to grow along with manufacturing capability, so did the need for satellites. Arianespace entered the commercial launch services market for Europe in 1980 with its Ariane 1 rocket. (The first commercial communications satellite to be launched by the Ariane 1 was Spacenet 1, built by RCA; it was launched on May 22, 1984). The satellite TV industry emerged during this time with the rise of Home Box Office (HBO), the Turner Broadcasting System (TBS), and the Christian Broadcasting Network (CBN). With this came the arrival of home 'big dish' C-band satellite dishes and an unprecedented number of viewing channels.

By the early 1990s, the commercial satellites orbiting Earth were primarily for GEO telecommunications. More than 400 geosynchronous and geostationary satellites orbit Earth today. The four largest global GEO satellite operators are Eutelsat, Telesat, Intelsat and SES. Intelsat is by far the largest, having produced over $2.6 billion in revenue in 2013. The company has more than fifty geostationary satellites in orbit, and the entire globe can be reached by their broadcasts. SES has fifty-five satellites in orbit, and the company has an ongoing launch schedule to replace aging satellites. Annual earnings are roughly equal to Intelsat.

Eutelsat has thirty-seven orbiting satellites which are capable of covering two-thirds of the globe. Earnings are nearly $1.5 billion per year. Telesat, based in Canada, has fourteen satellites that beam mostly to North America. Annual revenue is $900 million.

Although many of these satellites operate in the delivery of voice, data, national and local news feeds, personal communications and entertainment broadcasting, they are also employed in emergency management communications. These are vital in disseminating information of pending disaster so that communities can take necessary precautions, including evacuation. In areas where severe weather or another natural disaster has occurred, damaging all ground communication, mobile receiving devices can be brought into the area, and emergency communications can be established. These can be mobile or transportable VSAT terminals as part of a vehicle or maritime vessel, or handheld terminals.

As pervasive and vital as satellite communications are today, they comprise only 4 % of the global telecommunications industry. According to the Satellite Industry Association in the United States, total global telecommunications revenues in 2012, the most recent year for which they were available, reached $5 trillion [1]. Of that, the satellite industry generated $195 billion worldwide. The industry has experienced consistent growth, year-to-year, averaging over 7 % per year. As of 2015, there were over 1000 operating satellites from low-Earth to geostationary. This number includes government communications and military surveillance satellites, a number that will increase dramatically by 2020 if the announced fleet of broadband internet satellites by various corporations are built and launched.

The consumer services within the commercial satellite segment are made up of three primary areas. The largest is satellite TV, which generates over $91 billion annually. A distant second is satellite radio, with nearly $4 billion, and satellite broadband communications at $2 billion. Within the satellite TV area, HDTV is a large growth sector. There are over 7000 HDTV channels today.

In years past, the United States dominated the market of satellites manufactured and launched, but this has been eroded by European countries, Russia and even China. In terms of revenue, 75 % of the U.S. satellites manufactured were for the government. In terms of percentage according to country, the United States generated 70 % of all revenues from the manufacture of satellites, with Europe at 17 %, China at 5 %, Russia at 3 %, Japan at 3 % and all other countries making up 2 %. Historically, these percentages have fluctuated from year to year.

There are several technology trends on some satellites today that will find increased implementation in the future. High throughput satellite (HTS) technology employs ultra-wide bandwidth transponders with spot-beam antennas and frequency re-use as well as dedicated gateway beams that are grouped to form multiple spot-beams. These spot beams are smaller than older fixed-satellite service (FSS). HTS work in conjunction with ground-based very small aperture terminals (VSATs) and have greatly increased telecommunications speeds and much broader bandwidth. Five to ten times the capacity of older conventional satellites is achieved. The first HTS Ku-band satellite was launched in 2006 [2, 3].

An existing example of this satellite technology is the Hughes EchoStar XVII, launched in July 2012 by an Ariane 5 rocket. This satellite sends 60 Ka-band spot-beams to North America with a data throughput in excess of 100 Gbps. EchoStar serves 2 million HughesNet subscribers for dedicated Internet service. Built by Space Systems/Loral for Hughes, the satellite measures 8.0 m in length and 3.1 m by 3.2 m, with a deployed power generation solar array measuring over 26 m. Among the largest of satellites, it weighed over 6000 kg at liftoff. It has a minimum operational life of 15 years. In December 2010, Eutelsat launched its HTS KA-SAT aboard a Russian Proton rocket from Baikonur. The satellite was built by EADS Astrium and carries 58 Ka-band transponders. Broadband Internet is beamed to Europe and portions of the Mediterranean.

Boeing Satellite Systems International received an order for four of its largest 702HP satellites from Inmarsat. These INMARSAT-5 satellites are of HTS configuration and are capable of carrying over 100 transponders. The INMARSAT-5 transmits high-speed voice and data Ka-band transmissions. The first of these satellites was launched in December 2013 and the second in February 2015 by Proton rockets.

The Boeing 702 series also feature new satellite electric propulsion technology. Although the 702HP employs both conventional liquid propulsion and electric propulsion for station-keeping, the 702SP (for small platform) is Boeing's first all-electric propulsion satellite. The ion engine accelerates electrically ionized xenon gas through its ion thruster to more than 60,000 mph, but the level of thrust is lower than that of conventional liquid propulsion systems. Consequently, it can take such a satellite from 3 to 6 months to achieve its final orbital location after separation from the launch vehicle upper stage. The advantage of electric propulsion is a significant reduction of mass—by as much as 50 %—and thus reduced cost for both the satellite and for launch cost [4].

Ion propulsion has been in research and development for decades. Engineers at NASA's Glenn Research Center in Ohio began research into ion propulsion shortly after the space agency's founding in 1958. In July1964, the first operational test of the Space Electric Rocket Test 1 (SERT 1) ion propulsion system completed 31 min of operation. Similar successful tests were conducted during the latter 1960s and the 1970s. NASA subsequently built and tested the Ion Auxiliary Propulsion System (IAPS) from 1974 to 1983. This technology reached practical operation on the Deep

Space 1 spacecraft with a 30-cm ion propulsion system. The spacecraft operated from 1998 to 2001, traveling over 250 million kilometers with its IPS pushing the DS1 to 4500 m/s.

In April 2003, Boeing's Electronic Dynamic Devices division in Torrance, California, was awarded three contracts under NASA's In-Space Propulsion Technologies program. The three separate contracts included the Carbon-Based Ion Optics project, the NASA Evolutionary Xenon Thruster (NEXT) system, and the High Power Electric Propulsion project. All of these technology programs were delivered to NASA and employed in some of its deep space probes, but more importantly, the Boeing-developed technologies were employed on the company's own satellites [5].

Some of the earliest European research was conducted at the University of Giessen in Germany in the 1960s. Radio frequency ion production continued in Germany during the 1970s and 1980s at the Lampoldshausen Center. Finally, the first Radio-frequency Ion Thruster Assembly (RITA) aboard a European Space Agency (ESA) European Retrievable Carrier spacecraft was launched aboard the space shuttle Atlantis in 1992. The commercial product of this work today is the RIT-10 system as manufactured by EADS Astrium.

The above example of NASA research and development in ion thruster development resulting in more advanced commercial applications, as well as fulfilling additional NASA mission requirements, is indicative of the technology transfer the space agency has been involved in since its founding.

Commercial Spinoffs from NASA Research and Development

The congressional legislation that established NASA in 1958 did not have specific wording stating the agency should promote the commercial possibilities of its research and development. The space agency's original charter Policy and Purpose was not amended until 1984 to include the following: "(c) The Congress declares that the general welfare of the United States requires that the National Aeronautics and Space Administration (as established by title II of this Act) seek and encourage, to the maximum extent possible, the fullest commercial use of space" [6].

In 1962, NASA created the Technology Utilization Program and established TUP offices at each of its field centers around the United States. It further created industrial application centers. The agency began to put out a brief publication, titled Tech Briefs, to disseminate information of its available technologies for commercial applications. The annual Technology Utilization Program Report followed, first published in 1973 and distributed to congressional offices. By 1976, this publication became known as *Spinoff*. NASA found the annual document helpful to make the general public aware of the technology transfer to commercial products. It also helped to dispel criticism of the space agency, which some thought was unnecessary in light of more pressing needs—an argument that had been perpetuated since the Apollo program.

The technological demands of the manned lunar Apollo program the United States marshalled the collective intelligence across the fields of science, engineering, mathematics, industrial production and program management. The Manhattan Project was conducted in great secrecy as a program during World War II, but Apollo was conducted openly during peacetime against a different enemy. President John F. Kennedy made clear the need for national commitment if the Cold War was to be won by America against the Soviet Union.

For the hundreds of thousands of Americans who worked on the many projects in support of Apollo, it was the most challenging, rewarding and, for many, significant time of their lives. Many commercial byproducts came about as a result of the race to land astronauts on the Moon and prove the technical prowess of the United States and affirm to the world its superior form of government. Although Apollo was geopolitical in scope, it in fact had its most profound impact in uncovering the mysteries of the Moon and offered up an unbounded scientific return. Just as dramatic would be the influence this national effort would have in the quality of life for the present and future generations (Fig. 1.4).

The electronics that went into the Apollo capsule, Lunar Module, Saturn V instrument unit and related components had to be as efficient and lightweight as possible. The Apollo Guidance Computer pushed the development of advanced electronics to achieve this. The technological maturation of electronics and software as a result of project Apollo was one of the greatest benefits in eventual technology transfer that would have broad implications in commercial products of many different kinds. First-generation integrated circuits existed at the time Apollo was announced, but IC technology improved significantly as a result of this program and the demands of the U.S. Air Force Minuteman ICBM program.

"With Apollo, they needed to cut down on weight and power consumption," says Scott Hubbard at Stanford University. "Mass into space equals money. They want[ed] something very powerful and very light that doesn't take massive power. That was one of the driving requirements that led to the development of the integrated circuit, where you put all the components on a chip rather than having a board stuffed with individual transistors and other circuit components. There was a major shift in electronics and computing and at least half [the] credit goes to Apollo" [7].

NASA partnered contractually with hundreds of large, medium and small businesses in the development and production of needed hardware and software for the Apollo program. Other developments often became beneficial commercial products. The Apollo Extra Vehicular Activity (EVA) suits had a mesh-type undersuit that circulated coolant to maintain the astronaut's temperature. This development, along with fire-resistant fabrics also developed for NASA requirements, were adopted by commercial firms for use in firefighting suits, for racecar drivers, and other hostile-environment protective equipment. Metal-bonded polyurethane foam insulation developed for Apollo spacecraft found its way for application on the Alaska pipeline and other liquid transfer piping. Water

Fig. 1.4 Among the many commercial products that have resulted from NASA's space exploration efforts is the widespread production of memory-type foam used in mattresses and pillows (image courtesy of NASA)

purification filters developed during Apollo found commercial application in personal, single-source, residential and business water filtration systems.

Numerous commercial products also came to market from developments during the space shuttle program. NASA developed a lightweight flexible aerogel to insulate cryogenic systems on the orbiter spacecraft. Commercial refinement of this technology is now used to insulate new homes and replace existing fiberglass insulation with greater efficiency. Specialized infrared cameras NASA needed to observe the exhaust plumes of the shuttle main engines and solid rocket boosters were adapted by firefighting equipment manufacturers. NASA worked with industry partners to produce a specialized new foam cushioning material for shuttle astronauts on the flight seats that adapted to each astronaut and their flight suit. This memory foam is used in many commercial products today, most notably mattresses and pillows.

One of the many functions of the International Space Station is to be an orbiting laboratory for ongoing research and development of biomedical and pharmaceutical experiments that can best be successful in microgravity. The ISS assists in other R&D programs apart from these, and the ISS has become a center for commercial product development.

Over the last several decades, NASA and its field centers have developed hundreds of software programs that are often applicable to commercial business ventures. Today, many of these software programs can be licensed from NASA and are in use commercially today. The agency puts out an annual volume of software it has available for use in, among others:

- Materials and processing
- Propulsion
- Operations
- Structures
- Autonomous systems
- Aeronautics
- Electronics and electrical power
- Data servers processing and handling
- System testing
- Structures and mechanisms
- Environmental science
- Crew and life support
- Aerospace vehicle management
- Data and image processing [8].

The European Space Agency (ESA) shares the same goal to disseminate spinoff technologies from its space exploration efforts, but these are less well-known. NASA, for its part, works continuously to prove the widespread, commercial benefits that derive from its high-profile work, far more than perhaps any other U.S. department or agency. The space agency's Commercial Crew and Cargo Program (C3P) is a very visible aspect of its commercial partnerships with the aerospace industry. A lesser-known but important effort by NASA to meet its own research and development needs for its mission mandates and facilitate commercial spinoffs is its Innovative Partnerships Program (IPP). Another program, directed to small businesses, is the Small Business Innovation Research and Small Business Technology Transfer program. NASA signs contracts with businesses awarded these opportunities, and the agency and the company share costs in the development of the needed solution and helps the company in the transfer of the technology for commercial purposes.

Looking deeper, however, one finds that these outreach programs had congressional legislation behind them as well as NASA's own initiatives. This includes the Stevenson-Wydler Technology Innovation Act of 1980, the Small Business Innovation Development of 1982, the Federal Technology Transfer Act of 1986, the Omnibus Trade and Competitiveness Act of 1988, the Omnibus Trade and Competitiveness Act of 1988 and the American Technology Preeminence Act of 1991 [9].

There have been numerous research efforts to quantify the success of these technology transfers from NASA to the commercial sector. One published study specifically measured the economic impact to the companies that developed commercial spinoffs from NASA's life sciences programs. Fifteen companies were studied, and personnel were interviewed at each.

"This pilot study of 15 companies, using a very conservative measurement technique, found a large return to companies that have successfully commercialized NASA life sciences spin-off products," the published findings stated. "Value-added benefits totaled over $1.5 billion, and a NASA R&D total investment in these 15 technologies of $64 million was found to stimulate an additional $200 million in private R&D" [10].

These economic impact studies, some independently conducted and others contracted by NASA, go back to 1971. Most of the studies employ standardized economic computer models that have been employed in other macroeconomic surveys. However, these are an imperfect means of quantifying the economic benefits of NASA expenditures with companies receiving contract awards. In most cases, the companies themselves generally do not make available the economic data involved in adopting technologies that lead to successful commercial products the company was permitted to market. In a number of these studies, the researchers simply went through back issues of *Spinoff* and arranged interviews with company personnel profiled in each story.

In 2011, NASA decided to establish a formal means of determining the most promising categories that would have measurable benefits and collect the economic data during the time the research was being conducted. The categories included (a) jobs created, (b) increased revenue, (c) productivity and efficiency improvements, (d) lives saved, or not lost, and (d) lives improved [11]. The conclusion in the report stated that those companies' contacts were able to provide quantifiable economic data within these categories. This has helped, but there may never be a perfect system of capturing all the economic information in order to provide a comprehensive resource of annual benefits across the entire spectrum of activity by contracted companies to NASA.

NASA is not the only agency or group that is motivated to promote the benefits of space exploration and its practical and commercial realization to the general population. The International Space Exploration Coordination Group (ISECG) is comprised of more than a dozen space agencies from around the world. The member space agencies are the ASI (Italy), CNES (France), CNSA (China), CSA (Canada), CSIRO (Australia), DLR (Germany), ESA (Europe), ISRO, (India), JAXA (Japan), KARI (Republic of Korea), NASA (United States), NSAU (Ukraine), Roscosmos (Russia), and UKSA (United Kingdom). In a 2013 report, the ISECG stated:

"Space exploration will continue to be an essential driver for opening up new domains in science and technology, triggering other sectors to partner with the space sector for joint research and development. This will return immediate benefits back to Earth in areas such as materials, power generation and energy storage, recycling and waste management, advanced robotics, health and medicine, transportation, engineering, computing and software" [12].

During the latter half of the twentieth century, space activity was conducted primarily by national governments for the achievement of national goals. In the twenty-first century, the commercial space imperative has emerged as the most promising means of achieving significant goals in the shortest amount of time and most benefit to humankind.

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Chapter 2
Game Changer: SpaceX

The commercial space business is often one of faceless corporate management. This is not the case with SpaceX and its founder Elon Musk. The boldness of Musk's corporate vision, travails of launch vehicle development and the ultimate success of the Falcon rockets and Dragon capsules harkens back to the days of aircraft builders William Boeing, Donald Douglas, and Jack Northrop in the 20th century.

Born and raised in South Africa, Musk was the first in his family to move to Canada and then to the United States to attend college there. He received bachelor degrees in physics from the University of Pennsylvania and economics from the Wharton School. Musk abandoned his plans to get his doctorate in physics at Stamford University to pursue business opportunities in corporate e-commerce. In rapid succession he founded or was involved with Zip2, then X.com, which later became PayPal. Musk sold his share in PayPal in 2002 to eBay for $165 million.

The seeds of Space Exploration Technologies—SpaceX—were planted in 2001. Musk started informally discussing commercial space ventures with fellow entrepreneur Adeo Ressi. The subject of Mars came up and the possibility of mounting a mission of some kind to the Red Planet. Musk checked the NASA website to see what Mars missions the space agency was conducting and was shocked to learn there were none—at the time. NASA had successfully sent its Martian spacecraft Pathfinder with its small robotic rover Sojourner to Mars in 1997. In 2001, NASA's Jet Propulsion Laboratory was engineering identical exploratory robotic rovers, identified as Mars Exploration Rovers (MERs). These would be launched to Mars in 2003 (Fig. 2.1).

Musk believed the United States should have pressed on to the exploration of Mars after the Apollo lunar program ended in 1972. Upon learning there was no high profile mission to Mars, Musk decided he should be the one to get things started. Initially the plan was to obtain a launch vehicle of sufficient power to send a living payload to land safely on the surface of Mars. Musk and Ressi called their new company Life to Mars. In June of 2001, Musk contacted Jim Cantrell, president of Strategic Space Development. Cantrell's company specialized in business growth strategies for aerospace firms. He agreed to take on Musk as a client and help find the launch vehicle and services the startup would need.

Musk, Ressi and Cantrell dismissed the Atlas with Centaur upper stage as too expensive. They chose instead to go to Arianespace. The cost of using this agency's

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Fig. 2.1 SpaceX Falcon 9 boosters being assembled at the company's headquarters in Hawthorne, California (image courtesy of SpaceX, used with permission)

launch vehicle and services were also prohibitive. They then turned to the Russians, with which Cantrell had experience. Several trips to Russia proved demoralizing, as negotiations broke down. The team returned to the United States with no rocket or prospects of one. On the flight back, Musk made a decision. He told Cantrell he believed they should build the rocket themselves. Cantrell had given Musk every book on rocket propulsion and guidance he had, and Musk had been working out a possible design in his head for weeks.

At this point, Musk's vision expanded dramatically. He spoke to Ressi about starting a company that would challenge the status quo in launch vehicles and services. Ressi became alarmed, foreseeing the formidable challenges of such a venture and the staggering attendant costs. He brought in experts to speak with Musk of the daunting engineering involved, notwithstanding the small size of what his prospective company might be. Design and development could run into the hundreds of millions of dollars.

Musk dismissed all the arguments and objections. Musk fully embraced Dr. Wernher von Braun's most famous quote, "I have learned to use the word impossible with the greatest of caution." He planned to move ahead with his ambitious goals of dramatically lowering the cost of getting payloads to orbit, while holding on to the dream of Martian exploration and even colonization. It should be stated here that Musk had no experience in large-scale manufacturing at all; he had only been involved in online commerce. Ressi did not join Musk in his vision, and chose instead to pursue venture capitalism.

The first order of business was to find an experienced propulsion engineer who could design an engine from a clean sheet of paper. Musk believed there could be design and manufacturing efficiencies realized in this area as well. Instead of trying to recruit from Rocketdyne or Aerojet, he went looking for a maverick like himself. Musk found him in a propulsion engineer by the name of Tom Mueller. A fourteen-year veteran of TRW, Mueller was working on advanced propulsion concepts of his own design, manufacture and testing when Musk tracked him down. Impressed with Mueller's working knowledge, proven success in rocket engine design and the successful manufacture of actual flight hardware, Musk hired him away from TRW.

Musk founded Space Exploration Technologies, Inc., in June 2002 in Hawthorne, California. A large commercial building formerly used by Boeing was acquired adjacent to the Hawthorne Municipal Airport as the company's headquarters. Musk was ready to commit $100 million of his personal wealth to get SpaceX into the launch services industry. He became his own chief engineer and headhunter to recruit the talent and experience he needed for SpaceX. He lured Dr. Hans Konigsmann away from Microcosm, Inc., in El Segundo, California, to act as vice president of Guidance, Navigation and Control.

He next hired Gwynne Shotwell. She held degrees in mechanical engineering and applied mathematics. Shotwell had worked ten years at Aerospace Corporation in El Segundo, California, with responsibility in space systems engineering and technology, and in project management. She left in 1998 to work at Microcosm, Inc., as manager of the Space Systems Division with the added duties of corporate business development [1]. Through Dr. Konigsmann Musk met Shotwell and hired her to be vice president of business development.

"You could characterize all the early leaders at SpaceX as being very knowledgeable about the industry but wanting to change things dramatically and get the industry moving at a much faster pace," Shotwell recalled in an interview [2].

The Falcon 1

Musk wanted to develop a two-stage rocket with the capability of launching 1400 lbs. (635 kg) to low Earth orbit. It would be called the Falcon 1. Mueller worked on the design of the Merlin first-stage single engine; this was a turbo-pump-fed engine using liquid oxygen (LOX) and RP-1 kerosene as propellants. The smaller second-stage engine would be of a pressure-fed LOX/RP-1 design and was given the name Kestrel [3]. Musk handpicked the remainder of his team who would be responsible for rocket structure, software, manufacturing, and testing.

Through her previous contacts she had established with the U. S. Air Force, Shotwell succeeded in securing a Defense Advanced Research Projects Agency (DARPA) contract for two Falcon 1 launches. DARPA was interested in developing lower cost and reliable launch capability for small payloads [4].

SpaceX spent the remainder of 2002 and all of 2003 and 2004 in the design and development of the Falcon 1. The completed design measured 22.3 m in length and 1.7 m in diameter. Originally the first launch was scheduled to take place from Launch Complex 3W at Vandenberg Air Force Base. Due to concerns of this unproved launch vehicle and the proximity to the Titan launch complex, SpaceX was forced to move the launch to the small island of Omelek in the Kwajalein Atoll in the Marshall Islands. In June 2005, SpaceX shipped the launch equipment to Omelek, followed by the Falcon 1 the following month.

In November of that year the first launch attempt was made. Due to failures of the launch vehicle structure or systems over several launch attempts, SpaceX did not launch its first Falcon 1 until March 24, 2006. At roughly thirty seconds into the flight, the engine shut down abruptly due to a fuel leak fire, and the rocket and its payload were lost.

It would be a year before the second launch of a Falcon 1 took place, on March 21, 2007. This launch was more successful, completing first-stage burn, stage separation and ignition of the second stage's Kestrel engine. The payload fairing separated from the second stage precisely on time. However, the Kestrel engine shut down before the payload reached the required orbit. On August 3, 2008, the third launch of the Falcon 1 took place. During staging, the booster collided with the Kestrel engine, and this mission also failed. Musk and his team were discouraged, but they nevertheless felt confident that success with the Falcon 1 was near.

The fourth launch of the Falcon 1 was in fact less than two months away. The U. S. Air Force provided a C-17 transport for the first and second stage, payload and fairing and the launch team to Kwajalein. On Omelek Island the Falcon 1 was prepared and sitting on the pad for a September 28, 2008, launch. There were no delays of any kind, and at 4:15 PDT the Falcon 1, with its 165-kg mass simulator payload lifted off. Booster cutoff, staging and second stage ignition performed nominally. The second stage placed the payload in the desired orbit. There was also a test of the Kestrel to restart with a burn of several seconds to modify the orbit perigee. The final, near circular orbit was 621.55 km by 643.21 km. This mission became the first privately developed liquid propellant rocket to achieve Earth orbit. All mission milestones were achieved [5].

The last mission on the Falcon 1 launch manifest was for orbiting an Earth observation imaging satellite for the Malaysian government. This was successfully launched and deployed in its correct orbit on July 14, 2009. Although all mission objectives were achieved, this flight of the Falcon 1 was its last. SpaceX had, in fact, been at work on a larger and much more powerful launch vehicle. Although SpaceX had plans for a follow-on rocket, the Falcon 1e, it was never built. The company had, in fact, decided to quietly cease production of the Falcon 1 and not pursue any more customers for it [6].

The Falcon 9

In December of 2003, Musk displayed a Falcon 1in front of the National Air and Space Museum, even though the first flight was several years away. At a reception within the museum he informed congressional staffers, members of the FAA and other government entities the progress SpaceX had made since its founding. Later, he also announced a new rocket under development: Falcon 5. This was significantly larger with the booster powered by five Merlin engines. It would be capable of lifting 4200 kg to low-Earth orbit, or 1250 kg to geostationary orbit. In addition, it would have engine-out capability not seen since the Saturn V. The price tag for a Falcon 5 was targeted at $12 million. This rocket was designed to compete for payloads with the Boeing Delta 2 rocket [7] (Fig. 2.2).

Sometime during 2004, Musk changed his mind regarding the Falcon 5, opting for an even larger and more powerful rocket. Called the Falcon 9, the first stage of this rocket was to be powered by nine Merlin engines. This may have come about as a result of talks with management at NASA and with members of the Air Force Evolved Expendable Launch Vehicle (EELV) program office. Musk announced the Falcon 9 in the fall of 2005 while still not having launched a single Falcon 1. There had been some difficulties in the early development of the Merlin engine. Musk and Muller had initially chosen an ablative engine chamber and exhaust nozzle instead of a regenerative cooling design in an effort to simplify the engine and increase reliability. SpaceX finally reverted to a regenerative cooling design. By November

Fig. 2.2 The upgraded Falcon 9 booster features longer propellant tanks and deployable landing legs to permit reusability of the booster (image courtesy of SpaceX, used with permission)

2005, the total workforce at SpaceX numbered 160 employees. There were 40 engineers working on propulsion, 30 working on avionics, 30 devoted to structures and 50 involved in manufacturing [8].

During early development of the Falcon 9, Musk also planned to develop a capsule to ride atop the rocket. Consequently, the Falcon 9 and the capsule, to be called Dragon, would be developed concurrently. Development of the capsule outpaced development of the rocket to the point that work on the capsule was temporarily curtailed. Musk wanted to secure contracts with NASA after the space agency's announcement of the Commercial Orbital Transportation Services (COTS) program in January 2006. NASA would eventually award contracts for the resupply of cargo (to the International Space Station under the Commercial Resupply Services (CRS) program. SpaceX responded to the January request for proposals (RFP) with its recommendation of the Falcon 9 and Dragon capsule to fulfill NASA's needs. In May of that year, awards were given to six aerospace firms. SpaceX won an impressive $278 million [9].

The Falcon 9 that took shape in the SpaceX Hawthorne, California, plant had a first and second stage fabricated from a lithium aluminum alloy with a diameter of 3.6 m. At the base of the first stage was the thrust frame with mounting locations and required plumbing for nine Merlin 1C engines, each having regenerative cooling. The second stage was powered by a single Merlin 1C engine. Between the first and second stage was a passive aluminum and carbon fiber composite interstage. The Falcon 9 was designed to accept either a 5-m payload fairing or the Dragon capsule. With the Dragon capsule the launch vehicle had an overall length of 47 m. It would have a thrust at sea level of 3.8 MN, or 854,000 lbs. It would be capable of launching up to 9800 kg to the orbit of the ISS [10] (Fig. 2.3).

SpaceX acquired 300 acres of property in McGregor, Texas, to build test facilities for the first and second stages of the Falcon 9. The deactivated Launch Complex 40 the U.S. Air Force used for its Titan III and IV launches was designated the launch complex for the Falcon 9 in November of 2007. Existing Titan launch structures were demolished and removed in 2008 and the launch pad reconfigured for launch of the new rocket. For the first time in its history, Launch Complex 40 would now be a commercial launch complex.

On March 8, 2008, a test was conducted of the first stage with three Merlin engines running. In a manner similar to the staged development Dr. Wernher von Braun and his Saturn I and V managers employed, SpaceX employed methodical but rapid development testing. The first full duration 177-second test firing with nine Merlin engines on the first stage took place on November 22, 2008, at the McGregor site. Second-stage tests were also conducted.

During 2008, SpaceX started a new recruiting drive in anticipation of ramping up the Falcon 9 and Dragon capsule development and manufacture. Dolly Singh was brought into be head of talent acquisition. She personally recruited new company officers, program managers and senior engineers. Musk had told her the kind of people he was looking for to work at SpaceX.

"We searched for candidates with a proven history of building and breaking things…candidates who had been tinkering with hardware systems for years," she

Fig. 2.3 This SpaceX Dragon cargo resupply capsule was photographed from the International Space Station prior to docking on April 20, 2014 (image courtesy of SpaceX, used with permission)

said in an interview. “Building some of the world’s most remarkable machines is not for everyone; it requires just the right level of neurosis. If you didn’t have a history of enjoying the high pressure situations and daunting technical challenges, you would be unlikely to fit in. I knew the people who filled my open positions would be put to the test every day and would be asked to meet heretofore impossible targets. We looked for people with a history of defeating the odds, who had made careers of overcoming obstacles” [11] (Fig. 2.4).

In December 2008 SpaceX won a coveted Cargo Resupply Services (CRS) contract from NASA totaling $1.6 billion for twelve missions to the ISS [12]. This was a very strong vote of confidence from NASA after only one successful launch of the Falcon 1 and the first launch of the Falcon 9 two years into the future. Orbital Sciences Corporation was the other winner of a CRS contract and would use its Antares rocket and Cygnus capsule for its missions to the ISS.

The Dragon Capsule

Integral to the development to the Falcon 9 was the design and development of the cargo and eventual crew capsule, which SpaceX named Dragon. This would be the first new capsule design in the United States since the Apollo era. The last flight of

Fig. 2.4 Falcon 9 lifts off on February 11, 2015, with NASA's Deep Space Climate Observatory (DSCOVR) satellite (image courtesy of SpaceX, used with permission)

the Apollo capsule was the during the Apollo-Soyuz mission; the Apollo capsule returned to Earth with its American crew on July 24, 1975. The Dragon capsule was designed as a blunt cone design as opposed to the Apollo capsule, which was more conical in shape. From the outset, SpaceX designed the Dragon capsule to be human rated several years before the company would have to have its spacecraft meet NASA's stringent standards to accept astronauts, as stipulated in the Commercial Crew Program.

The complete Dragon spacecraft is comprised of the main pressurized section made primarily from machined, formed and welded high-strength aluminum alloy. Integrated below the pressurized section is the unpressurized service section, which contains the eighteen Draco thrusters, their propellant tanks and requisite plumbing and controls. These thrusters are oriented at several different angles and locations relative to the centerline of the capsule. They permit complete movement of the capsule once in orbit, and are used to deorbit the capsule for return to Earth. The heat shield is a SpaceX refinement of NASA's Phenolic-Impregnated Carbon Ablator (PICA-X) developed in four years at far less cost than the space agency had budgeted for. At the base of the capsule is the unpressured trunk capable of carrying additional cargo and deployable small satellites. On opposite sides of the trunk are stowed solar panels to provide power to the capsule; these are protected by covers that are ejected once the spacecraft is in orbit. The capsule also has a nosecone to protect the forward section with the hatch and the passive common berthing mechanism. Dragon is equipped with autonomous rendezvous and docking electronics for mating to the ISS [13].

Dragon was designed to transport up to 6000 kg to low Earth orbit and is capable of returning 2500 kg from the ISS. The cargo version of the capsule is fitted with three descent parachutes. It is retrieved after its ocean landing, and delivered to the Port of Los Angeles. Capsules returned to Earth from cargo missions can be refurbished and configured as free-flying DragonLab™ capsules for microgravity research and other technology demonstration missions.

Ushering in a New Era

The first Falcon 9 with a 5-m payload fairing was erected at Space Launch Complex 40 in January 2009 to undergo months of vehicle checkout and tests of SLC-40. The goal was to launch the rocket by the end of the year, but construction and flight qualification testing of the Dragon capsule pushed the maiden flight into 2010. The Dragon Spacecraft Qualification Unit would not have the reentry heat shield, thrusters or recovery system. Other systems of the spacecraft would be tested during flight and orbit. The Falcon 9 and Dragon would be monitored for performance milestones throughout the mission.

SpaceX scheduled the inaugural flight for June 4, 2010. It stated that the mission success would be measured by the percentage of mission milestones that were achieved, but cautionary statements were included in press materials. The tone of the statements made by SpaceX was a lack of confidence that the company would have a totally successful mission. The memories of the first three failed launches of the Falcon 1 were still fresh in everyone's minds. Mission control of the flight was not in Houston, Texas, or Kennedy Space Center, but in the SpaceX headquarters in Hawthorne, California.

After several launch delays, the Falcon 9 finally lifted off at 2:45 PM. All nine Merlin engines operated perfectly with main engine cut off at 2:54 after launch. The stages separated and seconds later the single Merlin Vacuum engine fired. It performed nominally until second engine cut off at 9:38 into the mission. The first privately designed and manufactured multistage launch vehicle and its payload reached its 155-mile high orbit within one percent of the designate perigee and apogee [14]. Musk and his SpaceX employees were jubilant, and NASA was relieved. Prospective commercial customers of satellite payloads also took notice. SpaceX, in fact, already had customers lined up on the Falcon 9 launch manifest.

The next launch of the Falcon 9 with complete Dragon spacecraft occurred on December 8, 2010. This was the first demonstration flight by SpaceX under

NASA's Commercial Orbital Transportation Services (COTS) contract. In addition, two cubesats for the National Reconnaissance Office would be deployed in orbit. This flight was a complete test of the Falcon 9 and Dragon capsule to perform orbital maneuvers and to deploy the satellites. The launch and orbit of the capsule was a success. After nearly two orbits, the Draco thrusters fired to slow the spacecraft and initiate reentry. The heat shield performed as designed, the three parachutes deployed and the capsule landed in the Gulf of Mexico.

The third launch of the Falcon 9 and Dragon capsule occurred almost eighteen months later. The initial mission was to have the capsule rendezvous with the ISS but only perform a fly-by in order to test numerous critical mission goals, including communication between the ISS and capsule, docking radar tests and other mission milestones. The follow-on mission to this would have the Dragon dock with the ISS, and its crew would transfer cargo from the capsule. In July of 2011, the possibility of combining the two missions was discussed if all the milestones of the first mission were accomplished. NASA agreed to this in December, and SpaceX modified the mission manifest to accomplish this.

On May 22, 2012, the Falcon 9 lifted off and had a nominal ascent to orbit. All initial milestones were achieved by day two in orbit. NASA gave SpaceX approval to initiate orbit adjustment burns to get the capsule within several kilometers of the ISS. On the third day of the mission, SpaceX controllers started the rendezvous maneuvers. The capsule orbited around the ISS in further tests of its control thrusters and communications with ground and crew on the ISS. On the fourth day of the mission, with all COTS-2 mission requirements achieved. NASA Mission Control in Houston approved the docking of Dragon with the ISS. In a series of precise movements by the capsule, slowly it was brought to within proximity of the Canadarm-2 less than 10 m from the ISS and then stopped. Expedition 31 ISS crew member, U.S. astronaut Don Petit, captured the capsule. Petit, with another crew member assisting, moved the capsule to the common berthing mechanism (CBM) of the Harmony module. The capsule docked and was secured to the CBM. This was the first time a privately manufactured spacecraft docked with the International Space Station [15].

The success of this mission, as well as the success of the capsule's return to Earth with return cargo, bode well for the CRS missions NASA contracted with SpaceX. These resupply missions would be shared with Orbital Sciences Corporation.

Dragon v2 Crew Capsule

SpaceX built on the knowledge gleaned from the cargo configuration of the Dragon to design the crewed version known as Dragon v2. Visually it is a completely new spacecraft, while employing both proven technology from Dragon and many new systems throughout. SpaceX chose a pusher-type propulsion design for capsule emergency crew escape from the Falcon 9 booster. New engines have been developed to achieve this, and given the name SuperDraco. The engine uses storable non-cryogenic hypergolic propellants. The SuperDraco has a thrust of 73,000 N (16,400 lbs.). The engine is grouped in redundant pairs on four sides of the capsule.

Dragon v2 has been designed to accept up to seven passengers or crew members, or a combination of four crew members and cargo for missions to the ISS. The capsule is designed for autonomous docking to the ISS, with manual override of capsule control if it is ever needed. SpaceX has also partnered with Bigelow Aerospace for access to the Bigelow Commercial Space Station in Earth orbit. The full seven-seat capacity of the Dragon 2 will be used for these missions. The SuperDraco propulsion system was originally conceived to be employed for the entire return to Earth. SpaceX has modified the capsule return profile so that the capsule will reenter the atmosphere, descend via three parachutes and initially land at a designated ocean landing site, much as the Dragon cargo capsule has done. The goal for Dragon v2 is to have the SuperDraco thrusters initiate deorbit and partial reentry whereupon three parachutes will be deployed. The capsule will descend to a specified altitude, and the SuperDraco thrusters will again be fired to allow a soft landing on deployed landing legs at one of various chosen landing sites. This will permit reusability of the capsule, which is not achievable with a water landing.

On September 16, 2014, NASA awarded two Commercial Crew Transportation Capability (CCtCap) contracts. The awards were given to Boeing Space Systems, which won $4.6 billion, and SpaceX, which was awarded $2.6 billion [16]. The award will permit SpaceX to proceed with full development of the Dragon v2. The CCtCap phase entails building flight test articles and proving all systems are safe for crew transportation to and from the ISS. Once this is achieved SpaceX (and Boeing) will receive contracts from NASA for crew transportation services to the space station. The crew capsules to be built by Boeing and SpaceX will allow the United States to once again launch NASA crews from Kennedy Space Center, or Cape Canaveral Air Force Station, eliminating dependence on the Russian space agency to do so. Those capsules will also permit the possibility of launching other commercial passengers to the ISS or other low-Earth orbit destinations.

Falcon Heavy

For over a quarter of a century, the space shuttle was America's heavy lift launch and crew transportation system. The maximum payload capability of the shuttle was 24,000 kg to low-Earth orbit. It was used for a variety of NASA, military and commercial payloads. It also carried the majority of the modules and structures for the International Space Station. With the retirement of the shuttle, the United States could only rely on the ULA Delta IV Heavy, capable of launching just over 22,500 kg to LEO [17]. Currently, this vehicle is launched from Cape Canaveral Air Force Station, Florida, and Vandenberg AFB in California.

Fig. 2.5 A Falcon Heavy launching from Launch Complex 39-A at Kennedy Space Center (image courtesy of SpaceX, used with permission)

The Falcon Heavy employs three of the upgraded Falcon 9 v1.1 boosters. The v1.1 booster is longer, carries more propellant, and features more powerful Merlin 1D engines. The cluster of nine 1D engines in each booster produces 5880 kN (1,323,000 lbs.) of thrust. The Falcon Heavy will have a liftoff thrust of 17,615 kN. The second stage is powered by a single Merlin 1D engine designed for vacuum operation (Fig. 2.5).

The Falcon Heavy is capable of lofting 53,000 kg (nearly 117,000 lbs.) to low-Earth orbit, making it by far the most powerful rocket in the world. The v1.1 configuration has booster return and powered descent soft-landing capability for reusability, which will further lower launch costs. The Falcon Heavy will employ complete reusability of these boosters.

Early in the Falcon Heavy's development, SpaceX determined a significant enough potential market for there to be more than one launch complex for it. The first launch site selected was Vandenberg AFB, at Space Launch Complex (SLC) 4. This was in anticipation of winning contracts from the U. S. Air Force and other government agencies for particularly large satellite payloads that exceed the capabilities of the Falcon 9. The company then contracted with NASA to lease the former Apollo and space shuttle Launch Complex 39A at Kennedy Space Center. This is the launch complex for the Falcon Heavy on the East Coast. Most of the existing service structures have been removed, and the pad area reconfigured to support the Falcon Heavy. SpaceX has issued statements that the company anticipates also launching crewed missions from 39A.

Finally, SpaceX will have a third Falcon Heavy launch complex in Brownsville, Texas, near the state's coastline and adjacent to the Mexican border. The test stand for the Falcon Heavy is at the company's test complex in McGregor, Texas.

SpaceX has an extraordinary business plan and aggressive pricing structure that has and will continue to shake up the launch services industry. It has responded to the need of the United States to provide commercial crew capabilities to the International Space Station. Its range of launch vehicles built at surprisingly low cost relative to its competitors is radically bringing down the cost of getting payloads to low-Earth orbit. The company has made no secret of its other ambitious plans to send payloads and even its crewed Dragon capsules further into space. The company's vision and launch capability may make other missions long considered out of the question now within the realm of possibility.

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Chapter 3
New Rockets and New Launch Methods

Among the principal drivers in the expansion of commercial space business is the trend of lower prices for the launch vehicle, and therefore of cost per pound to orbit. Suborbital flight services are also starting to emerge and there are new launch vehicles for these missions as well. The aggressive efforts by SpaceX to lower the cost of payloads to low-Earth orbit have had a profound effect in America and Europe in making existing rockets and launch services more affordable; there is also a new drive for cheaper alternative launch services and new rockets employing the latest propulsion and manufacturing technologies in an effort to drive costs down.

The ULA Atlas V and Delta IV

During the 1950s, the United States initiated a large Intercontinental Ballistic Missile (ICBM) development program. This involved two ICBM programs: the Atlas and the Titan. The U.S. government also began an Intermediate Range Ballistic Missile (IRBM) program named Thor. During this time, the United States did not have a significant space exploration program. That all ended with the launch of the small satellite, Sputnik, by the U.S.S.R. on October 4, 1957. Although the Soviet satellite was simply for communication, sending only a benign beeping signal to identify its presence in orbit, Sputnik spoke volumes about Russia's technological prowess. The United States had been working on a satellite program since 1954; the country was still working on the program to launch an orbiting satellite when news of Sputnik flashed around the world. This event effectively launched the Cold War Space Race.

The Atlas and the Titan underwent development flights until being deployed at various missile sites around the United States. These missiles formed the foundation of America's nuclear deterrent forces. As weapon systems, the Atlas and Titan were too vital and expensive to use in any civilian capacity—at least initially. Dr. Wernher von Braun and his team of engineers in Huntsville, Alabama quickly developed the Juno 1 rocket based on the Redstone missile. The Jet Propulsion Laboratory designed and built the Explorer 1 satellite. On February 1, 1958, the satellite was successfully launched into low Earth orbit.

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In July 1958, Congress enacted legislation establishing the National Aeronautics and Space Administration (NASA). The new space agency absorbed the existing National Advisory Committee on Aeronautics (NACA) and called on some of the best and brightest engineers, managers, scientists and academics willing to join the agency. In the early years, the NASA mission seemed driven by the accomplishments of the Soviet Union. The American efforts in space, both unmanned and manned, would have unforeseen and profound benefits in the commercial (private) sector. It would also have a dramatic effect upon consumers for hundreds of new products and medical research. These were identified as spinoffs.

The Soviet Union achieved another milestone when it launched its first cosmonaut, Yuri Gagarin, into orbit aboard the Vostok 1 capsule on April 12, 1961. However, the U.S. Air Force had been at work developing a manned program it called Man In Space Soonest. This program was transferred to NASA and became known as Project Mercury. On May 5, Alan Shepard became America's first astronaut of the Mercury manned program, on a suborbital flight launched atop a Redstone rocket.

On May 25, 1961, President John F. Kennedy addressed the U.S. Congress in one of the most significant speeches of his presidency. Kennedy boldly announced the United States' audacious goal of "…landing a man on the Moon and returning him safely to the Earth." Apart from the Mercury program, there would be the follow-on Gemini program involving two astronauts in a larger capsule, and finally the Apollo program with three astronauts per capsule. The Apollo program would require even larger rockets, identified as Saturn I and Saturn V. These were purpose-built launch vehicles.

To achieve the ability to orbit a manned capsule, the United States had to have a more powerful rocket. The Atlas ICBM was capable of launching such a payload, and the builder of the Atlas, Convair in San Diego, California, performed the modifications to the missile to achieve this. On February 20, 1962, a modified Atlas D with astronaut John Glen aboard his Mercury capsule became the first American sent into orbit around the Earth. There were three subsequent Mercury Atlas launches in the Mercury manned program. The Atlas performed perfectly in every case (Fig. 3.1).

For the larger and heavier Gemini capsule, NASA employed a modified Titan missile. The Gemini-Titan missions comprised of increasingly complex tasks, included rendezvous with another launch vehicle and Gemini capsule, and spacewalks. Between 1962 and 1966 there were twelve Gemini missions. All twelve missions were successful.

The Atlas ICBM was decommissioned in 1965 and the majority of these missiles were refurbished for use in launching military satellites, weather satellites and other commercial payloads. The Titan II ICBM, built by the Glenn L. Martin Company, remained in defensive service in the United States until 1987. Deactivated Titan missiles were refurbished for use as space launch vehicles for government and commercial payloads for many years. The Thor IRBM was deployed in England from 1959 to 1961. The Thor was modified with various upper stages for deploying

Fig. 3.1 The United Launch Alliance (ULA) Atlas V bears little resemblance to the first generation Atlas of half a century ago. It will be superseded by ULA's Next Generation Launch System (image courtesy of United Launch Alliance, used with permission)

payloads into Earth orbit. The Thor-Delta variant evolved to the fully commercial Delta launch vehicle.

The Atlas became the workhorse launch vehicle for government and commercial payloads for the remainder of the 20th century. The cryogenic Centaur upper stage, using Liquid Oxygen (LOx) and Liquid Hydrogen (LH2) for propellants, was specifically developed for this Atlas. The Centaur, fitted with two RL-10 engines, had the capability of launching probes to Mars and the outer planets. The Delta also became a very capable medium weight payload launch vehicle and likewise remained a reliable rocket for public and private payloads.

The Atlas underwent a redesign in the late 1990s. For the Atlas III, Lockheed Martin Space Systems (LM had purchased General Dynamics) switched from the decades-old thin-wall pressurized stainless steel skin for the booster and incorporated a rigid booster similar to the Titan. In addition, GD incorporated the Russian-built RD-180 engine from the Atlas IIAR offering 860,000 lbs. of thrust at liftoff. The combined changes in the launch vehicle reduced the number of parts by more than 15,000. Its first launch in May 2000 was a success [1].

The rocket underwent a further and final evolution with the Atlas V. This vehicle was designed to meet the requirements of the U.S. Air Force Evolved Expendable Launch Vehicle (EELV) program. The Atlas V would also meet the needs of the commercial satellite market, as well as payloads for NASA. Its first launch from the redesigned Launch Complex 41 at Cape Canaveral took place on August 21, 2002 launching a Eutelsat satellite into orbit [2]. The Atlas V continued to serve government and commercial launch needs into the 2010s.

The Delta rocket was first launched in May 1960, but this launch failed. The Delta went on to have a superb launch success record. It was lower cost with a lower payload capability versus the Atlas. The Delta launched hundreds of government and commercial payload over the next four decades. It was built by McDonnell Douglas until this venerable aerospace firm was purchased by Boeing, after which it was a Boeing product. The Delta has gone through numerous iterations over the years. It was superseded by the all-new Delta IV which was designed to primarily launch government payloads. The Atlas V and Delta IV are products of the United Launch Alliance (ULA), a corporate alliance comprised of Boeing and Lockheed Martin.

Orbital Sciences

Orbital Sciences was founded in 1982 in Vienna, Virginia. The company grew rapidly providing upper stage, satellite and suborbital launch vehicle products and services to government and commercial markets. Among the first of its unique launch vehicles was Pegasus, an air-launched small payload rocket capable of sending satellites into low-Earth orbit. The Pegasus was a new launch vehicle design; it was not a converted rocket or cruise missile (Fig. 3.2).

The Pegasus was designed to be taken aloft underneath a conventional commercial jet. Test flights used a B-52 bomber for this purpose while a Lockheed L1011 was modified to carry the weight and provide the connecting interface with the Pegasus. Appropriately, Pegasus was winged in order to provide necessary lift during initial phases of launch. The rocket has three solid propellant stages. The

Fig. 3.2 Orbital Sciences employs a modified L-1011 commercial jet to carry its air-launched Pegasus rocket to send commercial and government payloads to low-Earth orbit (image courtesy of NASA/JPL, used with permission)

diameter is 1.3 m and has a length of roughly 17 m. It has a payload capacity of 450 kg (1000 lbs.) The Lockheed L1011 takes the Pegasus to approximately 40,000 ft, the Pegasus is released and the booster engine ignited. The third stage takes the satellite payload to the desired low-Earth orbit. The Pegasus has launched over 80 satellites since it started operation in 1990 [3].

Orbital Sciences' newest launch vehicle is the Antares. This rocket was privately developed under a special 2008 NASA Commercial Orbital Transportation Services (COTS) agreement in anticipation of a cargo resupply contract to the International Space Station. The Antares had to meet NASA-mandated program milestones and performance and reliability standards in order to be considered for a cargo resupply contract. The first stage uses RP-1 and LOx propellants for the two Aerojet Rocketdyne engines. The second stage is powered by an ATK CASTOR solid propellant motor. The optional third stage uses a liquid bi-propellant engine. The Antares is 9.9 m in length, 3.9 m in diameter, and the payload fairing can enclose a satellite payload weighing up to 5000 kg [4].

While developing the Antares rocket, Orbital Sciences also developed the Cygnus cargo capsule which would carry the needed supplies to the ISS. The capsule is a large spacecraft, measuring nearly 3.0 m in diameter. It is made up of a pressurized cargo module and a service module containing avionics, propulsion and power systems. It has dual deployable solar arrays. Cygnus is designed to dock to the ISS Node 2 CBM [5] (Fig. 3.3).

On April 21, 2013, the inaugural launch of the Antares rocket with Cygnus Mass Simulator took place from the Mid-Atlantic Regional Spaceport on Wallops Island, Virginia. The rocket performed perfectly and placed the dummy payload in the correct orbit and inclination. The success of this mission was followed by a Cargo Resupply Services contract from NASA for eight resupply missions. The first of these resupply missions with Cygnus spacecraft took place on September 18, 2013.

Stratolaunch Systems and Swiss Space Systems

The expansion in the field of commercial launch vehicles and services has been driven significantly by entrepreneurs in the high-tech industries. These include Paul Allen, co-founder of Microsoft, Elon Musk of PayPal and other successful software ventures, and Steve Bezos, who founded Amazon.com. The efforts of Steve Bezos and his company Blue Origin will be covered in the chapter on personal spaceflight.

Paul Allen along with Bill Gates founded Microsoft in 1975. The spectacular success of this tech startup at the start of the personal computer age has been well documented. Both men became immensely wealthy over the subsequent decades. Paul Allen resigned from the Microsoft board of directors in 2000 to pursue his own ventures. Allen went into partnership with radical aircraft designer Burt Rutan early in 2001 to fund the development of SpaceShipOne and its carrier aircraft WhiteKnightOne [6]. SpaceShipOne reached the edge of space at 100 km on its

Fig. 3.3 The Antares launch vehicle is a reconfigured Soviet launcher with an Orbital ATK solid rocket second stage and optional third stage. The Antares with its Cygnus cargo module is part of NASA's cargo resupply mission to the International Space Station (image courtesy of NASA, used with permission)

suborbital mission on June 21, 2004. Its final flight, reaching 112 km, was on October 4, 2004.

SpaceShipOne (and subsequent similar spacecraft) were designed for personal spaceflight; it was an endeavor by Rutan to kick start the next big thing in human spaceflight. Allen wanted to pursue a much larger air launch vehicle (ALV) for use in commercial payloads. He founded Stratolaunch Systems in 2011, headquartered in Huntsville, Alabama. Although Rutan retired from his company Scaled Composites in March of 2012 he did work with Allen on the design of the Stratolaunch carrier aircraft and its payload rocket.

The size of the Stratolauncher is immense. It has a wingspan greater than the length of a football field—385 ft (117 m). It is designed to be powered by six General Electric jet engines from the Boeing 747–400. The vast assembly hanger was completed in 2013 at the Mojave Air and Space Port in California. The company has partnered with Orbital Sciences for the design of the payload rocket that will be carried aloft, given the name Pegasus II. ATK, the manufacturer of solid rocket motors for the space shuttle and Titan rockets, will provide the first- and second-stage solid rocket motors for Pegasus II. This rocket has a heavy lift payload capability of 13,500 lbs. (6120 kg) to low Earth orbit [7].

In September 2014, Sierra Nevada Corporation announced an integrated system for human spaceflight coupled to the Pegasus II launch vehicle for Stratolaunch Systems. This crewed or uncrewed spacecraft is a scaled-down version of its Dream Chaser lifting body spacecraft, which lost the NASA CCtCap award to Boeing and SpaceX. This smaller spacecraft is designed for suborbital point to point missions. [8] When completed and operational the Statolaunch vehicle will the largest and most payload-capable air launch vehicle in the world.

Another entry in the new launch vehicle market comes from Swiss Space Systems (S3). The company is headquartered in Payerne, Switzerland, southwest of Berne. It was founded in 2012 to create and operate an airborne launch system for small satellite payloads of up to 250 kg. Unlike Stratolaunch Systems, S3 intends to use existing commercial aircraft, and design and build a small reusable shuttle-like spaceplane. The carrier aircraft will be an Airbus A300. The spaceplane is based on proven design engineering from the European Hermes space vehicle and NASA's research vehicle, the X-38. This aerospace consortium includes Dassault Aviation, Thales Alenia Space, JSC Kuznetsov and RKK Energia.

The mission profile follows the A300 leaving any commercial airport runway and climbing to 10,000 m. The spaceplane will be released, climb aerodynamically for a brief period, and then fire its engine. The spaceplane with its payload climbs to about 80 km, opens its payload doors, the satellite with its upper-stage propulsion will then elevate and the stage engine will fire. This phase will take the satellite to its designated orbit and inclination, with the propulsion engine dropping off. Both the Airbus 300 and the autonomous spaceplane will return to the airport of departure, or a different selected airport. This launch system will reuse virtually every portion to dramatically drive down cost of getting small payloads to low-Earth orbit [9].

As a means of generating operating revenues until such time as payload launching services can proceed, S3 has a separate operation providing zero-G flights using its A300 that will be the carrier launch vehicle for its spaceplane. S3 ZeroG is part of the company's business model. The jet will fly repeated parabolic flight profiles for passengers in a central section of the plane (with no seats) to experience weightless for several minutes at a time. Similar flights are already being conducted in the United States by Space Adventures. The aircraft can also be contracted to perform such flights for companies and researchers.

Arianespace

Arianespace was founded in 1980 from a consortium comprised of the French space agency CNES, Astrium and the aerospace firms from ten European countries. The company identifies itself as the first commercial launch company. Its first launch vehicle was the Ariane I, sending to orbit various lightweight commercial satellite

Fig. 3.4 The Ariane 5 is the heavy lift launch vehicle built by Arianespace in Europe. It is launched from French Guiana near the equator (image courtesy of Arianespace, used with permission)

payloads. The Ariane family of launch vehicles grew over the years as satellites increased in size, weight and capabilities. The company drew customers from around the world, including the United States. Arianespace has the greatest segment of the launch market, capturing more than 50 percent of payloads launched annually.

The need arose to launch satellite payloads exceeding 4000 kg to geostationary transfer orbit. To meet this and future needs, Arianespace developed the Ariane 5 heavy lift launch vehicle, which is capable of sending 10 t (10,000 kg) to GTO or 20 t (20,000 kg) to low Earth orbit. The Ariane 5 features a core cryogenic stage carrying LOx and LH2 to power the single main engine. The rocket gets its lift capability from the addition of two solid propellant boosters mounted to each side of the core stage. The rocket has a cryogenic second stage that powers the payload to the desired orbit (Fig. 3.4).

To meet the need of cost-effective medium payload capability, Arianespace contracted with Russian rocket maker Starsem to launch the iconic Soyuz launch vehicle. This is a three-stage rocket with its distinctive four external liquid propellant boosters mated to a liquid propellant core first stage. It was the Soyuz that launched Russia's first satellite, Sputnik. The rocket has undergone continuous refinement and improvement over the decades since, with more than 1770 launches. Today's Soyuz can launch 3 t (3000 kg) to LEO and GTO.

To meet the growing requirement for lightweight scientific payload capability, Arianespace developed the Vega. This is a four-stage rocket with solid propellant first, second and third stages. The fourth stage features liquid bi-propellant. The Vega can launch 1500 kg to LEO or a Sun-synchronous orbit.

The Ariane 5, Soyuz and Vega are all launched from the Arianespace Guiana Space Center on the coast of French Guiana in South America. This is an ideal launch site, being only 5.3° north of the equator, providing advantageous launch capabilities [10].

International Launch Services (ILS)

One example of the shift from government sponsored launch services to commercial launch services is International Launch Services. The creation of this unlikely partnership between U.S. and Russian corporations began around 1990. Russia was exploring a means of commercializing its successful Proton launcher. The Russian state agencies and manufacturing entities met with numerous European and American companies in efforts to form a launch collaboration. The group, today known as Khrunichev State Research and Production Center, selected Lockheed Corporation, and they entered into a joint venture agreement on December 28, 1992. The Lockheed Khrunichev Energia International Inc. was incorporated in April 1993. In 1995, the present name, International Launch Services (ILS), was adopted. The company is headquartered in Reston, Virginia [11].

The history of the Proton launcher goes back almost as far as the Soyuz launcher. The first Proton was launched in 1965. The first-stage booster has six engine pods mounted externally around a core propellant tank. The non-cryogenic propellants are nitrogen tetroxide and unsymmetrical dimethyl hydrazine. The second and third stages use variants of the first stage booster engine. There is a fourth-stage "kicker" engine that permits the heavy lifter Proton to place a 6900 kg payload into GTO or 7200 kg into a super-synchronous transfer orbit.

The Proton is assembled at the Khrunichev plant in Moscow. The assembled rocket is flown to the Yubleiny Airfield at the Baikonur Cosmodrome, Russia's largest launch complex; it is operated by Roscosmos, the Russian space agency. To date, more than 390 Proton launch vehicles have been launched from Baikonur. The current Proton Breeze M launch vehicle has launched satellite payloads for customers in the United States, Europe and other nations.

Like Orbital Sciences in the United States, Russian companies have been converting decommissioned ICBMs into space launch vehicles. The smallest of these is called the Rokot; it was converted from the SS-19 Stiletto ICBM. It is a three-stage liquid propellant rocket. It is capable of sending nearly 2000 kg to LEO. It is converted and operated by Eurocket Launch Services and is launched from the Plesetsk Cosmodrome. The larger Dnepr-1 is a converted SS-18 Satan ICBM by ISC Kosmotras. It is a three-stage rocket burning hypergolic liquid propellants, capable of launching 4500 kg to LEO from launch complexes at Baikonur or the Dombarovsky launch complex. The Dnepr-1 is capable of launching cargo to the ISS.

Asia's Commercial Efforts

Japan's space program in general has reflected the country's economic conditions since the 1980s. Despite is geographic size, Japan prides itself on its technological capabilities and industrial might. However, its history of poor launch vehicle reliability and performance hampered the country's early civil and commercial space efforts. The majority of the satellites launched have been scientific satellites. Japan contributed the Japan Aerospace Exploration Agency (JAXA) *Kibo* module to the International Space Station, which was launched aboard the space shuttle.

Japan launched its first commercial satellite on May 17, 2012. The satellite was built by Mitsubishi Heavy Industries Ltd. in conjunction with JAXA for the Korea Aerospace Research Institute. JAXA's space center launch complex is located on Tanegashima Island. The majority of satellites launched by Japan remain scientific [12].

China in the second decade of the 21st century does not have a commercial space program. Instead, the nation has been focusing its efforts on government satellites and the development of its Long March rocket series to launch those satellites, robotic spacecraft and expanding its human spaceflight program. China is only the third nation to send crews into Earth orbit. Its spacecraft have docked with their own small space station and remained in orbit for fifteen days before returning to Earth. This Asian nation has taken the long-term approach to space exploration and is methodically making its way to becoming a spacefaring country.

China has also proven its technical capability in space exploration by sending a probe to the Moon, and have it land and deploy a small robotic rover. The country is slowly turning to the commercial space launch market, and this is a concern to some American and European launch service providers. Chief among these is SpaceX.

"We really feel at SpaceX that the competition is going to be the Chinese space program," Adam Harris, a vice president of SpaceX said at the 2013 AIAA Space Conference. "The Chinese government is certainly committed to furthering their program. They've announced Moon missions, they've announced further activities and they are doing it within their country" [13].

Although these comments were within the context of China's government-funded space program, the country has a follow-on heavy-lift launch vehicle family that is entering service: the Long March 5. These rockets are comprised of two different core booster diameters and combinations of supplemental bolt-on first-stage boosters. These rockets are being manufactured at the northeast China port city of Tianjin. The rockets are transported by ship to the island of Hainan, the location of China's new Wenchang Launch Center. They are capable of launching payloads currently carried by the Atlas V, Delta IV, Falcon 9 and Proton rockets. The Long March 5 launch vehicles will be used to launch the modules of its future large space station, given the name *Tiangong* ("Heavenly Palace"). China intends to develop areas adjacent to the launch center as a tourist destination, much like the Kennedy Space Center Visitor Complex in Florida.

In September 2014, the Indian Space Research Organization (ISRO) successfully placed its Mars Orbiter Mission satellite in orbit around the Red Planet. This was a government scientific payload, but it served to tell the world India had the technical capability of deep space missions. The ISRO was founded in 1969, at the height of America's Apollo program. What is India's capability in the commercial satellite market in the 21st century?

The ISRO, being a government agency, is not established to operate as a private business in the launching of commercial satellites. The private corporation that contracts launch services for the ISRO is Antrix. This company is headquartered in Bangalore, India, and has performed commercial launch services for a number of countries as customers. These include Canada, Argentina, Denmark, England, Luxembourg, France, Germany, Austria, Switzerland, Italy, Algeria, Holland, Israel, Turkey, Indonesia, Singapore, South Korea and Japan [14].

The IRSO has three primary launch vehicles for orbiting satellite payloads. The Polar Satellite Launch Vehicle (PSLV) has four stages and can launch a 3250 kg (7170 lbs.) payload to LEO, a 1600 kg (3500 lbs.) payload to Helio-Centric Orbit (HCO) or a 1400 kg (3100 lbs.) payload to GTO. Its medium-lift launch vehicle, the three-stage Geosynchronous Satellite Launch Vehicle (GSLV), can send 5000 kg to LEO and between 2000 and 2500 kg to GTO. The GSLV Mk III heavy-lift launch vehicle is capable of launching even heavier payloads to LEO and GTO [15]. The primary launch site for these rockets is the Satish Dhawan Space Center in Sriharikota, Andhra Pradesh, on the eastern Indian coastline

Suborbital Space Launch Efforts

The current commercial market for delivery of payloads to suborbit remains limited but will expand in the coming years. (Human suborbital spaceflight is covered in Chap. 6 on Personal Spaceflight). The threshold of space has been scientifically established at 100 km (62 miles). Due to its nature, suborbital flight does not include the prospect of satellites, the largest potential market. Different applications are the domain of suborbital payloads. These markets can include basic and applied research, aerospace technology test and demonstration, remote sensing and education.

In terms of basic and applied research, suborbital flight can be used for upper atmospheric samples and medical research for brief periods of microgravity. Aerospace technology can be explored in the development of small propulsion systems and their related avionics and software development. An ever-growing commercial need is in the area of remote sensing. This involves photographing Earth's surface both with and without specialized filters. Remote sensing has specific applications in determining localized weather conditions and geologic changes across one or more states. Colleges and universities will employ suborbital instrumented payloads for scientific study and research. Suborbital payloads can be delivered to near-space at much lower cost than orbital launch vehicles.

In September 2014, NASA selected four firms to provide commercial suborbital reusable platforms to carry technology payloads under its Flight Opportunities Program. The firms are Masten Space Systems, UP Aerospace, Paragon Space Development Corporation and Virgin Galactic. The three-year contracts have two-year extension options and a minimum value of $100,000. The flights will carry a variety of payloads during five diverse flight profiles to help meet the agency's research and technology needs, according to the NASA program's website.

Masten Space Systems, headquartered in Mojave, California, has pioneered the field of vertical takeoff, vertical landing (VTVL) launch vehicles. Masten has several launch vehicles under development capable of this means of commercial payload launch and landing. The company has received awards from NASA as part of the Commercial Reusable Suborbital Research program in 2010 and the Flight Opportunities program in 2011.

UP Aerospace employs a conventional reusable sounding rocket powered by solid propellant single-stage engine. Launched from its dedicated launch facility at Spaceport America in New Mexico, not far from Virgin Galactic, the SpaceLoft XL rocket can send a 36 kg (79 lbs.) payload to a height of 115 km and provide for up to 4 min of microgravity. Lower mass payloads can be delivered to an altitude of 160 km. Both rocket and the deployed payload return to Earth by parachute [16].

Paragon Space Development Corporation in Tucson, Arizona, has worked on a number of projects for NASA with regard to the International Space Station. It is developing the WorldView spacecraft for commercial personal upper atmospheric missions (fully described in the chapter on personal spaceflight). Under the Flight Opportunities program, Paragon will employ its balloon technology to take technology demonstrators to high altitudes and validate the technology before being applied to other missions.

Virgin Galactic can provide suborbital (as well as orbital) capability by employing its WhiteKnightTwo carrier aircraft (also used to carry passengers on SpaceShipTwo) and its LauncherOne air launch vehicle (ALV). LauncherOne has an orbital payload capability of 277 kg (500 lbs.) and larger payloads for suborbital flights as part of NASA's Flight Opportunities Program. LauncherOne takes its propulsion technology from the development work done on the passenger spacecraft SpaceShipTwo.

In February 2015, Virgin Galactic opened a new design and manufacturing facility for LauncherOne in Long Beach, California, near the municipal airport. The aircraft and launch vehicle depart from Spaceport America in southern New Mexico, the operational headquarters of Virgin Galactic. After reaching an altitude of roughly 50,000 ft, LauncherOne is released and fires its engine 4 s later. This

Fig. 3.5 Virgin Galactic uses the same carrier aircraft for its SpaceShipTwo and LauncherOne commercial satellite payloads (image courtesy of Virgin Galactic, used with permission)

effective second stage delivers the payload to the prescribed suborbital apogee for NASA missions, or to low Earth or Sun-synchronous orbit on commercial missions (Fig. 3.5).

The wide array of launch vehicles and forms of delivery of payloads is reflective of the expanding commercial space sector in the 21st century. It is also indicative of the imperative to keep exploring technological capabilities to lower costs of payloads to suborbit and low-Earth orbit.

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Chapter 4
NASA Commercial Partnership Programs

One of the most transformational events in the broad subject of commercial space business is the adoption of commercial practices and partners by NASA. Since its establishment in 1959, NASA grew in response to its management of the Mercury, Gemini and Apollo manned spaceflight programs. The space agency established a strict conduct of operations where NASA established the programs, set the guidelines and performed strict oversight of its contractors who built its needed hardware. However, NASA often designed and built much of that hardware itself at one of its numerous NASA centers around the United States.

During the historic Apollo lunar landing program, NASA's budget peaked at 3.8 % of the federal budget. After 1966, NASA's budget plunged dramatically, even though the first manned lunar landing would not occur until 1969. The last manned lunar mission was *Apollo 17* in December 1972. After Apollo came the space shuttle program and then the International Space Station (ISS). These were massive government programs under the management of NASA commensurate with its budget at the time. The ISS was also international in scope, with other countries designing and building specific modules of the space station. Numerous other prospective space exploration programs were put forth by NASA during the 1980s and 1990s, but the attendant costs and apparent lack of rationale and needed funding left these plans as just paper programs. Today, NASA's budget as a percentage of the federal budget is the same as when it was established; this is roughly 0.4 %—about one tenth of what it was during the competition to beat the Soviets to the Moon.

The space shuttle was designed to operate up to 100 missions before each shuttle would have to be retired. However, the promised lowered costs of getting payloads and crews to low Earth orbit never materialized. Costs of shuttle missions eventually exceeded half a billion dollars each. There were never serious attempts by NASA to initiate a replacement for the shuttle—it did not have the budget to do so, and continued to operate the complex spacecraft with no foreseeable end of operations.

It was then that history intervened to change the way NASA operated, at least with respect to its human spaceflight program. On February 1, 2003, the space shuttle *Columbia* disintegrated upon reentry, with the loss of its entire crew. This catastrophe revealed the weaknesses in the shuttle's design and its inability to

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protect the crew, which had first become apparent with the loss of the shuttle *Challenger* in January 1986. All the magnificent accomplishments of the space shuttle and its astronauts over more than two decades of service were momentarily forgotten.

The shuttle fleet was grounded. Members of the Bush Administration met with NASA Administrator Sean O'Keefe and upper managers to discuss the fate of the agency's human spaceflight program. A commission was established to ascertain the cause of the disaster. One thing was absolutely certain. More astronauts had died aboard the space shuttle than any other spacecraft NASA had flown. However, there was no other capable spacecraft to replace it, and the ISS needed to be completed; the space shuttle was the only launch vehicle capable and proven to complete the task.

The remainder of 2003 was spent by the agency formulating what it should do with the space shuttle, its obligation to complete the ISS, what the options of transporting crews to and from the ISS were, and what its human exploration goals should be. On January 14, 2004, President George W. Bush announced the Vision for Space Exploration at NASA headquarters. This new program was more ambitious than Apollo had been. The president stated the shuttle would return to flight to complete the ISS and thereafter be retired from service. New launch vehicles would be developed, missions to the Moon would be mounted, and plans were even drawn for human missions to Mars [1].

The Vision for Space Exploration was still in the mold of very large and expensive NASA space programs, but forces were already at work that would alter the ways things were done at NASA and how it would ultimately approach human spaceflight. The key problem was that the money to achieve this grand vision of renewed lunar exploration and beyond came at a staggering cost, but NASA hedged what that cost would be. However, the undeniable facts were that the shuttle would complete construction of the ISS and then it would cease operation.

Barrack Obama was elected president in November 2008. With the new administration came a new outlook on American human space exploration. There was no congressional will to fund the Vision for Space Exploration, and this program was later canceled. However, the seeds of NASA commercial endeavors had been planted years before, as far back as the early 1980s.

Early Commercial Efforts by the U.S. Government

The election of Ronald Reagan as president in 1981 coincided with efforts by advocates within NASA of greater exploration of commercial possibilities by the space agency. NASA drew up a policy paper outlining the options for initiating commercial space investments and opportunities. In a carefully worded section, the authors of the paper stated NASA needed to "…more effectively encourage and facilitate private sector involvement and investment in civil space and space-related activities" [2]. The paper called for NASA to redirect funds from its considerable research and development to promote commercial application of space technologies and foster private industry efforts with the help of NASA.

To achieve this, NASA created the Office of Technology Transfer. Specifically, this office was to work to ease the regulatory burden on private firms desiring to enter the commercial space market and offer incentives in investment to this end. The Reagan White House believed in the historical precedents of the benefits to the United States of free enterprise across many markets during the 19th century, and that government could specifically encourage this activity to achieve an even greater outcome.

In September 1984, NASA Administrator James M. Beggs formed the Office of Commercial Programs. This was established to encourage "…the private sector to become more involved in using space for commercial purposes and increased NASA's efforts to find private-sector uses for NASA-developed technology" [3]. Also during this period, the Office of Commercial Space Transportation was established within the Department of Transportation to handle the proper regulation of commercial launches and to accelerate the expansion of the commercial spaceflight industry.

There are a number of historical analogs of the U.S. government assisting in the commercial development of vital industries. Perhaps the most often cited is the transcontinental railroad, which offers some parallels in NASA's current involvement in the promotion of commercial space industries today. This was a massive civil engineering project involving three major railroads in its construction. The U.S. government offered land grants to the rail companies, direct funding to underwrite a portion of the expense of building each company's portion of the line, tax waivers or modifications to taxes, and contracts for services once operational capability was established, among other assistance.

In the early 20th century, the government performed much the same role in an effort to launch a viable commercial air transportation system in America. Although the era of flight was born in the United States, several European countries soon surpassed it in terms of aircraft design, development and manufacture. The U.S. government became involved to spur commercial development of this new mode of transportation, but passenger aircraft would take some years before becoming commonplace. The National Advisory Committee for Aeronautics (NACA) was established in 1915 to conduct flight research with the findings passed on for the use of commercial aircraft companies. NACA was actively involved in aeronautical research in experimental as well as commercial aircraft up to the time it merged with NASA in 1958.

In the immediate years preceding and during the new millennium there were significant pieces of legislation passed with respect to promoting commercial space business in the United States. In 1998, Congress signed into law the Commercial Space Act. This promoted the commercialization of the International Space Station, the creation of spaceports in locations other than Florida, a greater emphasis on commercial space launch services both for its own sake and in support of U.S. government payloads, and other commercial space incentives. This was followed by the Commercial Space Transportation Competitiveness Act of 2000. This legislation was written to provide funds to the Office of the Associate Administrator for Commercial Space Transportation and the Office of Space Commercialization.

Nevertheless, the space shuttle remained the single means of American human spaceflight. The Atlas and the Delta rockets continued as America's premier launch vehicles capable of delivering satellite payloads to low Earth orbit from launch sites in Florida. The International Space Station became operational in November 2000 with the arrival of the Expedition 1 crew. The crew arrived at the ISS aboard a Soyuz spacecraft, not the space shuttle. Another piece of legislation, HR 2684, was drafted with one section entitled Space Station Commercial Development Demonstration Program. This legislation was written to initiate actual demonstration missions to validate the commercial feasibility and economic validity of the private space sector providing services to and from the ISS. With the shuttle *Columbia* disaster in 2003 and the administration decision to retire the shuttle fleet, commercial cargo and commercial crew requirements were now a priority.

COTS and C3PO

In April 2005, Michael Griffin was appointed the new NASA Administrator. One of his initiatives was assigning $500 million to the development of commercial cargo capability to the ISS. The Commercial Office of Transportation Services (COTS) was established at Johnson Space Center. In November 2005 Griffin gave a speech to the American Astronautical Society. He stated, in part, "I believe that with the advent of the ISS, there will exist for the first time a strong, identifiable market for "routine" transportation service to and from LEO, and that this will be only the first step in what will be a huge opportunity to promote commercial space enterprise…I believe that the ISS provides a tremendous opportunity to promote commercial space ventures that will help us meet our exploration objectives and at the same time create new jobs and new industry (Fig. 4.1).

"The clearly identifiable market provided by the ISS is that for regular cargo delivery and return, and crew rotation, especially after we retire the shuttle in 2010, but earlier should the capability become available. We want to be able to buy these services from American industry to the fullest extent possible. We believe that when we engage the engine of competition, these services will be provided in a more cost-effective fashion than when the government does it" [4].

To facilitate this, the Commercial Crew & Cargo Program Office (C3PO) was organized at JSC under the COTS umbrella. Alan J. Lindenmoyer was selected to direct the C3PO. Lindenmoyer was a twenty-year veteran of NASA who had been involved most of that time with the ISS, specifically with contracts and configuration management. Lindenmoyer and his team established three primary goals of the C3PO:

- To implement the U.S. space exploration policy with investments to stimulate the commercial space industry.

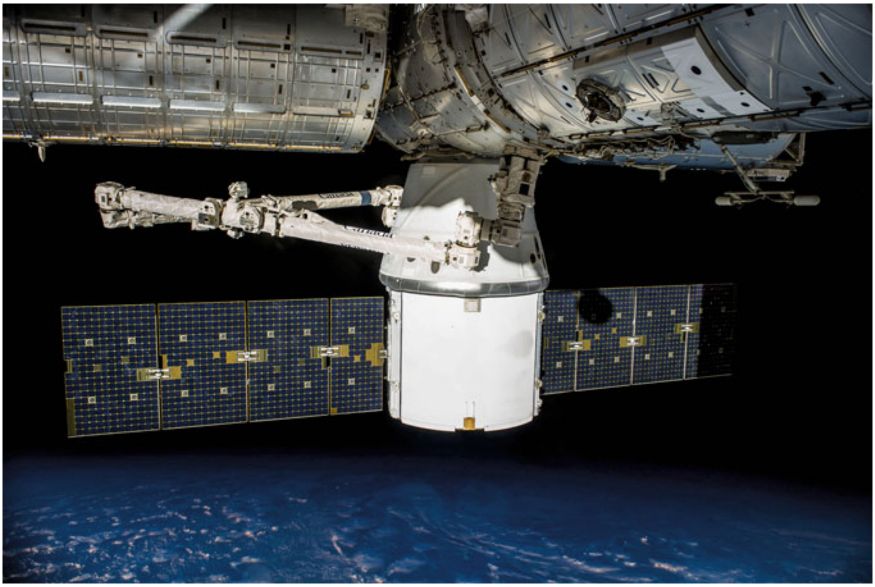

Fig. 4.1 The design and development of the SpaceX Dragon cargo capsule was achieved through a collaborative partnership with NASA through the Commercial Orbital Transportations Services (COTS) initiative (image courtesy of SpaceX, used with permission)

- To facilitate U.S. private industry demonstration of cargo and crew space transportation capabilities with the goal of achieving reliable, cost-effective access to low-Earth orbit.
- To create a market environment in which commercial space transportation services are available to government and private sector customers.

With the shuttle program set to end initially in 2010, and with the cancellation of the Constellation program, some means of meeting these new human spacecraft requirements needed to be implemented. President Obama mandated a blue-ribbon panel to evaluate America's space launch requirements. The published findings of the Augustine Committee stated Project Constellation was not economically viable without significant increases in the NASA annual budget, and made recommendations for replacement of the shuttle with another human-rated spacecraft.

"As we move from the complex, reusable shuttle back to a simpler, smaller capsule," the Augustine Committee report stated, "it is appropriate to consider turning this transport service over to the commercial sector. This approach is not without technical and programmatic risks, but it creates the possibility of lower operating costs for the system and potentially accelerates the availability of U.S. access to low-Earth orbit by about a year, to 2016. If this option is chosen, the Committee suggests establishing a new competition for this service, in which both large and small companies could participate" [5].

Instrumental in the formation of these new commercial partnerships between NASA and the aerospace industry was the financial structure established to pay for services and to measure progress with corresponding payments for achieving milestones. NASA would abandon the cost-plus contract structure. The respective industry partners would invest heavily in manufacturing and testing infrastructure, and NASA would provide significant financial payments to the companies that met project milestones that proved the company's capability to meet NASA requirements.

In October 2005, the first COTS Procurement Development Team meeting took place to establish the requirements for commercial crew and cargo. Four demonstrations were established as part of the performance capability the participating companies had to provide. These were (1) external unpressurized cargo delivery and disposal (2) internal pressurized cargo delivery and disposal, (3) internal pressurized cargo delivery, return and recovery, and (4) crew transportation. Instead of dictating to its providers the design and performance parameters for the necessary hardware, NASA instead established capability milestones that left it up to the companies the freedom to design the launch vehicles or interfaces and the cargo and crew capsules completely.

Gone were the specific design restraints NASA had operated under for decades. For example, the demonstration for internal pressurized cargo delivery, return and recovery was briefly worded thus: "…delivers cargo (payloads) that operates within a volume maintained at normal atmospheric pressure to a LEO test bed and provides for its safe disposal." After the draft announcement was posted, the C3PO held an Industry Day in Houston. Representatives from companies were impressed to learn that NASA would no longer be a program overseer but instead become an industry partner. Companies would be given much more latitude in the design of the hardware, but at the same time would have an incentive to keep costs down because they were bearing much of that cost themselves.

A legal framework needed to be drawn up to accomplish this so that both NASA and its industry partners would succeed. Specialists in intellectual property, procurement and commercial law drafted the legal structure for implementation of the COTS program. The old government procurement method was being abolished in favor of what would be called Space Act Agreements. NASA recognized there had to be a whole new way of meeting its mission statement and do it with as much commercial participation as possible. The COTS organization needed to start thinking like an investor, which it most definitely would be. A key aspect of these SAA's would be the possibility of the companies developing launch vehicles, spacecraft and capabilities that could be marketed to other customers.

In addition, COTS wanted small companies to compete alongside the aerospace giants because it knew small companies by their nature were driven by innovation, and that was what NASA was seeking. Also, smaller companies could often bring their innovative concepts to fruition quickly compared to the larger and longer established companies. COTS established milestones that would have to be met within each of the four capabilities listed above. The companies, regardless of their size, would be paid by NASA upon achieving those milestones. Thus, there was shared financial risk on the part of NASA and its commercial partner, and a definite incentive by that company to meet the mandated milestones.

The principal driver for COTS was the International Space Station and meeting its needs and that of its crews. COTS and C3PO would not be involved in the completion of the ISS, but would primarily be involved in the resupply of cargo, delivery of scientific payloads and other commercial development payloads, and delivery of crews to the ISS and their return to Earth. Initially, it was established that capability demonstrations would be to some undefined test bed in low-Earth orbit. Ultimately, NASA and COTS managers established that the most logical test bed destination was the ISS itself. This would naturally hasten the timeline to demonstrate the capability to actually rendezvous and dock to the ISS.

NASA had an abundance of documentation regarding spacecraft to ISS interface and docking. Instead of simply handing these requirements over to new as well as experienced aerospace firms, the COTS team condensed the material, with much of it rewritten, to a manageable length and easily understood text.

"The Space Act [Agreement] itself was so commercial-friendly, companies loved this," Valin Thorn, C3PO Deputy Manager at the start of the program, stated. "They knew this was not business as usual. They knew this was going to be a different way of doing business, and were very supportive of it and complimentary of NASA for developing this new way of investing" [6].

In January 2006, the COTS office requested proposals for resupply services for the ISS. Companies had until March 3 to submit their proposals. By that date, NASA received 21 proposals, ranging from the smallest but hopeful startups to the industry mainstays Boeing and Lockheed Martin. NASA used its years of experience dealing with company vendors and suppliers and employed a matrix of indicators to establish each company's capabilities in terms of achieving their respective demonstration or demonstrations. Six companies were selected from the proposals; interestingly neither Boeing nor Lockheed Martin were among the selected companies. NASA managers then visited each of the companies to see their facilities, meet with their officers and engineers and asked very pointed questions to further understand the company's operations and capabilities. NASA then down-selected to just two companies the space agency was confident would succeed in their demonstrations. Round One resulted in the selection of Space Technologies Corporation in Hawthorne, CA, and Rocketplane Kistler (RpK) based on Oklahoma.

NASA was aware that RpK did not have the strongest financial position to obtain the necessary level of private funding, but the company had a strong technical team and a viable design for a reusable rocket to lower launch and operating costs. Nevertheless, the company failed to meet several designated technical milestones and also failed to acquire the necessary level of funding to assure ongoing design and development of its proposed designs. In October 2007, NASA informed the officers of RpK it was terminating its Space Act Agreement with the company for these stated reasons.

Rather than revisit the proposals submitted during the original round of evaluations, NASA chose to have a second round of proposals submitted to select its second COTS provider. This time, NASA requested more detailed financial figures and greater assurances the company could acquire the level of private funding to move forward. NASA received thirteen proposals by the November 2007 deadline. The winning proposal selected in February 2008 came from Orbital Sciences in Dulles, Virginia.

Both proposals from SpaceX and from Orbital Sciences described the launch vehicles and the capsules they would develop and how the companies would achieve their respective milestones in hardware development. SpaceX would develop its two-stage Falcon 9 rocket and Dragon cargo capsule. Orbital Sciences would develop the Taurus II rocket and proposed that Thales Alenia Space in Italy would build the pressurized and unpressurized cargo modules. Perhaps most surprising to those following the selection process was that neither Boeing nor Lockheed Martin were selected in this round. SpaceX received $278 million as its award during the Round One phase, and Orbital Sciences received $170 million after its winning the Round Two phase (Fig. 4.2).

One aspect of the COTS program was NASA's desire to offer Commercial Space Transportation Capabilities Agreements (CSTCA), which were unfunded Space Act Agreements. These were offered to select companies that did not place "in the money" but were given the opportunity to continue their work using NASA facilities, personnel when available and other NASA assets. These agreements were conceived to give losing competitors incentives to continue their innovative research and development. It was hoped by NASA that the companies that were

Fig. 4.2 Orbital Sciences also supplies cargo resupply services to the International Space Station for NASA using its Cygnus cargo module (image courtesy of NASA, used with permission)

awarded CSTCA's would compete for future potential awards to keep them in the commercial space development business.

One example of this was the company SpaceDev. It lost its bid for COTS, presenting a mini-shuttle type of spacecraft to be launched aboard a conventional, existing launch vehicle. In 2008 SpaceDev was purchased by Sierra Nevada Corporation. Sierra Nevada then proceeded with development of the spacecraft and named it Dream Chaser. Sierra Nevada intended to compete in the selection of commercial crew transportation with Dream Chaser.

SpaceX and Orbital Sciences Vehicle Developments

At the time SpaceX won its $278 million award from NASA, the company was in development of its first launch vehicle, the Falcon 1. This rocket did not have a good launch record. Nevertheless, the much larger and more powerful Falcon 9, powered by nine Merlin engines, was under design development. According to its proposal to NASA, the Falcon 9 would be able to deliver 6,850 pounds to low-Earth orbit and fly as many as eight missions per year.

SpaceX had an aggressive development and testing schedule for the Falcon 9. NASA recognized this and anticipated there would be delays before the first launch of the new rocket would take place, and therefore delays in exercising the demonstration missions, particularly the first docking of the Dragon capsule with the ISS. The space agency was not surprised by requested extensions of the program milestones. Alan J. Lindenmoyer, the C3PO manager, knew that any new launch vehicle would typically experience unforeseen delays. The originally scheduled demonstration flight of the Dragon spacecraft to dock with the ISS was set for September 2009. SpaceX would miss this milestone by two and a half years.

"The average time to field a new launch vehicle is at least 27 months longer than initially projected," Lindenmoyer stated. "That's almost exactly the delay that SpaceX experienced from the predicted original launch date of the first demonstration flight to the actual" [7] (Fig. 4.3).

The first launch of the Falcon 9 took place on June 4, 2010, from a dedicated launch pad at Cape Canaveral. The rocket generated 1,125,000 lbs. of thrust at liftoff, and the Falcon 9 inserted its payload into orbit. The second launch of the Falcon 9 took place the following December. This was the designated C1 demonstration mission and the first launch of the Dragon capsule, which successfully reached orbit. During several orbits of Earth, it performed several scheduled maneuvers, the capsule survived reentry and performed an ocean landing.

Finally, the C2+ demonstration mission was scheduled for launch on May 22, 2012. NASA had made a unique provision with SpaceX on this mission. If the Dragon capsule achieved all the mission milestones up to and including rendezvous and close proximity to the ISS, NASA would at that time make a determination to allow the capsule to dock with the ISS. The launch went perfectly, and two days were spent on the long list of required performance milestones of the capsule. On

Fig. 4.3 The SpaceX Dragon 2 capsule is designed to carry crew members to and from the International Space Station. Pictured is the capsule used for launch abort tests (image courtesy of SpaceX, used with permission)

May 25th NASA granted SpaceX permission to have Dragon dock with the ISS. There was a temporary delay due to reflections from the Japanese module causing errors in the Dragon's thermal imagers. SpaceX software engineers resolved the issue.

Astronaut Donald R. Petitt used the Canadarm to grapple the Dragon capsule and brought it to the docking port, where it successfully docked with the ISS. This was an historic day in commercial spaceflight, witnessed by millions of people around the world during a live broadcast of this part of the mission. The atmosphere at SpaceX headquarters was jubilant. Over 1000 lbs. of cargo were delivered aboard the space station from the capsule, necessary return cargo was loaded and secured in the capsule, and the capsule returned to Earth for a landing in the Pacific Ocean on May 31, 2012.

With Orbital Sciences selected in Round Two, NASA had selected a more mature company than SpaceX. Orbital Sciences was founded in 1982. The company grew to develop and manufacture small satellites and the launch vehicle for them. This launch vehicle was called Pegasus. It was carried aloft, initially, by a B-52 bomber in much the same way NASA's X-15 rocketplane had been. Orbital Sciences later modified a Lockheed L-1011 commercial jet as the carrier aircraft, with the Pegasus rocket carried underneath the fuselage.

During the 1990s, the company expanded into the development of larger and traditionally launched launch vehicles. It developed these vehicles with the cooperation of Soviet and Ukrainian design and manufacturing companies. One of these rockets, the Taurus II, after significant redesign, became the Antares rocket, which formed the basis of its C3PO proposal to NASA. The Antares booster was powered by Aerojet AJ-26 liquid propellant engines, but in fact these were purchased surplus Russian Kuznetsov NK-33 engines. Aerojet would refurbish, test and validate the engines for powering the Antares. The second stage of the Antares was powered by a solid rocket motor from Alliant Techsystems, Inc. (ATK) in Utah.

Orbital Sciences also turned to outside suppliers to provide the cargo module the Antares rocket would launch to the ISS. Thales Alenia Space was selected to manufacture the pressurized cargo module. This was a good choice, as that Italian company had built the multi-purpose logistics modules for the International Space Station. The Orbital Sciences cargo module was given the name Cygnus. It would have a cargo payload capable of carrying nearly 4500 lbs. of unpressurized cargo or 5070 lbs. of pressurized cargo. The launch site for the Antares rocket would not be Cape Canaveral, as it was for SpaceX, but NASA's Wallops Island launch facility on the Virginia coast. The commercial name for the facility is the Mid-Atlantic Regional Spaceport (MARS).

Orbital Sciences completed a successful hot-fire captive test of the Antares rocket at the MARS launch complex on February 22, 2013. The rocket was launched two months later on April 21st. Booster and second-stage separation was nominal. The second stage propelled the Cygnus mass simulator, which was deployed in the planned orbit 155 miles above Earth. This successful first launch gave both Orbital Sciences and NASA the confidence the company could move forward to the next milestone.

The second launch of the Antares with an operational Cygnus payload module took place on September 18, 2013. Cygnus achieved proper orbit and performed its solar power array deployment and other mission milestones. An error in the cargo module's navigation software had to be resolved before the module could rendezvous with the ISS. The capture and docking with the ISS took place on September 29, 2013. More than 1500 lbs. of cargo was unloaded from the Cygnus spacecraft to the ISS. This proved Orbital Sciences' capability to deliver commercial cargo to the ISS. However, like SpaceX, Orbital Sciences experienced numerous development problems and thus delays in meeting the mandated milestones by nearly three years. Nevertheless, NASA now had two capable providers of commercial cargo for the ISS. Subsequently, Orbital Sciences received a $1.9 billion Resupply Services Contract from NASA.

NASA awarded Resupply Services Contracts to SpaceX and Orbital Sciences. SpaceX was awarded $1.6 billion for twelve resupply missions to the ISS. Orbital Sciences received a $1.9 billion contract for eight missions. SpaceX mission CRS-1, its first resupply mission under its award, was launched without issue. The Falcon 9 booster experienced a single 'engine-out' 1 min and 20 s after launch, but the rocket still placed the Dragon cargo capsule on its correct trajectory to the ISS and docked with the space station, unloading the needed cargo.

Orbital Sciences' first commercial resupply mission using the Antares rocket and Cygnus payload module took place on January 9, 2014. The Antares rocket performed nominally, and the second stage powered by a solid propellant Castor 30B motor successfully placed the payload module in the proper orbit, which later docked with the ISS. These two initial successful missions validated NASA's approach to commercial cargo resupply to the ISS.

NASA's Commercial Crew Program

The second critical element of NASA's C3PO was commercial crew development, or CCDev. In August 2009, NASA issued its announcement of this next stage. It called for the development of the human-rated launch vehicle and crew transportation spacecraft. The following month, thirty-six companies submitted their proposals. The first evaluations of these proposals eliminated half of them. The remaining eighteen proposals went through a more demanding review that resulted in eight companies with solid proposals. These included Ball Aerospace, the Boeing Company, Paragon Space Development Corporation, Blue Origin, Sierra Nevada Corporation, Space Exploration Technologies, United Launch Alliance and XCOR Aerospace [8].

The selection process was not over. Three of these companies were eliminated from the final round, failing to receive funded Space Act Agreements. The awards for the rest would be paid in increments, as each company achieved specific milestones. The companies were Sierra Nevada, SpaceX, the Boeing Company, United Launch Alliance, Blue Origin and Paragon Space Development Corporation. Sierra Nevada, Boeing and SpaceX intended to develop the human-rated launch vehicle and capsule. The remaining companies would develop technologies related to crew transportation services. Sierra Nevada would develop the Dream Chaser lifting body spacecraft, Boeing would develop its crew space transportation capsule (CST-100) and SpaceX would develop an advanced version of its Dragon capsule, called Dragon v2 (Fig. 4.4).

The development of the crew transportation systems to and from the ISS were vital to the United States because NASA would have to continue to pay the Russian space agency upwards of $70 million per astronaut aboard Soviet spacecraft. Many space industry observers asked how America could have relinquished its supremacy in human spaceflight and had to resort to its former Cold War enemy to provide the needed services. Nevertheless, NASA was moving as quickly as the American companies would allow to return American human spaceflight to its rightful place.

NASA established the Commercial Crew Program to administer the development stages of the participating companies. The agency felt it important that crewed launches take place from Kennedy Space Center, so this was where the CCP program office was located. Boeing, SpaceX and Sierra Nevada had to meet developmental and program milestones to receive the awards. NASA wanted to have two commercial crew transportation providers. With the CCDev2 announcement in April 2011, SpaceX received $75 million, Boeing received $92.3 million, Sierra Nevada received $80 million and Blue Origin $22 million.

When the CCiCap (Commercial Crew integration Capabilities) Space Act Agreements were awarded in August 2012, SpaceX received an additional

Fig. 4.4 The Boeing CST-100 crew capsule with service module is shown docked to the International Space Station. Boeing plans to include private spaceflight participants on select missions (illustration courtesy of Nathan Koga/NASASPACEFLIGHT.COM, used with permission)

$440 million, Boeing $460 million and Sierra Nevada $212.5 million. Blue Origin did not receive award funds to continue its capsule development, but the company vowed it would continue using its own funds.

Finally, NASA announced its CCtCap awards, which selected the two companies that would prove the capabilities of their crewed spacecraft safely to and from the ISS. As discussed earlier, on September 16, 2014, NASA announced that SpaceX and the Boeing Corporation would receive the CCtCap awards to develop their respective crew capsules. Boeing won a $4.2 billion award while SpaceX won a $2.6 billion award. These substantial awards would permit the companies to build and certify its capsules through development and testing through several actual low-Earth orbital missions. Once these are achieved, the two companies will be awarded crew transportation contracts much like SpaceX and Orbital Sciences did for commercial cargo.

Other NASA Commercial Programs

In July 2013, NASA's Advanced Exploration Systems Division in the Human Exploration and Operations Mission directorate issued a request for information (RFI) to help the space agency to formulate a robotic lunar landing capability. NASA wanted to expand the concept of commercial partnerships beyond low-Earth orbit. Specifically, the agency was interested in learning about and encouraging efforts in the development of lunar landers delivering commercial payload to the surface of the Moon. Small class payloads of from 30 to 100 kg and medium payloads from 250 to 450 kg were the goals. Increasingly, NASA was looking to the commercial aerospace industry to help formulate and achieve its exploration plans as well.

Six months later, in January 2014, NASA announced "partnership opportunities" for U.S. Commercial Lander Capabilities [9]. NASA had given this new initiative a name: Lunar Cargo Transportation and Landing by Soft Touchdown, or Lunar CATALYST, for short. At this time it called for proposals for the design, development and delivery of robotic landers to the lunar surface. However, these agreements would be unfunded Space Act Agreements, as NASA had drawn up with other companies for other commercial programs; if the missions were successful, they could lead to funded programs.

"As NASA pursues an ambitious plan for humans to explore an asteroid and Mars, U.S. industry will create opportunities for NASA to advance new technologies on the Moon," Greg Williams, NASA's deputy associate administrator for Human Exploration and Operations Missions Directorate, explained in a press release [9]. NASA wants to explore the possibilities of in situ resource utilization, which has long been a goal of advocates of lunar exploration.

NASA is also supportive of independent commercial, private efforts to exploit the potential lunar activities. The Google Lunar X Prize rewards private efforts of several firms to also build lunar landers. The potential rewards are great. In 2013, the X Prize Foundation contracted the British consultancy London Economics to perform an analysis of the possible economic benefits that could be achieved with a sustainable approach in commercial ventures on the Moon. These included harvesting or processing lunar material and spinoff technologies that can be applied to many industries on Earth. London Economics set the timelines at 10 years and 25 years from the present. Its final report concluded that there is a potential $1.9 billion return after 10 years and by 2040, roughly $6.4 billion in market value return on investment.

Nevertheless, the initial investments to mount these exploratory private missions to the Moon are substantial. The Google Lunar X Prize helps to underwrite some of that expense, which will help jump start the first commercial efforts to the Moon. This is the dawn of a new era in commercial space business both in low-Earth orbit and Earth's nearest planetary body. What was once just the province of government is becoming the market of private enterprise.

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Chapter 5
Reducing the Cost to Low-Earth Orbit for Small Satellites

For decades, commercial satellites, regardless of capability and function, have been very large and heavy affairs. New satellites designed and built in the United States, Europe and other nations continue this trend in order to extend their operational lifetime as well as increase their performance and take advantage of the full payload capability of the launch vehicle. Disruptive technologies are now permitting the manufacture of satellites much smaller, lighter, far less expensive and in many ways, as capable as larger commercial and government satellites that have existed for years.

The Federal Aviation Administration's Office of Commercial Space Transportation states that miniaturized satellites, or small sats, consist of six classes according to size and weight. Examples of the Femto and Pico classes of 1 kg or less are rare. More frequently launched are the nano class, between 1 and 10 kg, micro class between 10 and 200 kg, mini satellites between 200 and 600 kg and small satellites weighing between 600 and 1200 kg. In the decade between 2003 and 2012, 175 micro satellites and 122 nano satellites, including both commercial and non-commercial, were launched [1].

Within the nano class of satellites is a subset that has proved popular with government, universities and private companies alike because of its standardization. These are called cubesats. The cubesat design standard was developed by the California Polytechnic State and Stanford University in 1999. Measuring 10 × 10 × 10 cm and weighing 1.0–1.3 kg, this was given the designation 1U. Cubesats, by design, are capable of being 1U, 2U, 3U or 6U in configuration. This size and configuration makes them the preferred choice of colleges and universities because of their relatively low cost, technological sophistication and ability to launch with, or "piggyback" as part of, larger commercial and even non-commercial launches. Nanosats are primarily used for technology demonstrations for spacecraft and applications, i.e., communications and remote sensing. Nanosats have been launched aboard every type of rocket in operation today.

The nano and micro satellite classes will experience significant year-to-year growth in construction and launch from 2015 through 2020. One market assessment projects the annual launch of 300 nano and micro satellites in 2015, climbing to more than 400 of these two classes of satellites by 2020. However, the full market

A. Young, *The Twenty-First Century Commercial Space Imperative*,
SpringerBriefs in Space Development, DOI 10.1007/978-3-319-18929-1_5

potential for these classes could push actual numbers even higher. More than 2500 nano and micro satellites will be launched by 2020 [2].

The capabilities of satellites in these two classes are such that they are being employed as low-cost research spacecraft beyond low-Earth orbit. One satellite in particular, while being a NASA project, points the way to commercial possibilities for lunar orbit spacecraft and further destinations for Microsatellites. Two NASA probes, Lunar Prospector and the Lunar Reconnaissance Orbiter, detected the possible presence of subsurface ice at the Moon's polar regions, and several other probes found water molecules in the lunar regolith at latitudes close to the lunar poles. This is a tantalizing prospect, but the concentration and location of lunar water must be accurately determined before further robotic or even human missions can extract it. If such water could be processed in quantity, it would increase the possibility of future human expeditions to the Moon.

"As we reach the limits of existing data," a NASA scientific paper stated in 2013, "it is clear that a further investigation and mapping of water at the lunar surface [should] determine whether it can be considered an extractible resource, particularly in the lunar polar regions targeted for their subsurface ice reservoirs" [3]. Several NASA centers and affiliated principal investigators from universities collaborated on a spacecraft design around the cubesat standard to further determine the extent of lunar volatiles, as they are called, and at proximities never before attempted. The project is called Lunar Flashlight. It is configured as a 6U satellite. Incorporated in the satellite is an 8-m solar sail that will be the prime means of propulsion to the Moon after its deployment from NASA's Space Launch System.

Such a passive mode of space travel would take several months. Once in lunar orbit, the satellite would begin an elliptical orbit that would take it as close as 20 km above the lunar surface. The solar sails would direct reflected sunlight into specific craters and begin to take readings from its sensors. The findings from the Lunar Flashlight mission will aid in NASA's human spaceflight planning and provide possible incentive for commercial endeavors of various types through NASA's commercial partnership programs.

One commercial firm is already exploring this possibility. Planetary Systems Corporation of Silver Spring, Maryland, is developing a 6U cubesat with a mission entitled Lunar Water Distribution (LuWaDi). The proposed satellite will map the lunar surface for water and other volatiles using a near infrared spectrometer while taking advantage of its core capabilities of manufacturing containerized satellite dispensers, payload separation systems and subsystems.

Commercial Small Sats and Related New Space Companies

Silicon Valley, the technological conglomerate of many large and small engineering firms in the greater Santa Clara Valley in California, has naturally some of the most progressive satellite design capabilities in the world. It also has some of the most expensive real estate in America, which might explain why some firms locate in nearby counties. One of those firms pushing the technological envelope in satellite design is Planet Labs in San Francisco. The startup was founded in 2012 by Will Marshall and Robbie Schingler, who both left NASA to explore a low-cost cubesat design that would image Earth. They were joined by Chris Boshuizen, who also left NASA, lured by the possibility of commercializing the PhoneSat project where he was a co-investigator. The three engineers had a clear vision of what they wanted to achieve and believed cubesat technology could help them achieve it. They also had the financial acumen to secure over $13 million in venture capital from seven different investors.

Planet Labs builds low-cost imaging satellites to provide up-to-the-minute images of the entire Earth. Most available images are often months old, or more. The company founders believed there was a commercial need for more timely images, to help with tracking urban growth (or blight), construction site geography, agricultural monitoring, monitoring of natural resources and other applications. At the same time, in an effort to protect privacy, the company chose to limit the resolution so people and vehicles could not be identified (Fig. 5.1).

The first prototypes of their satellites, about the size of two toasters put end to end, were designed and constructed in a garage in Cupertino, California. The first demonstration satellite, measuring 10 × 10 × 30 cm (known as 3U), was completed in April 2012. A second satellite was built, and the two devices were given the names Dove 1 and Dove 2. The satellites featured deployable solar arrays to keep the onboard batteries charged. Both cubesats were launched aboard separate American and Russian rockets in April 2013. They were injected into their respective orbits and began returning images along their orbital planes in short order. Dove 1 and Dove 2 were technology demonstrators, and they succeeded brilliantly. The first operational fleet of 28 satellites was given the collective name of Flock 1. They orbit at an altitude of 450 km. These have been joined by many

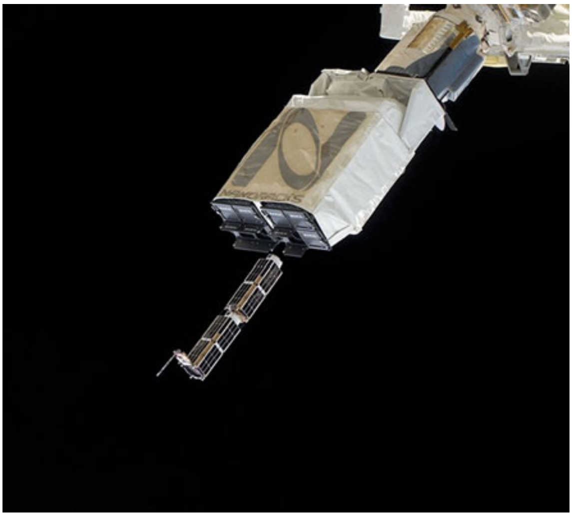

Fig. 5.1 Detail of deployment shows the two cubesats built by PlanetLabs to conduct earth observation and commercial imaging (image courtesy of NASA, used with permission)

other PlanetLab cubesats, and by the end of 2014, more than 70 were orbiting Earth. This is the largest deployment of cubesats by one company in commercial space history. In January 2015, Planet Labs announced it had procured an investment round of $95 million in addition to funds raised up to that point. These will be used to expand its sales and marketing, increase and improve its production capability, and further its product and applications to prospective customers.

Many high tech companies today had modest beginnings in a garage. Skybox Imaging actually formed in a classroom; the garage came shortly thereafter. John Fenwick, Dan Berkenstock, Julian Mahn and Ching-Yu Hu all met in an entrepreneurship class at Stanford University in 2008. Although the assignment was to conduct the steps to form a venture-backed company, they proceeded to do it in fact. They determined a market need for affordable remote sensing—Earth imaging. In January 2009, the group began courting angel investors for their startup and received an initial funding of $3 million. The team looked to commercial off the shelf (COTS) electronics (such as Field-Programmable Gate Arrays, or FPGAs), solar power generation, sensors and digital camera technology as the basis for their cubesat imaging satellite design as much as possible to keep costs low.

The company moved to a 3000-ft^2 facility in Palo Alto, California. Several years of design development followed. Manufacturing of their first production satellite, SkySat-1, began. The completed satellite measured 60 × 60 × 80 cm and weighed 83 kg. It featured four multispectral sensors and one panchromatic sensor and had video capability. At a 450-km orbit, the satellite could achieve an impressive 0.9-m resolution and downlink the images and video in real-time. It was launched in November 2014 aboard a Soviet launcher, achieved its proper orbit and soon began sending images back to Earth. These images were publicly released in December of that year. SkySat-2 was launched in July 2014, and images were released within 48 h of launch.

In June of that year, the company announced it was in talks with Google for acquisition. The global search engine giant wanted in-house imaging capability so it did not have to rely on other suppliers. The $500 million acquisition of Skybox Imaging by Google was completed two months later. The company is now headquartered in Mountain View, California, and proceeding with completion of its 24-satellite constellation, which will provide other products and services to its partners and clients.

The deployment of the Planet Lab cubesats was achieved with the technology of another startup in Webster, Texas, southeast of Houston. NanoRacks is another sign of a company responding to the commercial space imperative. The company was formed in 2009 in an effort to maximize the commercial opportunities inherent in the International Space Station. NASA was receptive to the idea because of its commercial crew and cargo initiative. The company pioneered the design of cubesat payload deployment hardware aboard the ISS. This service is, perhaps, what NanoRacks is most famous for, but the company has successfully launched into other commercial programs on the orbiting space station. Its client list includes NASA, the European Space Agency (ESA), the German Space Agency, PlanetLabs, and numerous universities and even high schools (Fig. 5.2).

Fig. 5.2 Two cubesats are deployed from the International Space Station by the NanoRacks cubesat deployer on February 11, 2014 (image courtesy of NASA, used with permission)

The company knew that research aboard the ISS was a potential commercial hot spot and worked to engineer NanoRacks Platforms, which support proprietary modules measuring 1U built upon the cubesat standard. Platforms is a research facility for companies to have space aboard the station for microgravity research. Each platform measures 17.0 in. by 9.0 in. by 20.0 inches. Up to sixteen payload modules can be mounted within the Platform. The Platform can supply power and data via USB connection. In this way, the researcher on Earth can monitor the status of the experiment or test. When the research phase for that module is completed, it is removed from the Platform by a crewmember and returned to Earth with the next cargo mission. This makes room for the next waiting customer module. NanoRacks has a second laboratory mounted to an external platform on the ISS for research, experiments and remote sensing in the near-vacuum of space. This is the External Platform program and was constructed and installed on the ISS in partnership with Astrium North America.

Orbital Sciences Corporation was among the first satellite manufacturers to engineer, manufacture and launch small satellites into low Earth orbit. Its Orbcomm satellites were first launched as a 35-satellite constellation for a data communications network. The latest group of these satellites, the Orbcomm Generation 2 (OG2), has a mass of only 172 kg. The company has contracted with Sierra Nevada Corporation and Argon ST, a Boeing subsidiary, for the manufacture of these small sats. Six of the OG2 satellites were launched aboard a SpaceX Falcon 9 rocket in 2014, to be followed by two more launches for the remaining 11 satellites.

The company also offers its GEOStar geosynchronous communications satellites capable of direct-to-dish broadcast digital television and business data communications, among other services.

The growth of small sats used in large constellation deployments is now a worldwide development. During the last quarter of 2014, there were numerous filings with the International Telecommunications Union (ITU) in Geneva, Switzerland, for ambitious plans by companies to launch from hundreds to thousands of satellites in various orbital planes to provide global Internet services. The filings came from Canada, France, Liechtenstein and Norway, but the identity of the companies making the filing is not divulged.

Others are not so secretive. OneWeb was formed with the financial backing of Qualcomm and Richard Branson's Virgin. OneWeb was launched by Greg Wyler, whose most recent successful satellite business is O3B, which has a fleet of satellites in a medium-Earth 5000-mile equatorial orbit to provide satellite Internet service to emerging nations. OneWeb is far more ambitious but will use a truly global constellation of more than 600 small satellites. Branson's Virgin Galactic launch vehicle, LauncherOne, will be deployed at runways around the world. This horizontal takeoff carrier vehicle will take an Orbital Sciences rocket to the proscribed altitude. The rocket's payload will be a group of OneWeb satellites, which will be taken to their required orbit by the rocket. The flexibility of LauncherOne will permit deployment of the satellites in low-Earth orbits. OneWeb will be fully operational between 2018 and 2020.

Elon Musk announced his plans for an equally large fleet of satellites to provide Internet service as well, in direct competition to OneWeb. His company, SpaceX, achieved a $1 billion financing arrangement from Google and Fidelity Investments in January 2015. "This funding will be used to support continued innovation in the areas of space transport, reusability, and satellite manufacturing," a corporate press release stated [4]. Announcements like this as well as those for OneWeb, show the dynamic nature of disruptive technology and make satellite industry forecasting a risky endeavor. At the same time, such announcements do not equate to actual hardware, and such announcements may later be altered or plans for such large constellations be scrapped altogether. Iridium was a bold plan to orbit a constellation of more than 60 satellites that would provide global personal satellite phone communication. The company did not secure enough customers, the handsets were very expensive and other related issues eventually resulted in Iridium filing for bankruptcy. Several years later, the assets were purchased for a fraction of the billions of dollars invested, the company restructured, handsets redesigned and service vastly improved, and eventually the new Iridium Corporation was built into a profitable enterprise.

A number of long-time manufacturers of large satellites in the United States have made initial steps toward offering SmallSats. Boeing Space & Intelligence Systems for the first time is designing and manufacturing satellites weighing 1000 kg or less. The company has manufactured its 702 and 601 series communications satellites since the 1990s. Boeing decided to enter the booming remote sensing market with its 502 series satellites. The prototype for the 502 was developed at the company's secretive Phantom Works. This technology demonstrator got the attention of HySpecIQ in Washington, D.C. The production 502 Phoenix will carry the first high-resolution hyperspectral payload in the commercial satellite industry. Depending on the required configuration and capabilities, the Boeing 502 Phoenix can weigh from 250 to 1000 kg (Fig. 5.3).

This specific technology of remote sensing uses spectral color bands to identify objects and materials in images. The satellite can process 200 visible spectrum and shortwave infrared data as an aid to oil, gas, mining, agriculture and environmental evaluation. HySpecIQ ordered two of the satellites, and these will be operational in 2018.

Small satellite technology, design, development, manufacturing and launch has actually been around for several decades. One of the companies that pioneered this satellite class has been Surrey Satellite Technology Ltd. in England. The company was started in the late 1970s and used what is in common practice today in small satellite design and manufacture—commercial off-the-shelf (COTS) electronic components and other hardware to lower the cost of development and improve reliability and performance. At the same time, the company's design engineers strove to package the equipment of smaller, lighter packages that significantly lowered launch costs for its customers. This had the additional benefit of drastically shortening the development time and delivery. The company specializes in

Fig. 5.3 The Boeing 502 Phoenix is the company's offering in the small satellite class. It employs the latest technology of Boeing's larger 600 and 700 series satellites (image courtesy of Boeing Defense, Space and Security Div., used with permission)

delivering satellites weighing under 1000 kg. The company was decades ahead of the satellite industry in filling this market niche, and today SSTL is regarded as the premier small satellite and launch provider in all of Europe (Fig. 5.4).

SSTL can provide satellites capable of Earth observation and imaging (remote sensing), maritime navigation and telecommunications, scientific research, military and other defense requirements and research and technology demonstration satellites. The company also designs the satellite payload platform and secures launch vehicle and services from a range of launch providers. The company's headquarters, which handles engineering, project management, mission analysis and administration, is located in Guildford. A nearby facility conducts the satellite manufacturing, integration and testing. SSTL's Optics Facility is located in Kent, and its Composites and Mechanisms Facility is based in Hampshire. Today the company is part of the European Airbus Group.

The technical capability of designing and manufacturing small sats is within the realm of possibility for companies in countries not previously thought to be participants. Just one example is the Space Technology and Science Group (STSG) in

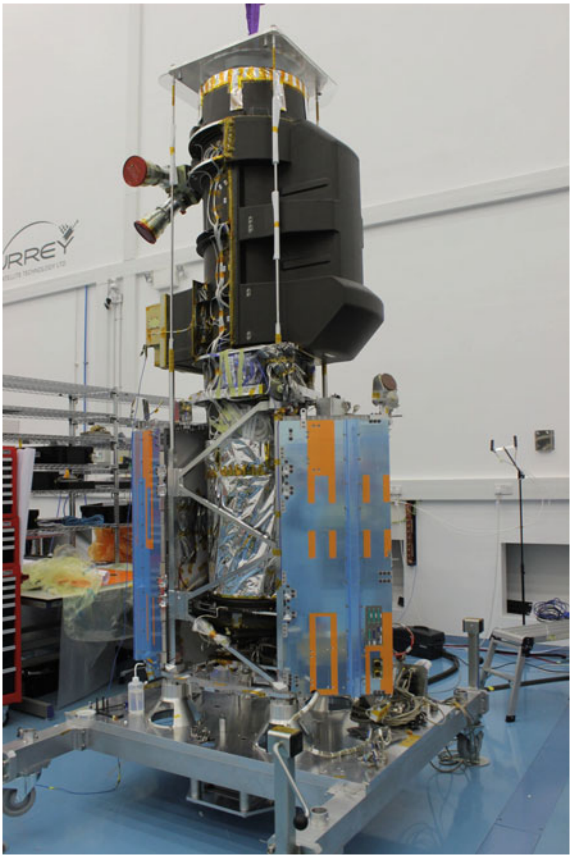

Fig. 5.4 Surry Satellite Technology Ltd. of England specializes in the design and manufacture of small satellites and ground systems (image courtesy of SST Ltd., used with permission)

Espoo, Finland, northwest of Helsinki. STSG is a consortium of scientists, engineers, academics, program managers and missions specialists pulled from other central European countries and even Baltic states. The company has designed, built and launched a variety of satellites, from low-Earth remote-sensing satellites to geosynchronous communications satellites.

As costs of launching small satellites into orbit continue to drop and new launch providers have the necessary capability, this niche within the worldwide satellite industry shows promise of growth in the decades ahead.

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Chapter 6
The Emergence of Personal Spaceflight

Within the commercial spaceflight industry, personal spaceflight perhaps holds the greatest interest with the public. The possibility of personal spaceflight came about, in part, with the flights of Burt Rutan's SpaceShipOne in 2004. This privately designed and funded spacecraft, launched from a carrier jet aircraft called WhiteKnightOne, broke the 50-mile altitude barrier into suborbital space. It also signaled the possibility of commercial personal spaceflight.

It was not Rutan's goal to pursue the design and construction of personal spaceflight transportation as a commercial enterprise. He simply wanted to prove it could be done, and he achieved that. SpaceShipOne now hangs in the Smithsonian Air and Space Museum.

In the United States, other potential markets exist for personal spaceflight as a result of NASA's commercial crew program (CCP). Both the Boeing CST-100 and the SpaceX Dragon v2 capsules are designed to carry six or more passengers. Steve Bezos's Blue Origin is also working on the development of a human-rated capsule. In addition, other spacecraft are being developed to meet the potential market demand for suborbital spacecraft. All these will be explored in this chapter.

A View of Earth from Near Space

Although there has been much press about emerging suborbital and potential orbital personal spaceflight, there is a less costly and more relaxing mode of viewing Earth at the threshold of space. A completely new spacecraft lifted into the upper regions of the stratosphere by balloon offers an experience almost as dramatic as the view from suborbit or orbit. This spacecraft was built by Paragon Space Development Corporation and operated by World View Enterprises, Inc. in Tucson, Arizona. The sleek World View® spacecraft, designed by the British industrial design firm Priestmangoode, is designed for a luxurious experience for passengers to enjoy views of Earth and space from four sides of the spacecraft. The capsule, which has received FAA identification as a spacecraft, can carry six to seven passengers (Fig. 6.1).

A. Young, *The Twenty-First Century Commercial Space Imperative*,
SpringerBriefs in Space Development, DOI 10.1007/978-3-319-18929-1_6

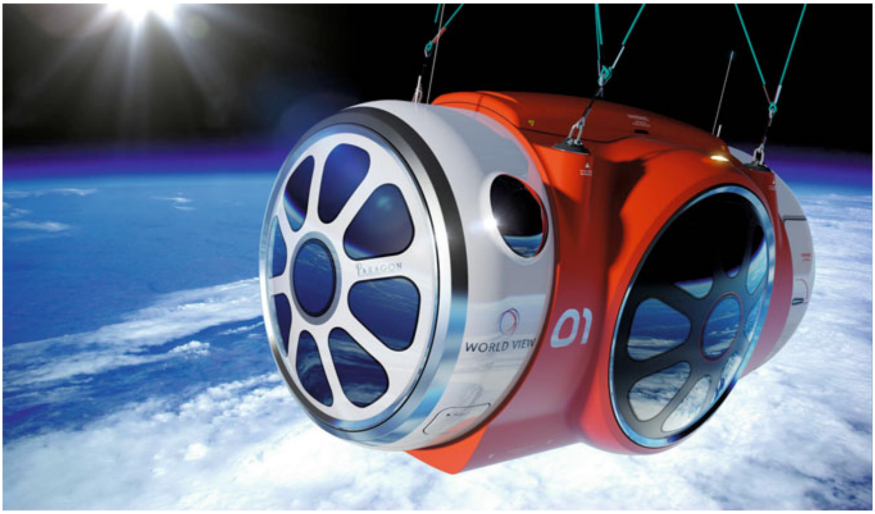

Fig. 6.1 The world view pressurized capsule can take passengers to an altitude of over 100,000 ft by balloon, remain there for up to 2 h, and then descend (image courtesy of World View Enterprises, used with permission)

Paragon Space Development Corporation, founded in 1993 by Dr. Jane Poynter and Dr. Taber MacCallum, has pioneered upper atmospheric balloon research vehicles, life support, environmental controls and thermal control in work for NASA and other commercial aerospace companies. World View was established in 2013 as a division of Paragon to create a balloon-launched spacecraft for purposes of scientific research and education, and ultimately as a commercial passenger spacecraft. World View's spacecraft rises to an altitude of 30 km using proven balloon technology, remains at that altitude for two hours, and then slowly descends to Earth using the same balloon to about 5 km, then will be piloted by a crew-member in a controlled glide under a large parafoil to a pinpoint and gentle landing.

"One of the exciting things about a balloon from a startup perspective is that they are low risk," Poynter stated in an article. "They have been around for decades, [but] there's room for enormous innovation, such as how we can make everything reusable" [1].

Numerous state governments in the United States have passed legislation specifically written for the promotion of commercial space activities. Among them are New Mexico, Texas, California, Colorado, Virginia, Florida and now Arizona. In February 2014, the Arizona House of Representatives introduced HB2163. The state legislature passed the legislation, and it was signed into law by Governor Jan Brewer [2]. Although the legislation varies from state to state, all states have limited liability sections that protect the companies. In a practical sense, this is achieved by having the prospective passenger sign a liability release agreement.

Much the same thing is achieved every time a commercial jet passenger purchases a ticket; buried in the terms of agreement in buying the ticket is the limited liability clause. Commercial spaceflight companies, whether they intend to launch payloads or passengers, need such legislation as protection from crippling lawsuits. The liability release agreement states that the personal spaceflight passenger recognizes there is the possible risk of injury or death in the event of an unforeseen failure of the spacecraft. Such legislation and limited liability agreements will become commonplace as personal spaceflight activities increase in the early 21st century.

World View Enterprises is expanding the services of its spacecraft to the research and education market. Naturally, the company touts the advantages of balloon-launched services over suborbital rockets. The stated advantages are:

- gentler rides
- longer duration flights
- lower altitudes (an advantage in remote imaging)
- greater range over targeted areas of Earth
- an absence of zero gravity
- lower cost per flight [3]

Suborbital Spaceflight

The historic flight of SpaceShipOne into the realm of suborbital space in 2004 was the tipping point for the potential of non-governmental human spaceflight. A new phrase was coined: space tourism. What was once the domain of governments was now open to private enterprise. Burt Rutan and his team achieved this goal in pursuit of the $10 million Ansari X Prize; his company, Scaled Composites, was the only one to achieve it. The financier behind Rutan's research and development of WhiteKnightOne and SpaceShipOne was Microsoft co-founder Paul Allen. Design development began on these air and spacecraft in 2001, and in only three years they were ready to compete for the Ansari X Prize. The competitive flights of SpaceShipOne took place on September 29, 2004, with a maximum altitude of 103 km, and on October 4, with an altitude of 112 km. These flights met the requirements to win the historic prize.

In July 2005, Scaled Composites announced it had signed an agreement with Sir Richard Branson's Virgin Group. Branson saw the potential of commercial suborbital human spaceflight. This new agreement formed The Spaceship Company in Mojave, California, which would design and manufacture the unique launch aircraft and suborbital spacecraft for commercial passenger flights. Branson formed Virgin Galactic to pursue his next business venture [4]. Deposits for the $200,000 suborbital flights were already being made, even though it would be several years before commercial service would begin. The Virgin Galactic website described how passengers would experience their trip into space, the short period of weightlessness, and the gentle return to the landing site. There was also the means to reserve a seat on SpaceShipTwo. However, setting a date when flights would begin would prove to be difficult for Branson. This was flight technology more demanding than had ever been attempted by private companies before, and it would take longer than hoped to achieve (Fig. 6.2).

Tragedy struck on July 26, 2007. Engineers for Scaled Composites were conducting a test of the hybrid rocket engine during a 'cold flow' test with pressurized nitrous oxide. An explosion took place that killed two Scaled Composites employees immediately and a third was seriously injured and later died in the hospital. It was reported that similar tests had been conducted on SpaceShipOne without incident.

Although considerably larger and more complex than the first-generation carrier aircraft and spacecraft, WhiteKnightTwo (WK2) and SpaceShipTwo (SS2) were displayed to the media on December 7, 2009, at the Mojave Air and Space Port in southern California. The next several years were spent performing methodical flight tests of the WK2 and glide tests of SS2. The first powered flight of SS2 took place on April 29, 2013. At 45,000 ft, SS2 was released from WK2, the rocket engine was ignited, and the spacecraft was soon supersonic. The engine fired for 16 s, and SS2 achieved an altitude of 56,200 ft. It then entered its glide phase and landed. The second powered flight took place on September 5th, which tested the feathering system (tilting of the rear booms to create drag and slow the spacecraft).

Scaled Composites continued its test program of SS2 according to schedule. However, on October 31, 2014, during a powered test flight, the feathering system

Fig. 6.2 The Virgin Galactic SpaceShipTwo has been years in development in an effort to make suborbital spaceflight as safe and comfortable for spaceflight participants as possible (image courtesy of Virgin Galactic, used with permission)

deployed prematurely. The aerodynamic pressures on the spacecraft resulted in its destruction and subsequent crash in the Mojave Desert. Co-pilot Mike Alsbury was killed, but pilot Pete Siebold survived. The National Transportation Safety Board began its investigation of the accident. Despite this setback, Virgin Galactic issued a statement that its development program would move forward and completion of the second SS2 in 2015. The Spaceship Company plans to produce several more SpaceShipTwo craft, so there will be a small fleet of these spacecraft.

Today, commercial passenger aircraft flights operate reliably, but the development of the first aircraft came at a high cost of lost life and planes. The development of new spacecraft such as the SS2 and others that eventually will be flown will not be free of risk. Suborbital human spaceflight is in its formative years, and will emerge fully realized for those who can afford the significant cost and accept the attendant risks.

Other means of suborbital spaceflight are also coming to the fore. The XCOR Aerospace Lynx spacecraft has experienced similar delays and missed milestones, which is endemic to the field of personal spaceflight. The development of new propulsion technologies, airframe materials and construction, provision for crew cabin pressurization and environmental controls and flight testing all involve years of design development and validation. A failure during development in any area invariably has an impact on the schedule.

XCOR was founded in 1999 in Mojave, California. The company initially worked on the design and development of rocket-powered aircraft. The first project, the EZ Rocket, was the first private aircraft to be powered by two small isopropyl alcohol and liquid oxygen-burning rocket engines. The aircraft chosen was the proven EZ Long, retrofitted with the XCOR rocket engines. From the start of the project to first flight took nine months. The EZ Rocket was flown 26 times, with numerous flights before crowds at air shows. The rocket engines could be stopped and restarted during flight. It was operated between 2001 and 2005 and was a successful technology demonstrator.

XCOR's next rocket-powered aircraft was the Rocket Racer. XCOR employed another high performance personal aircraft known as the Velocity SE. In this airframe the company installed a newly designed rocket engine they called the Rocket Propellant Piston Pump. Instead of a complex turbopump typically used on rocket engines, XCOR used its RP3 to deliver kerosene and liquid oxygen to the combustion chamber. This engine underwent several thousand firing tests. The XCOR RP3 engine performed without failure over 40 flights of the Rocket Racer. It validated the proprietary rocket engine propellant delivery system.

XCOR research and development funding has been derived from government research contracts, investment capital from investors, commercial development programs and other consulting services. With strong financial backing, XCOR initiated the design, research and development of its next commercial program. The company initiated an ambitious program to design and fly the first suborbital spacecraft to takeoff from a conventional runway, achieve a peak altitude of 100 km, reenter the atmosphere and land at the same runway. This spacecraft is called Lynx. It would be powered by four XR-5K18 rocket engines using the proven propellant pump design. The Lynx employs an all-composite airframe. Unlike the Virgin Galactic SpaceshipTwo, the Lynx will carry one pilot and one passenger.

Lynx flight operations of the fully commercial Lynx II will take place from one of two spaceports. These will be Mojave Air and Space Port in Mojave, California or the island of Curacao off the Venezuelan coast. Development flights are taking place from Mojave. The flight profile includes takeoff from the MASP runway, full-powered ascent for 3 min while reaching nearly Mach 3, engine shutdown at 58 km, and coasting to an apogee of 100 km. The pilot and passenger will experience weightlessness, or microgravity, as it is correctly termed, for several minutes with an impressive view of Earth below and the blackness of space beyond. Gravity will soon take hold of the spacecraft, and the pilot starts the controlled reentry. To slow the spacecraft down, the pilot pulls the Lynx out of its dive, and both pilot and passenger experience a full 4 Gs. Then the Lynx enters a glide pattern, slowly circling the Mojave spaceport site before landing on the same runway it departed from.

Another competitor in the suborbital human spaceflight market is Blue Origin. This company was founded in 2000 by Steve Bezos, who made Amazon.com one of the most successful online merchandizing companies in the world. Bezos had a similar if somewhat less ambitious program to that of Elon Musk at SpaceX of pursuing private launch vehicle and passenger capsule design and development. Blue Origin is headquartered in Kent, Washington—home of Amazon.com—with testing and launch facilities in Van Horn, Texas.

The primary launch vehicle Blue Origin has been developing is called New Shepard. It is unconventional in size, shape and even fin orientation. It consists of a propulsion module powered by the company's liquid hydrogen/LOX BE-3 engines, with a crew capsule that can carry several passengers. The capsule can also be configured to carry scientific payloads. The company states New Shepard Crew Capsule will achieve an altitude of 100 km after separating from the propulsion module. The capsule will experience a period of microgravity of several minutes, before beginning reentry as a conventional capsule, and will parachute to its designated landing site. The propulsion module is reusable and will again fire its engines to initial a powered vertical descent back to its launch site.

As a commercial aerospace corporation, Bezos' Blue Origin is a much smaller and lower-profile company than Elon Musk's SpaceX. The company has not benefitted from government largess to the same degree as SpaceX, although it has received small awards from NASA with respect to commercial program development. The most powerful rocket engine Blue Origin has built and tested to date is the BE-3, with over 160 starts, and a combined engine operation of more than 10,000 s. Each engine has a thrust of 100,000–110,000 lbs. (444,000–489,000 Newtons). The engine has completed a suborbital mission duty cycle at full thrust for 145 s, shut down for 4.5 min, followed by engine restart and throttling to 25 % for the reentry phase of the reusable booster.

In December 2013, Blue Origin president and program manager Rob Meyerson told *Aviation Week & Space Technology,* "We have been focused on the suborbital mission as the starting point to serve as practice for later development of our orbital launch system. That way, we intend to prove out underlying technologies while building out a very small and innovative company capable of repeated successes. Over the next several years you are going to see us flying our New Shepard suborbital system in a development phase, and then starting to fly astronaut passengers over the next several years" [5].

In September 2014, Jeff Bezos and United Launch Alliance (ULA) president and CEO Tory Bruno held a joint press conference. ULA had signed an agreement with Blue Origin for the development of a 550,000 lbs thrust (2.45 million Newton) LOX/liquefied natural gas (LNG) booster engine. This new, more powerful booster stage engine, the BE-4, is being designed for a new generation of ULA launch vehicles. ULA also stated that two BE-4 engines would replace the Russian-built RD-180 used on the Atlas V rocket.

"We are going to do for space, and for your lives, what the Internet has done for the information age," Bruno boldly proclaimed [6]. This is a profound statement and holds great portent of what the new ULA launch vehicles will be capable of and what their potential cargos and passengers might be.

In a prepared press release at the time, Bezos stated, "Blue Origin is methodically developing technologies to enable human access to space at dramatically lower cost and increased reliability, and the BE-4 is a big step forward."

The Potential of Human Orbital Spaceflight

In May of 2001, U.S. citizen Dennis Tito became the first private individual to fly aboard a spacecraft up to the International Space Station. He did not fly aboard the space shuttle; he flew with two Russian cosmonauts aboard a Soyuz spacecraft. A successful and wealthy businessman, he paid the Russian government $20 million dollars for the privilege of making his dream come true [7]. The media referred to him as a "space tourist," and this became a commonly used phrase for non-governmental individuals who ventured into space. The FAA officially refers to these individuals as spaceflight participants.

Over the next eight years, six other spaceflight participants rocketed to the ISS and spent one to two weeks aboard the space station. They all paid for their flights to the ISS from private funds. They are Mark Shuttleworth of South Africa, Gregory Olsen of the United States, Anousheh Ansari (creator of the Ansari X Prize) of the United States, Charles Simonyi of the United States, Richard Garriott of the United States and Guy Laliberté of Canada. Several others, with business backing, also flew to the ISS. Although NASA often objected to these individuals having less than the rigorous training most astronauts and cosmonauts undergo, the space agency had little power to prevent them, as they all flew aboard Soyuz spacecraft launched from the Russian Cosmodrome in Kazakhstan (Figs. 6.3 and 6.4).

An American company called Space Adventures, founded in 1998, was closely involved in the logistics of getting many of these budding spacefarers to low-Earth

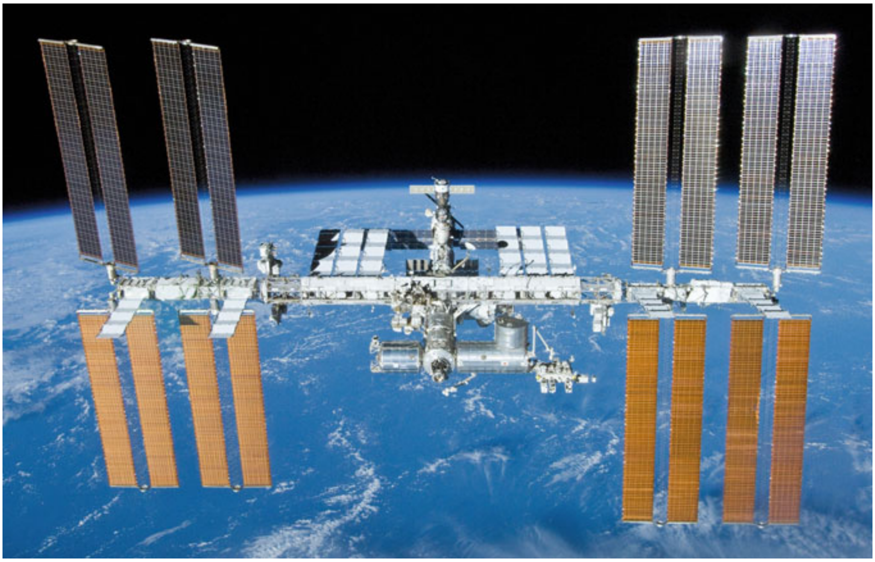

Fig. 6.3 The International Space Station has become a destination of select spaceflight participants from around the world. More will travel there when Boeing and SpaceX crew capsules start service to the ISS (image courtesy of NASA, used with permission)

Fig. 6.4 Anousheh Ansari, an Iranian-American entrepreneur, flew aboard the International Space Station in September 2006 through arrangements made by Space Adventures (image courtesy of NASA, used with permission)

orbit to experience the wonder of their home planet below. None of them, however, flew aboard the space shuttle. They all flew on Soyuz spacecraft. NASA's selection of Boeing and SpaceX to proceed with design development and testing of their respective spacecraft as part of the commercial crew program will change the launch venue from Russia to Cape Canaveral, Florida, for NASA astronauts and mission crewmembers, and future commercial passengers as well.

It is the NASA's CCP that will open the door for prospective spaceflight participants to ride aboard a Boeing or SpaceX capsule. The Boeing CST-100 and the SpaceX Dragon v2 capsules are intended to get NASA crews to and from the International Space Station. Four crew members will typically fly aboard these capsules, but each can take up to seven occupants, and those three extra seats will allow private spacefarers of considerable means to also travel to the ISS and spend a week or more there. NASA is agreeable to taking along such passengers, if they meet the psychological and physiological requirements so as not to put themselves or NASA crewmembers at risk. These new civilian astronauts must be physically fit and successfully pass all mandated training. Their training, however, will be less rigorous than that of the pilots, engineers and scientists who will be performing missions aboard the space station.

Boeing won a $4.2 billion award from NASA in September 2014 to proceed with design development of its flight test capsule as part of its commercial crew transportation capability (CCtCap) program. Boeing let it be known there would be room aboard the capsule for civilians to fly to the ISS as well. The Boeing CST-100 and its crew and passengers will be launched aboard an Atlas V rocket from Launch Complex 41 at Cape Canaveral, not far from Launch Complex 39 that sent the massive Saturn V rocket with their Apollo crew members to the Moon and the space shuttle to low-Earth orbit.

Boeing has been in the commercial passenger jet business since its 707 first took flight in 1958. The company sees this heritage as key to its success in this niche market of taking passengers along with flight crews aboard the CST-100. Boeing Space Exploration engineers on the capsule program partnered with designers in Boeing's Commercial Airplanes division in the design of the capsule's interior. This was a natural and synergistic blending of these two divisions. The capsule program borrowed some innovative features from the latest commercial jet innovations.

"We are going from military-like interiors toward this inflection point of commercial space travel…the next step is to think about the human experience," Boeing engineer Tony Castilleja noted in the company's corporate magazine [8].

"We are moving into a truly commercial space market, and we have to consider our potential customers—beyond NASA—and what they need in a future commercial spacecraft interior," stated Chris Ferguson, former space shuttle pilot and today director of Crew and Mission Systems on the CST-100 program. Ferguson stated in the corporate magazine that he desires "…an inviting and comfortable environment for that commercial customer, so they can look back and say that it was a wonderful experience…so they can say, 'I had the ride of my life" [8].

Partnering with Boeing to prepare passengers for limited trips to the ISS is Space Adventures. The company has ambitious plans of taking them aboard the CST-100 capsule to low-Earth orbit and has even proposed potential circumlunar missions. Boeing likes the fact that Space Adventures has had the experience to organize similar commercial missions with the Russians.

"We've got a great relationship with Space Adventures," John Mulholland, Vice President and General Manager of Boeing Commercial Programs, told *Space News* in November of 2012. "I love the idea of flying people up to the International Space Station. It brings additional awareness to all the good things that are being done on the space station. You build advocacy. So we really hope to be able to partner with Space Adventures and NASA to fly customers in extra seats to the International Space Station."

SpaceX won a $2.6 billion award from NASA as part of the space agency's CCtCap award in September 2014 also. The capsule is an advanced, human-rated version of its Dragon capsule designed to shuttle cargo to and from the ISS. The design of the Dragon for commercial crew has a more stylish exterior design. Influencing the design of the exterior are the four aerodynamic provisions that contain two Super Draco thrusters—very powerful rocket engines designed to separate the capsule from the launch vehicle in a launch abort emergency. Like the Boeing CST-100, the SpaceX Dragon v2 capsule has a service module attached to its base that will carry the power generation, environmental controls and other capabilities to support the capsule. One potential configuration is to employ parachutes for much of its descent and the use of the thrusters during the last phase for a gentle touchdown on land. Initial crewed Dragon v2 capsules will perform ocean landings.

SpaceX has not been as open about its desire to take commercial passengers aboard the Dragon v2. However, the company's CEO, Elon Musk, has strongly championed private, commercial space business and may meet Boeing's private passenger efforts as well. The commercial crew Dragon will be launched aboard the company's Falcon 9 launch vehicle from the reconfigured Launch Complex 40 south of Kennedy Space Center.

Sierra Nevada Corporation was one of the competitors for one of the two commercial crew awards, which it did not win. The spacecraft proposed by Sierra Nevada for NASA's requirements was the Dream Chaser. This spacecraft was in design development at SpaceDev, founded by aerospace entrepreneur Jim Benson, when SpaceDev was purchased by Sierra Nevada in 2008. The basis of the Dream Chaser was NASA's HL-20 lifting body research and development program; the HL-20 was never built. In 2010, Sierra Nevada won a $20 million award to further explore the Dream Chaser design as part of the $50 million awarded that year for the commercial crew development (CCDev) program [9]. Two years later, Sierra Nevada received $212 million from NASA as part of the commercial crew integrated capability (CCiCap), which was the next phase in the program. The spacecraft was designed to carry up to seven crew member or a combination of crew and cargo.

As the Dream Chaser design evolved, the company selected the United Launch Alliance (ULA) Atlas V as the launch vehicle. The company built an Atmospheric Test Vehicle for captive carry, drop, glide and landing tests. During the period between 2012 and 2014, Sierra Nevada also worked on the program milestones and fund-raising requirements; it established its industry partners to convince NASA it could indeed proceed with development testing, production and flight certification to meet NASA's commercial crew requirements.

In September 2014, NASA made the long-awaited down-selection to two companies that would actually build the commercial crew transportation system to get crews to and from the International Space Station. The two companies were SpaceX and Boeing. Nevertheless, Sierra Nevada management had developed contingency plans if it did not win the CCtCap award. It also filed a protest with the U.S. government, but the original decision was ruled valid. The company moved on to exploring other commercial prospects for the Dream Chaser. After CCtCap decision, Mark Sirangelo, head of Sierra Nevada's Space Systems division, outlined the plans for Dream Chaser.

"We are actively developing new customers," Sirangelo explained. "Those markets fall into three main categories: Working in space, discovering in space and observing from space. We are looking at satellite deployment, debris removal, being able to deorbit or reposition things in space and potentially being able to construct things in space" [10].

Sierra Nevada sees the potential in Dream Chaser for microgravity research and other science applications. The company announced the Dream Chaser for Science initiative. This involves a smaller Dream Chaser spacecraft, given the name DC4Science. Sierra Nevada would partner with Stratolaunch Systems. The smaller Dream Chaser would be 75 % in size of the original spacecraft. This would permit it to be carried as the payload upper stage of the Orbital Sciences launch vehicle that in turn would be carried aloft by the massive Stratolaunch aircraft. At 30,000 ft, the aircraft would drop the Orbital Sciences rocket with Dream Chaser. The rocket has two stages and would carry the spacecraft to its planned low-Earth orbit. However, the original Dream Chaser had been under development for years and by 2015 it still had not been launched aboard an Atlas V rocket. Neither Sierra Nevada nor Stratolaunch Systems gave a date when this new launch system would be operational.

The International Space Station is not the only planned destination for companies seeking to take their spacecraft to low-Earth orbit. Bigelow Aerospace headquartered in northern Las Vegas has been pioneering new human-rated space habitats. One of the Bigelow space habitat structures has already been demonstrated in space. NASA has agreed to have one of the Bigelow space habitats remained docked to the ISS for long-term tests. The Bigelow habitats are launched in a compressed state and are deployed—sometimes referred to as inflated—once in low-Earth orbit. Both Boeing Corporation with its CST-100 capsule and Sierra Nevada with its Dream Chaser are now partnering with Bigelow Aerospace to achieve a new era of space habitation.

The principal space habitat Bigelow has been developing is the BA 330. The number derives from the spacecraft's interior pressurized volume of 330 m^3. It will be capable of sustaining up to six astronauts or private space passengers. The habitat has an overall length of 13.7 m and measures 6.7 m in exterior diameter. The wall of the habitat, approximately 0.5 m thick, is made of up to 36 layers of fabrics and synthetic materials that, combined, provide the ballistic (micrometeoroid) protection, radiation shielding and thermal protection the crews will need to survive in low-Earth orbit. The BA 330 will have the requisite solar arrays for power generation and complete environmental control system. The habitat is designed with fore and aft airlocks, and one end fitted with a docking node, identified as the NASA Docking System (NDS) for the Boeing CST-100, SpaceX Dragon v2, Dream Chaser or other spacecraft to dock to the BA 330 (Fig. 6.5).

Bigelow Aerospace has shown numerous different configurations with multiple BA 330 s joining to a common five port docking node, along with a Bigelow-designed and manufactured propulsion unit the company describes as a space tugs. The Standard Transit Tug, powered by conventional propellants, could propel a BA 330 to the desired orbit and be used to maintain the habitat's orientation and orbit. The company also proposes a version of the BA 330 for missions beyond low-Earth

Fig. 6.5 Four Bigelow BA-330 expandable modules are shown as part of a space station, with a Boeing capsule approaching to dock (image courtesy of Bigelow Aerospace, used with permission)

orbit. These have been targeted for lunar orbit missions or for further destinations in space. Bigelow has also mapped a number of lunar surface habitat configurations that would give lunar crews generous living and laboratory facilities.

Bigelow looks to companies like SpaceX to have the lift capability of the Falcon Heavy to launch the BA 330 and its propulsive hardware to low-Earth orbit or even launch missions to the lunar surface. Although much of what Bigelow proposes seems fantastic to the layperson, the company currently has flight test habitats in low-Earth orbit; Bigelow is committed to seeing the BA 330 become the first commercially designed and built human spacecraft habitat. Once the viability of the BA 330 is proven, other commercial possibilities for it will unfold.

The Prospect of Commercial Missions to the Moon

The lunar landing missions during the Apollo program for many remain the apex of human spaceflight. Many volumes have been written about Apollo's geopolitical significance, the vast expansion of technological capability, the creation of almost inconceivable launch vehicles and spacecraft and the marvelous growth in scientific knowledge regarding the Moon. The romantic appeal of human exploration of the Moon is one of the greatest events of the 20th century. Although Apollo, and the manned Mercury and Gemini programs that preceded it, were entirely directed by NASA, it succeeded through the concerted efforts of 400,000 Americans in private companies.

The first lunar landing mission of *Apollo 11* with astronauts Neil Armstrong and "Buzz" Aldrin on July 20, 1969, became the most-watched television event in history. Everyone who watched the ghostly black and white television image of Armstrong setting his boot on the lunar surface of the Tranquility landing site remembers where they were that day. It was certainly America's finest moment and a triumph of President John F. Kennedy's declaration of what the United States had to achieve. The euphoria, however, would soon dissipate, and NASA's budget for the Apollo program was already three years in its decline.

The *Apollo 12* mission with Pete Conrad and Alan Bean on the Ocean of Storms five months later extended the astronauts' time on the lunar surface. The world was gripped by the drama of *Apollo 13* when the Service Module experienced a catastrophic failure and the astronauts had to abort their mission to land on the Moon and return to Earth. Nevertheless, the missions of *Apollo 14* through *17* continued the scientific exploration of various regions on the Moon to unlock its mysteries. This capability was expanded by the addition of a lunar roving vehicle on Apollo 15, 16 and 17. NASA's budget, and political will in general, cancelled the planned missions of *Apollo 18, 19* and *20. Apollo 17* in December 1972 closed the door on America's lunar exploration program.

However, NASA initiated several long range mission studies during the 1980s and the 1990s that were worthy of a great spacefaring nation, and all of them called for a return to exploring the Moon. Attempting to recapture the political drama engendered by President John F. Kennedy's original congressional speech, President George H. Bush announced on July 20, 1989, the ambitious Space Exploration Initiative. Spread over a twenty- to thirty-year period, the reported cost of such a program was $500 billion [11]. This and subsequent human space exploration programs beyond low-Earth orbit, such as the Vision for Space Exploration, would all meet the same political fate. America's human spaceflight program would remain Earth-centric, with the space shuttle and the International Space Station consuming much of NASA's budget.

In 2010, the Golden Spike Company was founded in Colorado with the objective of providing a human exploration expedition to the Moon for countries, corporation, and individuals in the 2020s. The company began to assemble its board members and advisors, establishing its business plan and prospects for financing. One of the board members was Apollo astronaut James Lovell. In September 2013, Lovell wrote an opinion piece that was published by several news outlets. He wrote, in part, "…for many people, including old astronauts like myself, the human exploration of the Moon remains America's crowning achievement amid the stars. It is certainly an event worth repeating, and many of us have long argued for sending new generations of explorers back to our closest celestial neighbor as a first step toward developing the skills and technologies needed to travel deeper into our own Solar System" [12].

Golden Spike does indeed have an impressive group of corporate members and scientific advisors. They are veterans of the aerospace corporations, universities and scientific institutions. The company intends to draw on new commercial aerospace technologies and launch vehicles and personal spacecraft to form the basis of the lunar exploration architecture. The biggest technological challenge is the design of its lunar lander. However, this will be mitigated by sending two, not three, astronauts on lunar missions, employing several existing launch vehicles, and using Earth-orbit refueling. The refueled upper stage, along with the capsule and service module, will then proceed to rendezvous with a lunar orbiting lander launched earlier. As with Apollo, the astronauts will transfer to the lander, undock and descend to the lunar landing site. They will proceed with their mission objectives over several days. Upon mission completion, the astronauts in the ascent stage of the lander will return to the orbiting spacecraft. They will proceed with trans-Earth injection, the capsule will separate from the spacecraft and reenter Earth's atmosphere. Depending on the capsule, it will come down either on land, water or perhaps a mobile landing platform at sea.

Golden Spike believes it can provide national governments missions of two days duration on the lunar surface for roughly the cost of robotic missions to Mars. The company quotes a price of around $1.5 billion. Spacecraft autonomous rendezvous and docking, with similar technology for the lunar lander, would preclude the need for exhaustively trained pilot astronauts and permit other candidates to fly the mission. The company believes current Atlas, Delta Heavy and Falcon rockets have the performance to achieve the mission profile. The Boeing CST-100 and SpaceX v2 capsules, with modifications, could perform circumlunar missions. Lunar landing technology capability is mature, based on robotic missions to Mars, but new systems must be designed and tested for the Golden Spike lunar lander.

The company admits the biggest challenge is not in the area of technology or engineering, but on proving its capability to nations to achieve private lunar missions and getting them to commit. One of this nations might possibly be the United States. NASA could see a Golden Spike mission as an extension of its commercial partnership program. When one considers the contract award of $2.6 billion to SpaceX and $4.2 billion to Boeing for development of their respective crew capsules, funding of a mission to the Moon by NASA using Golden Spike is within the realm of possibility. Although this is years away, one should recall the previously cited quote by Dr. Wernher von Braun regarding his reluctance in using the word impossible.

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Chapter 7
Commercial Space, National Competitiveness and STEM

The commercial space imperative is now driving advances in rocket propulsion and launch vehicles, cargo and crew capsules, mission planning and management, satellites and other payloads of previously unimagined size, and new manufacturing processes and technologies. These changes are happening globally. Eleven years into the twenty-first century, the United States was in the position of no longer having the capability of launching its own astronauts from American soil. With the retirement of the space shuttle, America now had to face the geopolitical embarrassment and expense of having Russia provide these launch services.

How the United States temporarily lost its ability to conduct human spaceflight is known and documented, but the loss of this capability also heightened the perceived awareness that America was slipping in many of the fields within engineering and science while emerging countries were flexing their intellectual and technological prowess by designing, building and launching rockets and orbiting payloads. China and Russia were, for a time, the only nations launching humans into orbit. The one nation on Earth that succeeded in sending explorers to the Moon had lost its preeminent position of being the leader in human spaceflight. America's competitiveness globally was seriously called into question. There was no shortage of critics of the U.S. educational system, lack of investment in research and development, and possible solutions to resolve the problems.

All the aspects that make up commercial space industries as well as human spaceflight are engines of innovation and technological advancement. These provide many measurable and immeasurable benefits to society. When the wheels of the space shuttle *Atlantis* came to a stop on the Kennedy Space Center shuttle landing strip on July 21, 2011, the United States entered a new yet familiar era when its astronauts, international crew members and impressive missions were grounded. And yet, it was this very same human spaceflight finale that would usher in a new era of commercial human spaceflight.

Between the end of the Apollo-Soyuz mission in July 1975 and the first shuttle mission STS-1, with astronauts John Young and Robert Crippen aboard in April 1981, was almost six years. A similar period will have elapsed between the last shuttle flight STS-135 in 2011 and the first crewed missions to once again depart from the Florida spaceport. SpaceX and Boeing with United Launch Alliance (ULA) will resume American crewed missions launched from the Florida cape so

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they no longer have to be launched aboard Russian launchers and capsules from the Baikonur Cosmodrome. Although temporary, this human spaceflight gap is symbolic of other sectors of the American economy that have suffered in recent decades.

In 2009, the *Harvard Business Review* published a report on the status of America's high-tech product competitiveness relative to other nations around the world. The article cited research by the National Science Board on the U.S. trade deficit in technological industries. The sectors included biotechnology, life sciences, aerospace, information and communications, advanced materials, electronics, nuclear technology, weapons, optoelectronics, life sciences, computer software and flexible manufacturing. The U.S. trade balance in these sectors began declining in 2000, when the country had a surplus of $27.8 billion. By the next year it stood at $4.8 billion and thereafter entered into a dramatic deficit. By 2007, this trade deficit stood at $53.6 billion [1]. The report also stated average weekly wages across all sectors had remained essentially flat since 1980; the standard of living for most Americans had not risen at all in 30 years.

The *HBR* article pointed to a number of technical product industries that have vanished from the United States. Research and development, product innovation and manufacturing capability are all inextricably intertwined, and with all of them, the jobs as well. Outsourcing to overseas manufacturing locations of certain portions of a product led to fewer products manufactured in the United States and American plants closed. Among the lost American industries the article reported are 'fabless' semiconductors with DRAMs at risk of also disappearing, electronic displays; lithium-ion, lithium polymer and NiMH batteries used in millions of portable electronic devices; virtually all desktop, notebook and other portable computers, low-end servers and hard-disk drives; blade and mid-range servers, mobile handsets, optical-communications components and core network equipment are at risk of also being lost. These are examples only in the electronics sector.

A much more broadly based and detailed study was conducted by the Information Technology and Innovation Foundation, issued in 2011. Using a matrix of sixteen national indicators, it measured the global competitiveness standing of the United States and European countries against other countries in the world. The sixteen indicators were grouped according to six major categories:

- Human capital: Higher education attainment in the population, ages twenty-five to thirty-four years, and the number of science and technology researchers per 1000 employed.
- Innovation capacity: Business investment in research and development (R&D); government investment in R&D; and the number and quality of academic publications.
- Entrepreneurship: Venture capital investment and new firms.
- Information technology (IT) infrastructure: E-government; broadband telecommunications; corporate investment in IT.
- Economic policy: Effective marginal corporate tax rates; the ease of doing business.

- Economic performance: Trade balance; foreign direct investment inflows; real GDP per working-age adult; GDP per hour worked, or productivity [2].

Although these categories are general in nature for the purposes of the original research, they are reflective of the commercial space sector and underscore the importance of the commercial space imperative.

With regard to the above analysis, the research findings proved the United States is not number one in any of the sixteen indicators or even the six categories. The EU fared even worse. The overall score placed the United States fourth, behind Singapore, Finland and Sweden. The EU-15 countries ranked 18th. The United States was 10th in higher education attainment, 6th in science and technology researchers, and 5th in business investment in R&D. In terms of venture capital investment as a percentage of GDP, the United States ranked 11th, after the United Kingdom (4th), Ireland (7th), France (8th) and even Spain (9th). Trade balance as a percentage of GDP is a prime indicator of a nation's competitiveness, but the United States has fallen dramatically in this respect. It ranked 37th out of 44 nations surveyed. The report stated that progress in the sixteen above categories between 2000 and 2011 relative to other nations, the United States ranked second to last place; the country was 43rd, just ahead of Italy.

"Overall," the report stated, "these trends suggest that absent concerted public sector effort by the United States and Europe to boost innovation and competitiveness, this century will not be the Atlantic century, but rather the Pacific century, or perhaps more accurately the Southeast Asian century.

"Regaining global innovation-based competitiveness means moving aggressively into next-generation industries, including advanced IT, robotics, nanotechnology, biotechnology, and high-level business services, while at the same time maintaining output in highly efficient and competitive traditional industries…" [3].

Competitiveness and Science, Technology, Engineering and Math (STEM)

Coupled with the ability to compete globally is the national impetus to have men and women educated in the fields of the sciences, technologies, engineering disciplines and mathematics. The study of these needed core skills and the general perception that the United States in particular is lacking in these vital fields has been the focus of foundations, think tanks, research organizations, corporations, the media and the federal government itself (Fig. 7.1). The Organization for Economic Cooperation and Development surveyed 150,000 men and women in 24 different countries between the ages of 16 and 65. The respondents in the United States "ranked 21st in mathematic problem solving," a *U.S. New and World Report* article stated [4].

Not a session of Congress goes by where there is not a hearing on the status of education in the United States and the state of STEM education in particular. In Washington, DC., on April 2013, a hearing took place sponsored by the Subcommittee on Early Childhood, Elementary and Secondary Education. Chairman of the subcommittee, Todd Rokita, reported that in the previous ten-year period, the number of STEM jobs grew three times faster than non-STEM positions. He added that the Bureau of Labor Statistics expected the United States would create over 9 million jobs in STEM fields over the next decade. The general consensus is that there will be a dramatic shortfall of qualified graduates for all the jobs. There is no lack of effort on the U.S. government's behalf to address this education crisis, it was reported. Thirteen government agencies administer over 200 STEM education programs. The Department of Health and Human Services, the Department of Energy, the Department of Education and the National Science Foundation account for the majority of administered programs [5].

It was reported in the hearing that a mere 5 % of American college graduates receive degrees in engineering compared to 12 % of European students and 20 % of Asian students. Greater efforts were needed to be done to introduce engineering education with emphasis on science and mathematics from kindergarten through the 12th grade. Those at the committee hearing had vested interests in seeing a greater emphasis on courses in science, engineering, technology and mathematics in state and local school systems, along with increased funding by the Department of Education and the other agencies that disburse funds.

The STEM debate is not one-sided, and there are other voices saying there is concern but no crisis. In 2008, the Rand Corporation issued a comprehensive report on the status of science and technology with respect of American competitiveness. The report stated, based on RAND's findings, that the United States accounts for 40 % of global R&D spending, employs 70 % of the world's Nobel Prize winners, employs 37 % of Organization for Economic Cooperation and Development (OECD) researchers, produces 63 % of highly cited publications, and is home to 75 % of the top 20 universities in the world. It also stated that, although China, India and South Korea show significant inputs to R&D relative to their own economies, those countries have a small share of patents, peer-reviewed journals and citations. The report went on to state that United States R&D funding and subsequent low unemployment among science and engineering is "vibrant," adding, "…there is no evidence of a current shortage of S&E workers. However, the diminishing share of degrees awarded to U.S. citizens, particularly for the higher degrees such as doctorate and master's, suggests that S&E careers are becoming less attractive to U.S. citizens; alternatively, U.S. citizens encounter more competition (from foreigners) in applying for a limited number of spots at S&E colleges and universities" [6].

"In short," the RAND report summarized, "our assessment of the measures we have examined indicates that the U.S. S&T enterprise is performing well. We find that the United States leads the world in S&T and has kept pace or grown faster than the rest of the world in many measures of S&T. We also find that the United States has continued to invest in its S&T infrastructure and … S&E workers through immigration. However, there are potential weaknesses in the persistent underperformance of older K-12 students in math and science, in the limited attractiveness of S&E careers to U.S. students, and in the heavy focus of federal research funding on the life sciences…" [7].

A contrarian view to the conventional wisdom of there being a STEM crisis was published by the Institute of Electrical and Electronic Engineers (IEEE). The report cited sources stating that wages for U.S. STEM workers in the fields of math and computer science have stagnated since 2000, which has had a dampening effect on graduates considering entering those professions. In 2014, it was reported that IBM laid off nearly 50,000 employees worldwide, dropping from 431,000 to 380,000 [8]. The IEEE report, published in 2013, stated that new college graduates with engineering degrees as well as those with Ph.D.'s still find it difficult to secure long-term employment. Consequently, there is a career exodus from STEM professions. As many as 58 % of STEM degree holders leave their chosen profession within ten years of receiving their degree, according to a 2011 study by Georgetown University [9].

What impact will new commercial space endeavors have on employment in the fields of aerospace engineering, electronics, manufacturing, software programming and related fields? One could track the employment growth of SpaceX as an example, albeit an extraordinary one, of the growth in STEM jobs within the commercial space sector. From its founding in 2002 through the end of 2014, the company continued to grow to more than 3600 employees.

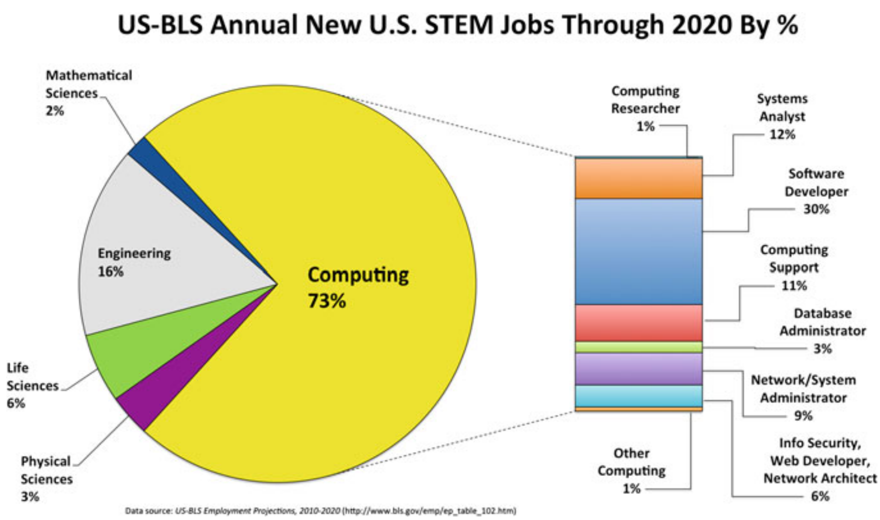

Fig. 7.1 The United States Bureau of Labor Statistics reports the preponderance of job demand in the STEM fields through 2020 will be in computing (image: U.S. Bureau of Labor Statistics)

The Commercial Space Imperative and Prospects for the Future

The topics covered in this brief volume point to an increasing trend in the emergence of commercial space businesses and the creation of products and services that did not exist prior to the turn of the century. Although government-funded space activity remained relatively flat for decades, the new commercial space sectors, or NewSpace, demonstrate creativity, vision, breakthrough technological capabilities, significant profits for their investors and in some cases, inordinate wealth for the founders. As these commercial businesses grow, so do the number of employees within the company. Some industries, like remote sensing, are proving to be successful commercial space enterprises. Others, like those interested in mining resources from the Moon or asteroids, have yet to be proven and stretch credulity.

History is replete with pioneering efforts in new fields of endeavor before they eventually became successful industries and launched competitive firms to offer better products or services. If the present state of commercial space business is any indication, the future will see further expansion in many areas and the creation of new industries, technologies, products and services yet to be imagined.

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