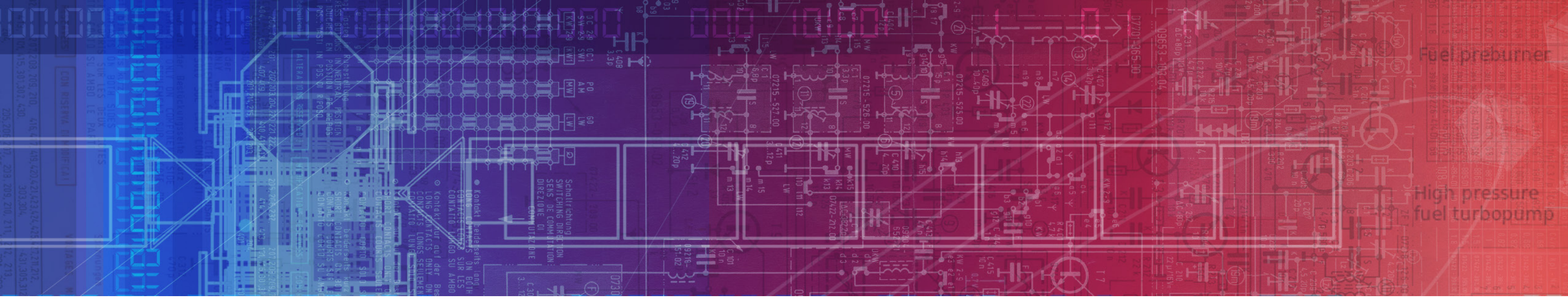
National Aeronautics and Space Administration

Public-Private Partnerships for Space Capability Development

Driving Economic Growth and NASA's Mission

April 2014


Fuel preburner
High pressure fuel turbopump

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National Aeronautics and Space Administration

Introduction

This report is the result of a study into potential areas of public-private partnerships for space capability development that could meet NASA's mission objectives as well as generate significant economic returns to the American economy. The study focused on 8 areas of space capability development that show positive indicators of private-sector interest and investment, new business formation, and alignment with NASA's goals – thus making them strong candidates for economic stimulation with increased NASA partnerships. The term "public-private partnerships" is used to represent a broad spectrum of partnership implementation methodologies and is not meant to convey a specific agreement mechanism or strategy. Please note that the 8 areas highlighted in this report do not represent an exhaustive examination of all the potential areas that could benefit from public-private partnerships.

The National Aeronautics and Space Act, 51 USC § 20112(a)(4), and the National Space Policy, 2010, mandate NASA work with industry to advance the commercial space sector:

National Aeronautics and Space Act

To seek and encourage, to the maximum extent possible, the fullest commercial use of space

National Space Policy

A robust and competitive commercial space sector is vital to continued progress in space. The United States is committed to encouraging and facilitating the growth of a U.S. commercial space sector that supports U.S. needs, is globally competitive, and advances U.S. leadership in the generation of new markets and innovation-driven entrepreneurship

Three examples from NASA's history of space capability development illustrate the great potential for economic impact: the history of NASA's assistance in the growth of the American semiconductor industry, NASA's investments that helped establish the U.S. commercial communications satellite industry, and NASA's partnerships for the development of U.S. commercial cargo space transportation systems. Each of these contributed to U.S. economic growth in different ways; through providing substantial early demand as an anchor customer for an important component technology, through the direct development of a commercially valuable space technology, and through investing in the development of new private-sector space transportation capabilities.

Integrated circuits

The worldwide revolution in personal computers, mobile phones and digital home applications has been made possible by the low-cost production of integrated circuits – a process that was given a critical early boost from the Apollo Program with demand for large numbers of integrated circuits for the Apollo Guidance Computer. Although integrated circuits had been independently invented in the corporate labs of Texas Instruments and Fairchild Semiconductors, it was the Apollo Program, and other U.S. space programs, that made up over 70 percent of the worldwide demand for the components as late as 1965. Although progress in integrated circuits was not an objective of the program, the need to advance computing capabilities to meet the needs of the Apollo Program led to the program becoming an early anchor customer in the development of integrated circuits technology. With the

Figure 1. The Display and Keyboard (DSKY) mounted in the Main Display Console of Apollo 13's Command Module "Odyssey." The DSKY is connected to the Apollo Guidance Computer. Source: Bruce Yarbro/Smithsonian Institution.

stringent quality and performance requirements of Apollo, early semiconductor companies learned through filling a government need how to scale-up the production of a technology that would soon have broad application. The price of these circuits would plummet as these companies perfected manufacturing methods aided by Apollo. This demand provided an opportunity for American semiconductor manufacturers in Silicon Valley to increase the scale of their operations, thereby reducing the cost of semiconductors to the point where their incorporation into other applications – such as personal computers – became economically possible. The U.S. investment in the Apollo program thus provided a critical source of early demand as an anchor customer in the origin of modern day Silicon Valley.

Communication Satellites

In addition to providing a source of demand for new technological capabilities, NASA has also engaged in the direct development and demonstration of promising new commercial space technologies which have, in turn, provided the basis for American leadership in commercial satellite applications. The explicit development of communication satellites was one of the core objectives laid out in President Kennedy's famous speech to Congress that announced the Apollo objective on the 25th of May, 1961. In addition to the challenge of a Moon mission and weather satellites, he also highlighted, "Third, an additional 50 million dollars will make the most of our present leadership, by accelerating the use of space satellites for world-wide communications." AT&T was also developing its own Telstar commercial satellite. Shortly thereafter, NASA signed a contract with the Hughes Corporation to build Syncom for the demonstration of synchronous orbit, on-orbit station keeping, and measurements of communication link performance in synchronous altitude. NASA continued this active role of assisting the U.S. commercial communications satellite industry up through the late 1970s with the Applications Technology Satellite 6 (ATS-6), launched in 1974, which was both the world's first Direct Broadcast Satellite (as part of the Satellite Instructional Television Experiment between NASA and ISRO) and the first experimental

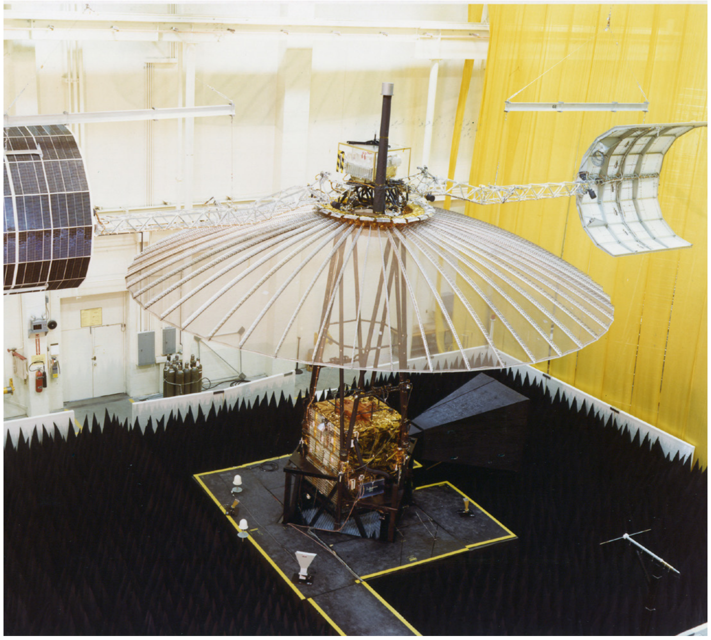


Figure 2. NASA's ATS-6 undergoing testing. Source: NASA.

use of ion thrusters for in-space electric propulsion on a communications satellite. NASA has thus historically had success in developing and demonstrating genuinely commercially valuable space technologies, and then allowing for the successful transfer of those technologies and capabilities to American industry.

Commercial Orbital Transportation Services

The Commercial Orbital Transportation Services (COTS) effort is an important example of the potential for partnerships to enable capability development that is then available to both Government and industry customers while also advancing U.S. economic competitiveness. The forecast shortfall in International Space Station (ISS) logistics needs after the Shuttle retired provided a significant market opportunity for the emergence of commercial space transportation services. To stimulate the commercial space transportation industry's ability to fulfill these needs, NASA established a two-phased approach. The first phase was the COTS partnerships for the development and demonstration of transportation systems to low-Earth orbit. The follow-on phase was the procurement for Cargo Resupply Services (CRS) to support the extended operations of the ISS which offered a predictable and reliable market for the new transportation systems. Although the CRS procurement was conducted under an independent full and open competition, the contractors were required to demonstrate the ability of meet ISS integration requirements prior to execution of the resupply missions.

Under the COTS effort, NASA used its Space Act Agreement authority to enter into partnerships for the development and demonstration of new commercial cargo space transportation systems to low-Earth orbit (LEO). Through competitively-awarded funded Space Act Agreements with SpaceX and Orbital Sciences, NASA acted both as an investor and advisor by providing seed money and technical expertise that resulted in two new U.S. private sector space launch vehicles and spacecraft – the Falcon 9/Dragon and the Antares/Cygnus. COTS was the first NASA program since the development of the Space Shuttle in the 1980s to successfully result in new space transportation systems capable of carrying cargo to and from human destinations in LEO. In addition to this critical achievement, these new capabilities eliminated NASA's dependence on Russia

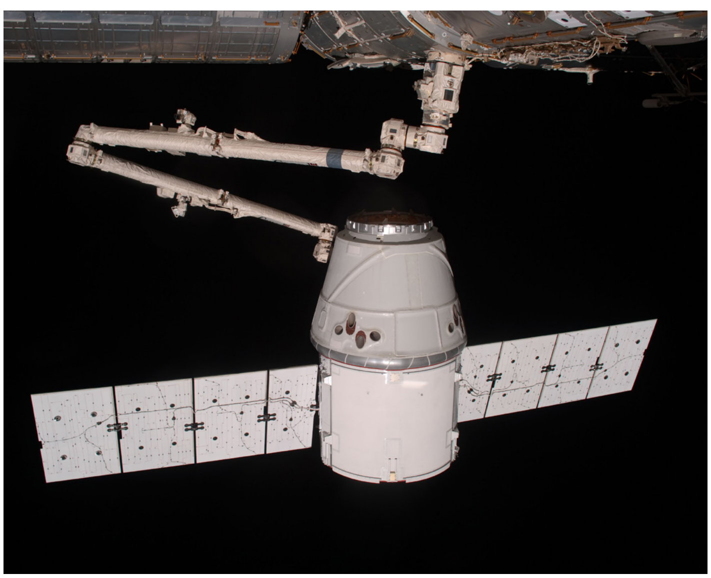


Figure 3. SpaceX's Dragon vehicle is berthed with the International Space Station on May 25, 2012 as part of COTS-2+, the second demonstration mission required under NASA's Commercial Orbital Transportation Services (COTS) program. Source: NASA.

and other foreign countries for cargo transportation to the ISS. Development and demonstration of these new transportation capabilities was achieved at a significantly lower cost than traditional NASA development efforts. Using a fixed price, milestone based payment approach, the financial risk to the Government was minimized and over half the development costs were financed by the COTS partners. Furthermore, the availability of new low-cost U.S. launch capabilities in the private-sector is allowing the U.S. to be globally competitive and recapture a larger share of the launch market lost to international competitors over the past decade. Through partnerships, the COTS example demonstrates that NASA can enable the development of critical space capabilities, realize cost-savings by leveraging private-investment and innovation, and contribute to U.S. economic growth and economic competitiveness.

This study has focused on areas where there are positive indicators of potential economic impact and potential for partnership between NASA and industry. The objective, however, is not to provide a single set of answers but rather to explore a set of questions. Where could increased NASA demand stimulate an important general purpose technology next, as it did with semiconductors? Where could NASA help develop and demonstrate the technology for a whole new U.S. industry – as it did with the commercial satellite industry? Where could NASA apply the commercial space partnership model pioneered in the COTS effort to further develop the capabilities needed for sustainable exploration of the solar system, while cost-effectively leveraging private sector investment and NASA expertise driving economic growth in the process? This study provides some of the core material - empirical data and economic analysis - to assist with thinking through these critical questions. This report provides empirical data and economic intelligence in the following areas – satellite servicing, interplanetary small satellites, robotic mining, microgravity research for biomedical applications, liquid rocket engines for launch vehicles, wireless power, space communications, and earth observation data visualization.

Satellite Servicing

- Global satellite industry largest commercial space market with $190B in revenues
- $2.2B (1997-2007) in lost revenue from GEO satellites launched to wrong orbit
- $700M in insurance claims since 2008 as a result of satellites deployed to wrong orbits or fuel leaks
- 86 potential satellite servicing opportunities identified for 1990-2010
- Two major companies, ATK and MDA Corporation, invested significant sums in satellite servicing

Interplanetary Small Satellites

- Number of cubesats launched each year is growing
- Four companies currently operate constellations of satellites under 150 kg; two start-ups, Skybox Imaging and Planet Labs, began launching small satellites in 2013
- Over $100M raised by small satellite companies in venture capital and angel investment over the last few years
- Over $1M in capital has been raised through Kickstarter for new small satellite companies

Robotic Mining

- Total profits from terrestrial mining was $133B in 2011
- Global market for mining expected to grow 8.5 percent annually through 2018
- U.S. companies—including Planetary Resources, Moon Express, and Deep Space Industries—have announced plans to mine extraterrestrial resources

Microgravity Research for Biomedical Applications

- $93B U.S. biotechnology industry has over 2,000 companies; industry expected to grow as population ages; 57 percent of the industry is biomedical technologies
- Large biotech companies, Amgen and Merck, are conducting research on ISS
- Demand for drugs to treat diseases similar to those resulting from extended spaceflight is high; ~30 percent of the best-selling 100 drugs are for degenerative diseases like arthritis, cancer, and osteoporosis

Liquid Rocket Engines for Launch Vehicles

- Aerojet Rocketdyne and SpaceX are primary manufacturers of LREs, four other U.S. companies at various stages of developing LREs
- $2.5B to $3B annual revenue for the commercial launch industry with an average of 19 launches a year
- In the next 10 years, the commercial launch market is expected to grow to an annual average of 31 launches

Wireless Power

- Demand for electricity is expected to double between 2000 and 2030
- The wireless charging market is expected to grow from $1B to $6B by 2020

Space Communications

- Telecommunications is a $4.9T industry; communications satellite services is $114B and grew 7 percent in 2012
- In 2002, telecom satellites provided 1.4 terabits per second; demand expected to grow to 1,000 terabits per second by 2020
- U.S. and European governments investing in laser communications that can significantly increase data rates

Earth Observation Data Visualization

- Global geospatial services industry revenues estimated at $73B in 2012
- Space-based remote sensing technology revenue is estimated to grow at CAGR of 7 percent from 2012 to 2017
- Demand for geospatial data is increasing; smart phones market penetration is growing at 20 percent a year, and use of sensors is growing at 30 percent a year
- One established commercial satellite remote sensing company, with at least four new companies being formed in the U.S.

Table 1. Major economic indicators for each capability area

Satellite Servicing

Satellite servicing involves the robotic or human capability to rescue, reposition, repair, inspect, or refuel satellites. Satellite servicing capabilities also offer the potential to mitigate and remove orbital debris. As humans venture farther from Earth, crews will need to be more self-reliant. The ability to perform servicing on spacecraft is thus likely to increase in importance. Satellite servicing has the potential to increase the service life of on-orbit assets and save costs by reducing mission risk. NASA is currently advancing this industry by testing technologies for servicing spacecraft. Public-private partnerships could help close the business case for U.S. companies, allowing the U.S. to become the world leader in satellite servicing while providing NASA capabilities for fixing or extending the life of its spacecraft.

Commercial Application

Commercial satellite servicing applications involve using autonomous servicing spacecraft for a variety of scenarios including: rescuing satellites in stranded orbits; repositioning satellites into orbital slots or graveyard orbits; refueling satellites; inspecting satellites; assisting with the deployment of jammed solar arrays and antennas; moving out-of-place thermal blankets and cables; and transplanting components from retired satellites into operating ones. Satellite servicing systems can also be used as a proxy upper stage to deliver satellites with less propellant, which could translate into lower launch costs. Once deployed by the launch vehicle, the on-orbit servicing spacecraft would pick up the satellite and transport it to its destination. Satellite servicing may also provide an option to identify and remove orbital debris.

Some geosynchronous satellite telecommunication operators like Intelsat welcome the opportunity to launch satellites featuring greater transponder capacity in lieu of propellant mass. More capable satellites could improve the competitive advantage for satellite telecommunication providers over competitors providing terrestrial services.

NASA Application

NASA deployed and successfully tested a satellite refueling demonstrator during the 2011-2013 Robotic Refueling Mission aboard the International Space Station (ISS). This mission demonstrated that satellites not specifically designed for refueling could in fact be refueled using a remote control robot. However, NASA crewmembers have serviced and repaired satellites

Figure 4. NASA's Robotic Refueling Mission system being installed on the International Space Station. Source: NASA.

and spacecraft on orbit for the past 30 years. NASA's first servicing mission was the 1973 Skylab mission to affix a new thermal shield lost during launch and to deploy a stuck solar panel. The shield, which also served as protection from micrometeroids had to be replaced to ensure Skylab did not overheat. Other on-orbit repair missions include the 1984 rescue mission of the Solar Maximum Mission, the 1984 rescue and refurbishment of Palapa B2 and Westar 6, and five Hubble Space Telescope servicing missions since 1993. General maintenance and servicing of the ISS also strengthens satellite servicing capabilities.

The Defense Advanced Research Projects Agency (DARPA), with participation by NASA engineers, conducted the successful Orbital Express satellite servicing demonstration mission in 2007.

Market Overview

There are 1,046 satellites in operation around Earth;

432 are in geosynchronous orbit (GEO) and 614 are in medium Earth orbit (MEO) or LEO.[1] Satellites in GEO represent the greatest market potential for satellite servicing because that's where most of the high-value, commercial communication satellites are located.[2]

Satellite services such as television, telephone, data, and remote sensing generated about $190 billion in revenue in 2012.[3] Companies that operate satellites in GEO are responsible for the majority of this revenue. A typical GEO communications satellite with 48 transponders will generate about $96 million in annual revenue, with a potential increased operating revenue total of $480 million over a five-year life extension enabled by satellite servicing.[4] Each year, around 25 GEO satellites are retired; about 10 (40 percent) of them are only retired because they run out of propellant.[5] Satellites may also be deployed to wrong orbits due to hardware failure. For example, in 1990, Intelsat 603 was deployed to the wrong orbit due to a launch vehicle upper stage failure. In 1992, it was rescued by the Space Shuttle and redeployed to the proper orbit, ultimately generating $800 million for Intelsat through 2012.[6] In cases of partial loss, the satellite can use onboard fuel to complete its journey, ultimately reducing its service life. Satellite operators have filed about $700 million in insurance claims between 2006 and 2010 as a result of satellites deployed to wrong orbits or experiencing fuel leaks.[7]

In 2011, Intelsat planned to invest $280 million in a Space Infrastructure Servicing (SIS) system being developed by Canada-based MacDonald, Dettwiler, and Associates, Limited (MDA). This deal was suspended because MDA could not close the business case.[8] However, MDA continues to pursue the SIS.

The Department of Defense (DoD) is also interested in pursuing satellite servicing, and has invested in a few missions that can contribute to building this capability. The Air Force spent about $180 million on two successful missions (XSS-10 in 2003 and XSS-11 in 2005) designed to explore proximity operations and the orbital maneuvering necessary to carry out inspections. DARPA, in collaboration with NASA, is currently pursuing a satellite disassembly and reassembly proof-of-concept mission called Phoenix, which is expected to launch in 2016 or 2017. Phoenix's objective is to repurpose components from a retired satellite and combine them with new elements transported to orbit to create a new satellite. DARPA plans to award $36 million in contracts to support the effort, and has already signed contracts with MDA for $28 million and ATK for $1.7 million to develop the satellite bus.[9]

In the near-term, missions designed to test proofs-of-concept for replicating techniques ideal in a typical operational environment, will characterize the market. These missions are expected to take place through the end of the decade. In addition, the industry is seeking to standardize satellite fittings, orbital protocols, and procedures to help reduce servicing costs and the potential for damage to a satellite being serviced. Some satellite operators, like SES Global, project that satellite servicing is likely about ten years away, while others, like Intelsat, are more publicly optimistic about the potential of satellite servicing.

Demand

Between 1990 and 2010, 556 satellites were launched to GEO.[10] Of those, 128 satellites reached end of life (EOL) status that could be categorized as either serviceable (85 percent) or non-serviceable (15 percent). Some of the satellites reached EOL as planned when their propellant tanks became depleted, while others became inactive due to technical or unknown causes. According to a 2011 study by The Aerospace Corporation, 86 of the 128 inactive satellites have been identified as potential on-orbit servicing

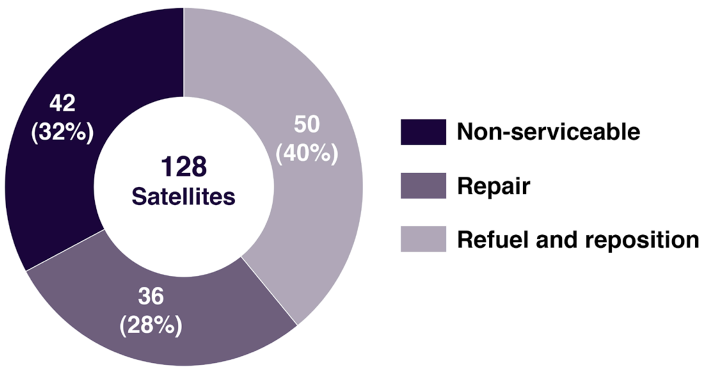


Figure 5. Approximate size of the satellite servicing market by type, based on historical EOL data for satellites launched from 1990 to 2010.

targets. About 50 of these represent opportunities for refueling or repositioning and 36 are potential targets for repairs and deployment assistance. (See Figure 5.)

In addition, there are approximately 2,500 inactive satellites in orbit around the Earth.[11] DARPA projects that 1,300 GEO satellites, most of which are inactive due to depleted propellant tanks, are candidates for component replacement and refurbishment. The total value of these satellites is about $300 billion.[12] DARPA's Phoenix mission aims to explore techniques that could be used to tap this market.

Another potential area of demand that is not yet well understood involves on-orbit inspections, which may aid failure analysis to improve designs, determine repair or other corrective actions, and assist in assignment of liability in insurance claims. Mitigation and removal of orbital debris may also benefit from satellite servicing capabilities.

Supply

ViviSat, backed by ATK, and MDA, who recently acquired Space Systems/Loral, are the two North American companies currently involved in satellite servicing.

ViviSat is offering a system that attaches itself to a satellite running low on propellant and provides station-keeping and maneuvering services. ViviSat's ATK-built Mission Extension Vehicles (MEV) will do precisely what their name describes, but will not be capable of refueling or otherwise servicing a satellite. MDA, the company that designed and manufactured the robotic arms used aboard the Space Shuttle and ISS, aims to provide a full servicing spacecraft using its SIS vehicle. The SIS will feature robotic limbs capable of grasping satellites and servicing them as needed. ViviSat's MEV is designed to dock with about 90 percent of GEO satellites. MDA's SIS docks with about 75 percent of GEO satellites.[13] The cost to develop, launch, and operate a notional satellite servicing spacecraft similar to an SIS is estimated to be about $540 million.[14]

In addition, Germany's space agency, DLR, signed a study contract with Astrium to design DEOS, a robotic technology demonstration mission focused on the repair and refueling of satellites. DEOS is tentatively planned for launch around 2018.[15]

Barriers and Uncertainties

The technologies necessary to service satellites exists today, however, there are several technical and economic challenges. Technical challenges include rendezvous, docking, or berthing with a satellite; ensuring a fully sealed connection for propellant transfer; the identification and swap out of components; and autonomous operations. The technologies involved are not new and are not necessarily complex, but their integration into a mission remains the biggest technical hurdle. In terms of economic challenges, it is not clear how perceived risks in a rescue mission are handled from a cost perspective. Various factors, both space- and ground-based, dictate whether building a new satellite or simply refueling one already on orbit would be the optimal path.[16]

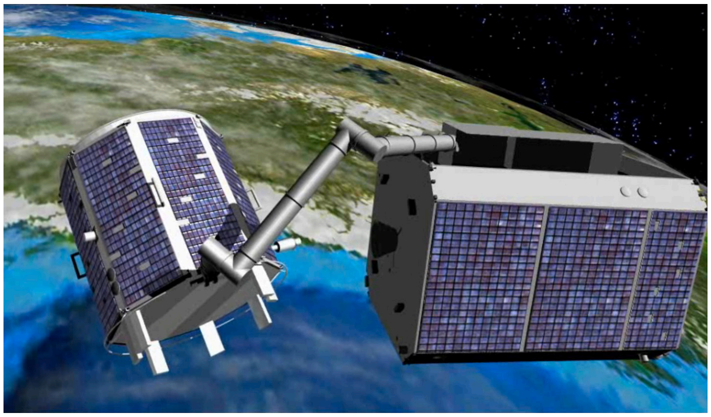


Figure 6. Artist impression of the servicer turning the client for docking maneuver. Source: SpaceTech GmbH.

Satellite Servicing

COMMERCIAL APPLICATION

Revenue from Global Satellite Market (2012): **$190B**

LARGEST COMMERCIAL FLEETS

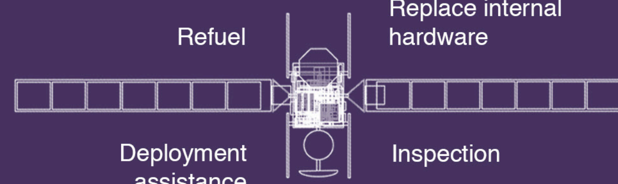
Intelsat (55)

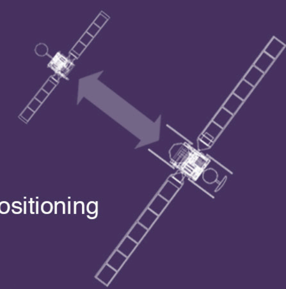
Eutelsat (30)

SES Global (52)

Telesat (14)

NASA APPLICATION





MARKET OVERVIEW

CURRENTLY ACTIVE SATELLITES

TOTAL: 1,046

GEO: 432

281 Commercial	Communications (100%)
151 Government	Communications (68%) Other (32%)

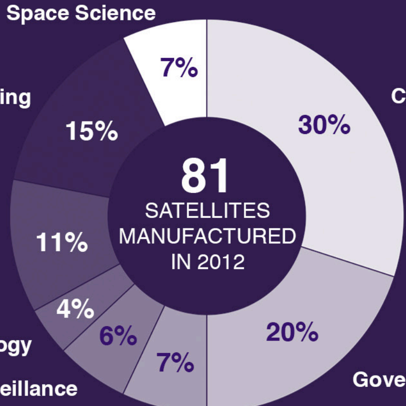
TOTAL INACTIVE: ~2,500

86 potential satellite servicing opportunities identified for 1990-2010

50 for refueling

36 for repairs

ALL ACTIVE SATELLITES BY FUNCTION



Interplanetary Small Satellites

Interplanetary small satellites are spacecraft that conduct missions beyond low Earth orbit (LEO) and have a mass less than 500 kg. Interplanetary small satellites are designed to reduce costs by reducing mass. Small satellite approaches for interplanetary probes aim to push innovation and reduce mass without reducing capabilities. Private-sector small satellite companies have also independently raised over $140 million in venture capital and angel financing over the last few years.[1] A number of these companies have interplanetary ambitions. Public-private partnerships in small satellites could help NASA explore the universe while pushing technology that would help improve the capability of U.S. satellites.

Commercial Application

Small satellites are becoming a larger component of the overall commercial telecommunications and remote sensing market, with companies such as ORBCOMM, Skybox Imaging, and Planet Labs launching small satellites. These small satellites are often components of constellations consisting of multiple satellites. Several commercial providers operate small satellites primarily for asset tracking and remote sensing. The masses of these satellites range between 100 and 500 kg. Universities and research centers tend to deploy satellites with masses below 10 kg for purposes of technology demonstration or education, with 10 cm x 10 cm x 10 cm (1U) cubesats (< 5 kg) representing the majority of these. From 2004 to 2013, 198 cubesats were launched.[2] About 360 are projected to launch through 2019.[3] An emerging commercial application for small satellites is near real-time remote sensing, with two U.S. companies, Planet Labs and Skybox Imaging, pursuing constellations beginning in 2013.

Although there are currently no commercial companies employing interplanetary small satellites, Planetary Resources is developing its earth orbiting remote sensing telescopes to identify asteroids for purposes of resource extraction.

NASA Application

NASA has launched small satellites into interplanetary space since the 1960s as part of the agency's science and communications technology programs. The low mass was dictated by the capabilities of launch vehicles of the time rather than advances in satellite technology, but the constraint motivated

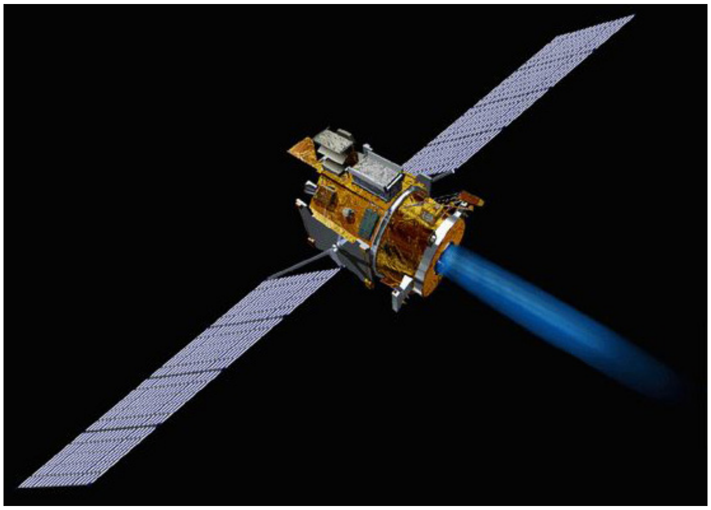


Figure 7. NASA's Deep Space 1, which had a mass of 370 kg, visited asteroid 9969 Braille and comet Borrelly. Source: NASA.

miniaturization of electronics and sensor technologies that in turn fueled commercial applications like global broadcast television and satellite telephone calls. As launch vehicles became more capable, the masses of interplanetary spacecraft grew. Since the 1990s, however, NASA has launched several small interplanetary spacecraft, including lunar orbiter Clementine (with DoD), asteroid probe Deep Space 1, comet probe Stardust, Lunar Prospector, and the Gravity Recovery and Interior Laboratory probes that orbited the Moon.

Interplanetary small satellite missions include the Lunar Atmosphere and Dust Environment Explorer (LADEE), launched in September 2013, and InSight Mars lander mission, planned for launch in 2016.

NASA continues to foster small satellite development to support exploration objectives because advanced research in this area could transform the way the agency explores the solar system. For example, to help alleviate high launch costs, NASA arranges free launches for selected university payloads through the agency's CubeSat Launch Initiative (CSLI), which manages the Educational Launch of Nanosatellites (ELaNa) missions. Some small satellite program objectives are to use a swarm of small satellites linked through an intelligent network, microlanders and rovers for planetary surface investigations, and the use of a single large platform that stores and deploys small probes and landers.

Market Overview

Demand for inexpensive small satellites is growing, while companies currently operating large satellites are seeking lighter platforms that translate to cost savings. ORBCOMM operates a constellation of 40 asset-tracking satellites, the largest number of small satellites operated by a private entity, and has plans to launch eighteen 142-kilogram satellites through 2014. BlackBridge and DMCii are companies that operate constellations of five small satellites or less, each with masses below 150 kg. New companies like Skybox Imaging and Planet Labs are launching constellations of small satellites to provide near real-time remote sensing data easily purchased through the Internet. Planetary Resources plans to launch a cubesat technology demonstrator in 2014 and at least one small telescope into LEO by 2015. The telescope will be used to identify asteroids for potential mining, with selected candidates becoming targets for physical exploration.

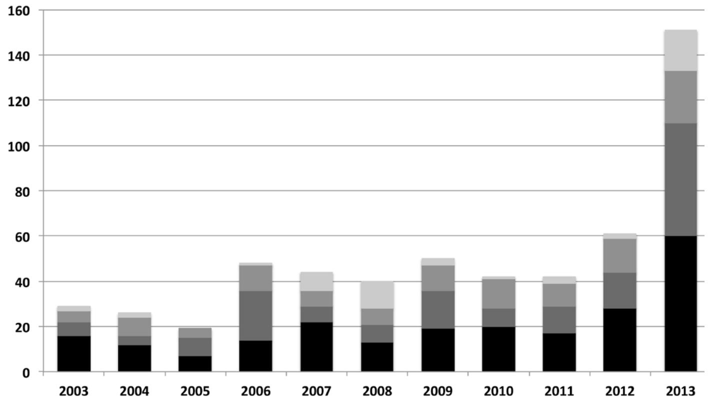


Figure 8. Small satellites (<500 kg) launched worldwide (2004-2013).[4]

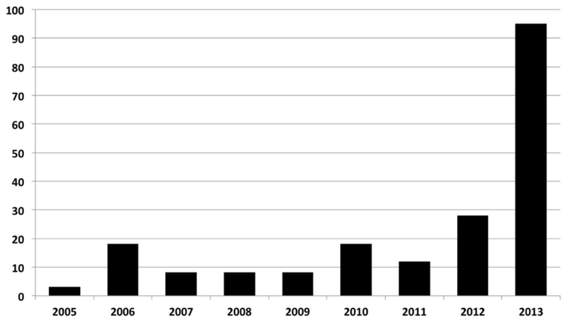


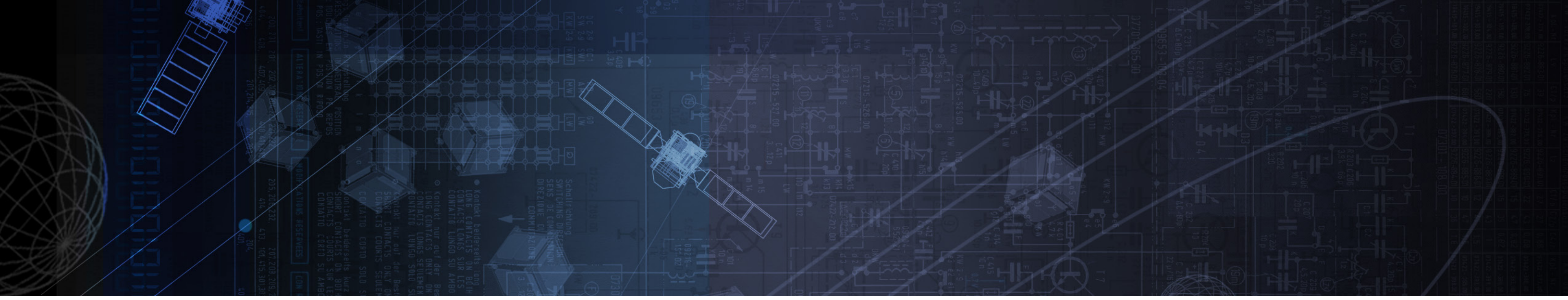
Figure 9. Cubesats (1U through 6U) launched worldwide (2005-2013). No cubesats were launched in 2004.[4]

Though GEO satellites generally have masses above 500 kg, some GEO operators are looking to decrease the mass of platforms in an effort to improve their business cases. Companies like Satmex and Asia Broadcast Satellite have recently contracted with Boeing for satellite buses that decrease mass by using solar electric rather than chemical propulsion. This lower mass means significant cost savings by allowing less expensive launch options like dual manifesting or using smaller launch vehicles. Lockheed Martin Corp., Space Systems Loral, and Thales Alenia plan to produce satellite buses featuring solar-electric propulsion in the next few years.

In the past 10 years, approximately 523 satellites weighing less than 200 kg have been launched worldwide.[4] This number includes cubesats. About 70 percent of these are operated by civilian space agencies and non-profit organizations. Only ten percent are commercially operated, none of which are interplanetary. In 2013, 151 satellites with mass at or below 200 kg were launched. That number is expected to grow to substantially during the next few years. About 198 cubesats (1U up to 6U stacks) were launched during the past decade, with 48 percent launched in 2013 alone.

Projections for small satellites under 50 kg tend to be low as these satellites are primarily built by universities that do not publish details of missions, and are launched as secondary payloads.

New companies have been able to use Kickstarter to raise over $1 million in $500 increments, which is a new way of infusing capital into the space market.[5]



Demand

The number of small satellites launched each year is steadily growing, because of the relatively low costs associated with their construction and operation. 1U Cubesats (< 5 kg) represent the largest portion of this growth with nearly 290 ready to launch by 2015 or in various phases of integration.[6] About 150-200 cubesats are planned for launch in 2014 with 360 expected through the end of the decade. In addition, an unprecedented 250 cracker-sized "kicksats" will be released in early 2014.[7] Most of the expected cubesat launches are part of constellations being explored by the U.S. government or non-profit organizations.

In 2010, the National Reconnaissance Office contracted Boeing to build as many as 50 triple-unit (3U) cubesats as part of its Colony program.[8] DARPA and the Army's Space and Missile Defense Command (SMDC) are also investigating applications using small satellites.[9] DARPA's Space Enabled Effects for Military Engagements (SeeMe) program features disposable microsatellites and SMDC-One, a 4-kilogram communications demonstrator.[10] DARPA is also investigating options designed to facilitate rapid delopyment of small satellites at more affordable costs with its Experimental Spaceplan (XS-1) program announced in September 2013.[11]

Demand for small interplanetary satellites is sporadic and is currently entirely composed of government operators like NASA. If Planetary Resources or other small satellite start-ups were successfully fielding interplanetary small-satellite capabilities, this may spark more commercial demand for interplanetary small satellites.

Supply

Most major U.S. satellite manufacturers also build small satellites as part of their product line. Internationally, UK-based Surrey Satellite Technology Ltd. (SSTL) is considered a worldwide leader in building a variety of small satellites. UK-based Surrey Satellite Technology Ltd. (SSTL) is considered the worldwide leader in building a variety of small satellites. The table on the next page shows the major manufacturers of small satellites. Other providers are attempting to appeal to the small satellite market with off-the-shelf kits that can be modified to suit buyers' needs. Most buyers are universities, research institutions, and government agencies.

The U.S. Department of Defense is working with industry partners to develop on-demand microsatellites. Microcosm, a U.S. company, was awarded a contract by the U.S. Army to develop the Nanoeye microsatellite, which will provide the military with access to low-cost small satellites that can be launched on demand as their needs arise.[12] Microcosm is also working with NASA Ames Research Center on Hummingbird, a new class of rapidly-build interplanetary space probes featuring small, low-cost satellites.

Barriers and Uncertainties

Configuring small satellites to function within a network, which involves precision flight and proximity operations, remains a challenge. This has been demonstrated on systems like the GRAIL mission to the Moon, which involved two linked satellites.

Decreasing telecommunication satellite size requires continued advances in miniaturization and ensuring that these satellites remain fully capable despite decreasing mass. However, while smaller components may translate into smaller satellites, it may also mean adding a higher number of components within the same volume as a traditional satellite, increasing capability but also mass. Put another way, the solution presented by this approach is that instead of lowering the cost per kilogram of launch, the objective is to increase functionality of the satellite per kilogram launched.

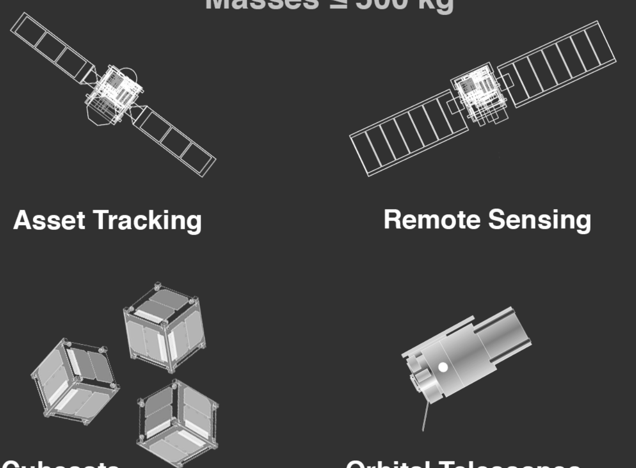
Small satellite developers and manufacturers may change the nature of the space industrial base by lowering the barriers to entry and allowing more suppliers to enter the market place to satisfy diverse market needs.

If small satellites are used for services once provided by large satellites, operators would need to reconsider business models to reflect the technical differences between the two approaches.

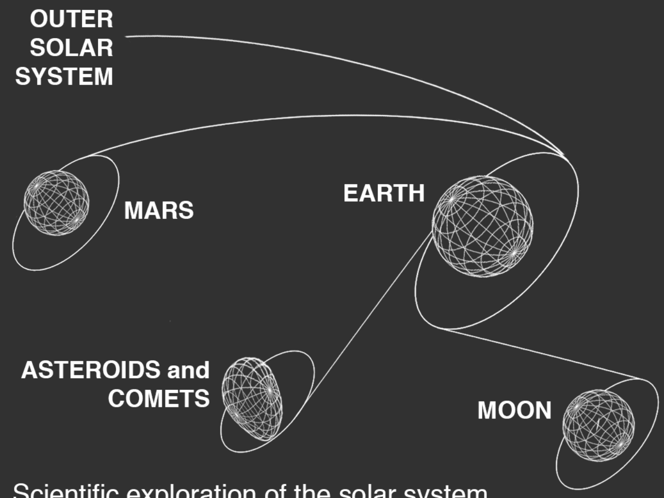
Interplanetary Small Satellites

COMMERCIAL APPLICATION

Masses ≤ 500 kg



NASA APPLICATION

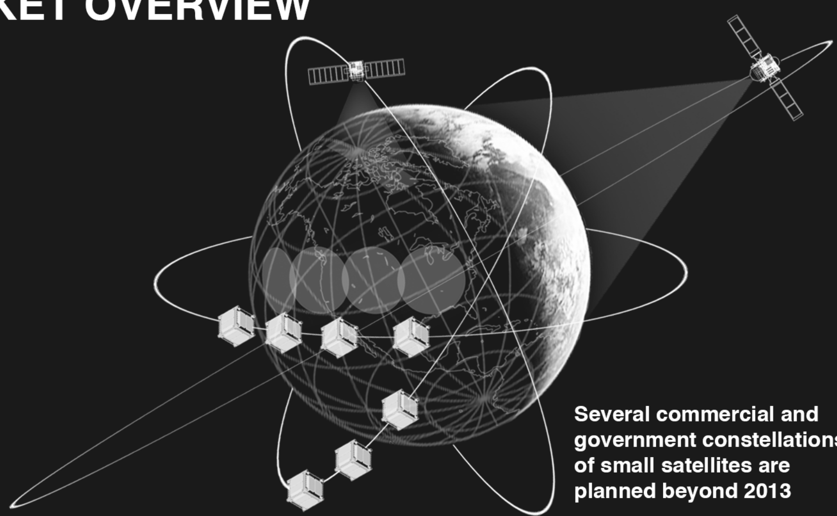


Scientific exploration of the solar system, including orbiting probes and landers

MARKET OVERVIEW

528 small satellites launched from 2004 to 2013 (primarily to LEO)

- **232** Test and development satellites
- **107** Scientific satellites
- **89** Communications satellites
- **78** Remote sensing satellites
- **19** Military satellites



Several commercial and government constellations of small satellites are planned beyond 2013

SUPPLIERS

	Company	Payload Mass Limit
NANOSATS	Interorbital Systems	0.25 kg
	Northrop Grumman/Applied Minds	1 - 3 kg
	Clyde Space	1 kg
	GOMSpace	1 kg
	NanoSatisFi	1 kg
	Pumpkin	1 kg
	Tyvak Nano-Satellite Systems LLC	1 - 10 kg
	Planet Labs	3 kg
	Andrews	10 kg
μ SATS	Boeing	10 kg, 180 kg, 500 - 1,000 kg (all in development)
	Surrey Satellite Technology (SSTL), EADS Astrium Company	15 kg, 50 kg, 150 kg
	ATK	15 kg, 200 kg, 500 kg (all in development)
	Microcosm	20 kg
	Andrews	40 kg
SMALL SATS	Planetary Resources	100 kg (in development)
	Skybox Imaging	100 kg
	Sierra Nevada Corporation	100 kg, 150 kg, 500 kg
	Ball Aerospace	150 kg
	Northrop Grumman Corporation	200 - 500 kg
	Orbital Sciences Corporation	Up to 500 kg

Robotic Mining

Robotic mining Robotic mining is the extraction, processing, and transport of materials using autonomous or semi-autonomous equipment. In-situ resource utilization (ISRU) in space is of interest to NASA for sustaining long duration missions in deep space. Emerging commercial space mining ventures are similarly interested in mining asteroids and other planetary bodies for minerals and resources. On Earth, the mining industry is also leading to the development and utilization of robotic mining technologies. Partnerships between NASA, commercial space companies, and American mining technology companies could position the U.S. for economic growth and leadership in autonomous mining technologies.

Commercial Application

Some terrestrial mining companies use robotic mining equipment for accessing, processing, and transporting raw materials. The use of robotic or semi-autonomous mining equipment such as precision drills, loaders, rock breakers, and haul trucks reduces labor and equipment costs, increases safety, and increases productivity.

Technologies used to develop terrestrial autonomous mining equipment will also be needed by commercial space mining ventures. These ventures plan to develop robotic mining capabilities that identify, characterize, extract, and process volatiles, metals, and rock from the Moon and asteroids. These materials could support space exploration through the extraction, processing, and provision of volatiles in-space—hydrogen and oxygen from ice—and potentially address demands on Earth, particularly platinum group elements (PGEs) which include platinum, palladium, and rhodium from asteroids.

NASA Application

Robotic mining capabilities are critical to NASA's plans for long-duration space missions to asteroids, the Moon, and Mars. NASA is developing robotic prospecting and mining capabilities necessary for space exploration through a number of programs, including the Regolith Advanced Surface Systems Operations Robot (RASSOR), the Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE), and the Moon Mars Analog Mission Activities (MMAMA).

The Lunabotics Mining Competition is a university competition sponsored by NASA, Caterpillar, SpaceX, Newmont Mining Corporation, and Honeybee Robotics. Competitors are challenged to design and build an excavator that can mine and deposit a minimum of 10 kilograms of simulated moon dust within 10 minutes.

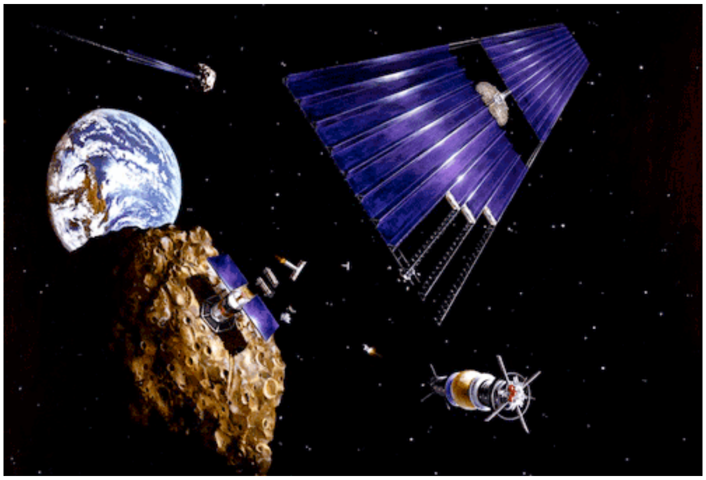


Figure 10. Artist rendition of a robotic mining mission on a near Earth asteroid. Source: NASA/Denise Watt.

Market Overview

In 2011, the global mining industry posted a record \$133 billion in profits and is expected to witness significant growth until 2017.[1] Companies have adopted new technologies like robotics to increase productivity, which are anticipated to lead the industry towards sustained growth.[2] In 2010, the top 40 mining companies announced \$120 billion in capital expenditures.[3] In 2011 these companies invested \$98 billion in capital projects and announced a record \$140 billion in capital expenditures for 2012 as they expect demand to remain strong. The global market for mining equipment is expected to grow 8.5 percent annually through 2018.[4]

While demand has been high, supply has failed to keep up, a situation that is likely to continue due to:

- decreasing grades and rising input cost, which are changing cost bases;
- evolving fiscal regimes and resource nationalism;
- continuing disruptions to production;
- increasing remoteness of deposits; and
- higher capital costs to bring supply to market.[5]

Access to space-based PGEs is an incentive for prospecting, extracting, and processing materials from asteroids.[6] PGEs are rare, expensive, and critical to today's economy.

Demand

The global mining industry is expected to grow at a compound annual growth rate (CAGR) of 7.4 percent from 2012-2017, reaching $1.7 trillion. Growth is driven by increased demand for iron ore by power plants, the construction industry, and ports; use of aluminum in the transportation sector; and growth of the oil and gas sector.[7] The global market for mining equipment is expected to grow 8.5 percent annually through 2018 to $117 billion, and the Asia/Pacific region will likely remain the fastest growing market.[8]

To date, the adoption of automation in terrestrial mining has been slow due to technical and labor issues. Several large mining companies are already using autonomous or semi-autonomous equipment and remote virtual control room technologies that allow miners to operate equipment from thousands of miles away. Table 2 provides examples of near-term demand for robotic mining equipment.

Company	Selected terrestrial robotic equipment investments
Rio Tinto	Investing in $518 million for autonomous heavy-haul trains, ready in 2015.[9] 150 Komatsu autonomous haulers, and remote operations center.
BHP Billiton	12 to 15 automated Caterpillar trucks by late 2013.[10]
Fortescue Metals Groups	Planning to commission a large fleet of autonomous Caterpillar haulers at its newest mines.[11]

Table 2. Selected future autonomous mining equipment investments for terrestrial mining.

Demand for PGEs, considered by some commercial firms to be a potential driver of extraterrestrial mining, is tied to economic growth, since the demand for platinum used in catalytic converters increases as vehicle sales increase.[12] PGEs are also used in the agriculture, chemical, petroleum, electrical, electronic, dental, medical, and aerospace industries.

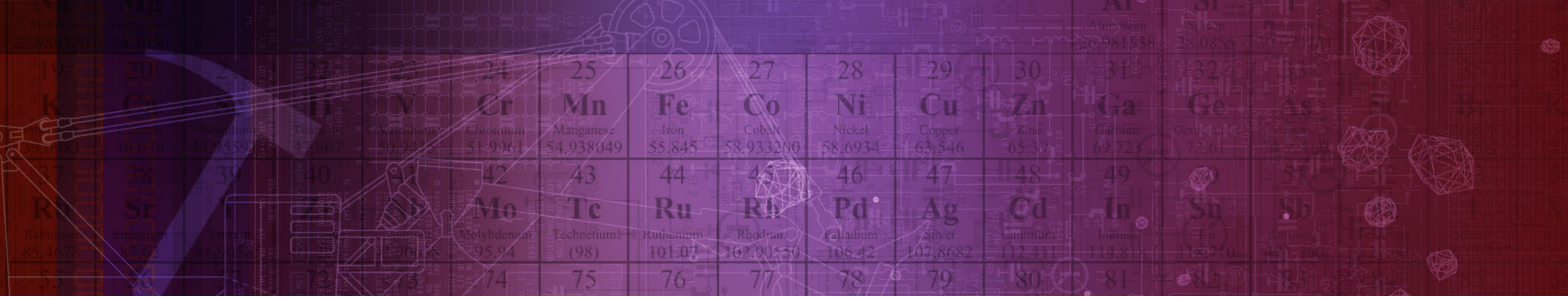
There was a small surplus of PGEs in 2011. Other commercial firms, such as Planetary Resources, see water and other volatiles for use in space as being the core drivers of the development of space mining capabilities.

Supply

A number of countries manufacture terrestrial mining equipment, including automated equipment. These include U.S.-based Caterpillar, Komatsu (Japan), Sandvik (Sweden), Atlas Copco (Sweden), Hitachi Construction Machinery (Japan), and Volvo Construction Equipment (Sweden).

Several institutions are also investing in robotic mining technology, including Canada's Northern Centre for Advanced Technology (NORCAT), Carnegie Mellon University's Robotics Institute, and the Colorado School of Mines. In 2013, Anglo American and Carnegie Mellon University's Robotics Institute initiated a five-year agreement to explore and develop robotic technologies for mining applications.[13] Additionally, Rio Tinto and university partners support at least four separate research centers dedicated to advancing mining robotics for driverless trucks and automated trains.

Four U.S.-based companies plan to develop automated technologies and equipment that enable commercial mining of the Moon and asteroids. These ventures are summarized in Table 3 on the following page.



Barriers and Uncertainties

Commercial space-based mining ventures face a number of hurdles, including raising sufficient financing to start development and operations, designing and testing space-qualified equipment, proving sufficient demand to offset launch and development costs and yield profits, and determining the composition and deposits present in asteroids. Additionally, although there are good reasons to believe that prices for PGEs will remain high or increase, PGE prices are vulnerable to the discovery of more cost effective substitutes.

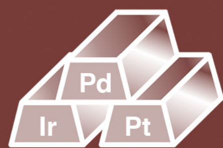
Company, Plans, and Timelines	Investors/Partners	Investments/Technologies
Planetary Resources, Inc. Plan to launch a low Earth orbit telescope in 2015 to spot candidate asteroids. Followed by subsequent missions to gather hi-resolution imagery to assess the value and feasibility of mining candidate asteroids.	Investors (partial list): Larry Page (Google), Eric Schmidt (Google), Ross Perot, Jr., (The Perot Group), Bechtel	Investments not announced. Over $1.5M raised through Kickstarter in 2013. Technology development contracts related to miniaturized technologies for resource recovery,[14] deep space optical communications, and efficient micro-propulsion.[15]
Deep Space Industries, Inc. Plan to launch Cubesats in 2015 to scout out near-Earth asteroids followed by a 32-kg probe to return up to 45 kilograms of asteroid samples back to Earth.	Investments unknown. Stated attempt to raise $3M in 2013; and $10M in 2014.	Investments unknown. Attempting to raise $3M in 2013; and $10M in 2014.[16]
Moon Express Moon Express plans to send a series of low-cost robotic missions to the Moon for mining its resources.	Founders/Investors: Bob Richards (co-founder of ISU), Barney Pell (Powerset), Naveen Jain (InfoSpace, Intellius)	NASA awarded Moon Express $500K as part of the Innovative Lunar Demonstration Data (ILDD) Program.[17]
Astrorobotic Astrobotic delivers payloads to the lunar surface, and prospects for resources using rovers and landers.	Partners: Carnegie Mellon University, Caterpillar	NASA awarded Astrobiotic a contract to develop technologies for exploring caves on the Moon, Mars, and beyond as part of its Innovative Advanced Concepts program.
Shackleton Energy Plan to send two robotic prospecting missions to the Moon by 2015 to characterize the nature and extent of water available. Mining starts in 2021,[18] at the earliest.	Founder/Investors: Bill Stone (Stone Aerospace), Dale Tietz, Jim Keravala	A 2011 crowdfunding campaign attempted to raise $1.2M but did not reach the target amount.[19]

Table 3. Commercial space mining ventures.

Robotic Mining

COMMERCIAL APPLICATION

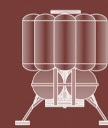
Volatiles



Metals

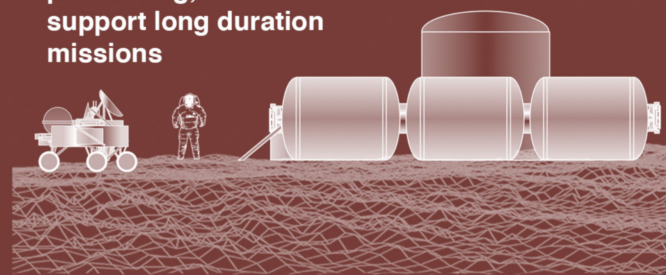
Regolith and Rock

NASA APPLICATION

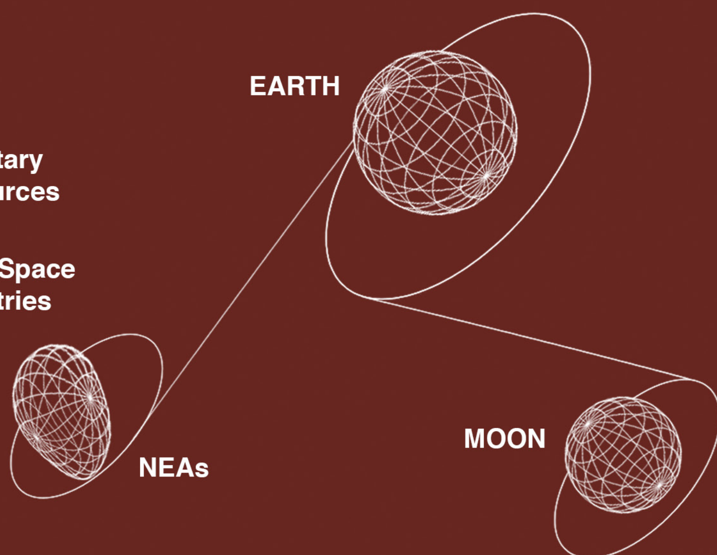


Propellant transport

In situ extraction, processing, and use to support long duration missions



MARKET OVERVIEW



Planetary Resources

Deep Space Industries

TOTAL MINED FROM EARTH (in 2011):
Iron, ferro-alloy metals: 1.5 trillion tons
Non-ferrous metals: 79 billion tons
Precious metals: 27 million tons
Industrial materials: 715 billion tons
Mineral fuels: 14 trillion tons

Profits: $133B (2011)

Astrobotic Technology

Shackleton Energy

Moon Express

CURRENT AUTOMATED MINING EQUIPMENT SUPPLIERS

- Caterpiller (USA)
- Komatsu (Japan)
- Sandvik (Sweden)
- Atlas Copco (Sweden)
- Hitachi Construction Machinery (Japan)
- Volvo Construction Equipment (Sweden)

- Northern Centre for Advanced Technology (Canada)
- Carnegie Mellon University's Robotics Institute (USA)
- Colorado School of Mines (USA)

POTENTIAL NON-TERRESTRIAL ROBOTIC MINING SUPPLIERS

Planetary Resources
Arkyd 100, Arkyd 200, and Arkyd 300

Astrobotic Technologies
Polaris, Red Rover

Shackleton Energy
Prospectors, lunar in situ processing propellant depots

Moon Express
Lander Test Vehicle

Deep Space Industries
Cubesat prospectors, MicroGravity Foundry series

Microgravity Research for Biomedical Applications

Microgravity is used in several research areas, including biomedical sciences. This report focuses on its use in biomedical applications. Microgravity is used by researchers in numerous areas of biomedical science as a tool for discovery in a variety of medically important applications. Biomedical research in the ISS microgravity laboratory environment offers an unparalleled, sustained opportunity for discovery in a variety of medically important applications leading to social and economic benefits.

Commercial Application

Microgravity's potential value to biomedical and pharmaceutical research has prompted several organizations to conduct exploratory research in space, including Amgen, Merck, and the J. Craig Venter Institute (JCVI). Companies are most interested in conducting space-based microgravity research to address five medical concerns. Current research in these areas is being hindered by terrestrial gravitational effects, which can be overcome in space.

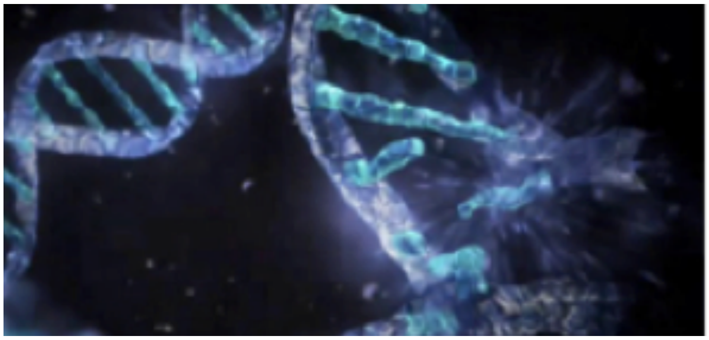


Figure 13. Space radiation targeting a DNA strand. Source: NASA.

1) Drugs to treat diseases affecting the elderly. Pharmaceutical and biotechnology companies have increased research into drugs that treat conditions commonly observed in elderly populations.[1,2] Studying the effects of microgravity on humans in space can provide insights into cardiovascular disease and osteoporosis that could help focus future drug development efforts.[3,4]

2) Drugs to treat cancer. Microgravity research complements current trends in cancer research by reducing the mechanical stresses experienced by tissues grown in bioreactors, and facilitating the development of tissues into more mature, differentiated forms, enabling researchers to observe cancer cells and tissues in an environment that is more representative of conditions in the body. One area of contribution includes the refinement of bioreactor designs optimized to grow tumors in the laboratory to test the effectiveness of new drugs, and improvements in microencapsulation technology as a potential approach to deliver drugs to cancer cells.[5,6]

3) Drugs to treat infectious diseases. Some bacteria are more virulent in space; this finding could have important implications for the development of therapeutics.[7,8] There have been several cases of humans developing resistance to current antibiotics creating a public health problem of increasing magnitude. Better understanding of the triggers of virulence obtained through research on the ISS could hasten the development of new treatments.

4) Tissue engineering and regenerative medicine using space-grown stem cells. Ground-based research using rotating wall bioreactors has shown that reduced-stress cultures encourage stem cell proliferation while sustaining stem cells' ability to differentiate and demonstrate growth of larger, better functioning, and more organized tissue.[9,10,11] Space-based culture is a logical next step for this promising area of research.[12] This has important implications for therapies like regenerative medicine and tissue engineering, which rely on stem cells and are already yielding clinical products.

5) Protein crystallization for drug discovery and development. In many instances, microgravity produces larger, better-organized protein crystals during crystallization than Earth-based methods, providing higher-resolution protein structures that help focus drug development.[13] A number of crystallization experiments have been conducted on the ISS. A protein crystallized on the ISS is now a candidate

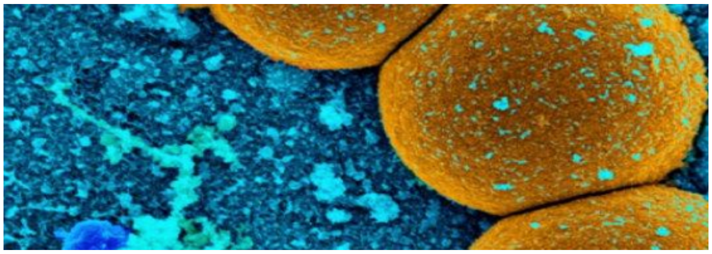


Figure 14. NASA is partnering with industry to develop treatments for antibiotic-resistant organisms. Astrogenetix is developing a vaccine candidate to address methicillin-resistant Staphylococcus aureus (MRSA), a common antibiotic-resistant bacterium, as part of the ISS National Laboratory Pathfinder Vaccine missions. Astrogenetix previously developed a vaccine candidate targeting Salmonella based on research conducted on Space Shuttle flights. Source: Photo Researchers.

treatment for Duchenne's muscular dystrophy and market leader Merck is currently negotiating with the Center for the Advancement of Science in Space (CASIS), the manager of the U.S. National Laboratory segment of the ISS, to conduct crystallization research on therapeutic monoclonal antibodies on the station.[14]

NASA Application

NASA began exploratory microgravity experiments in 1973 with Skylab. Since that time, less than one year of dedicated laboratory research time has accrued.[15] Hundreds of biotechnology experiments have been performed on the ISS, most studying the effects of microgravity on human health to enable humans to live and work in space. Human exposure to microgravity is associated with health conditions like bone loss, muscle atrophy, decreased cellular immune response, impaired wound healing, and neurological alterations. NASA's ISS research can provide insight leading to new therapeutics to treat these and similar conditions, many of which are also prevalent in our aging population.

The CASIS is under a cooperative agreement to help NASA maximize the use of the ISS for research. In November 2012, CASIS announced its first research grant awards for three projects that advance protein crystallization in microgravity. The projects will determine the three-dimensional structures of protein molecules, potentially leading to more focused drug development.

Market Overview

The U.S. biotechnology industry is expected to be a $93 billion industry comprised of nearly 2,000 businesses in 2013. Exports will account for $7 billion (7.5 percent) of industry revenue in 2013, and international trade will play a larger role in the near term as larger companies expand to operations overseas.[16] The largest segment of the industry (57 percent) is in human health technologies, which includes medical diagnostics and pharmaceuticals. Cancer was the biggest focus of the U.S. biotechnology industry in 2012, accounting for 43 percent of the clinical pipeline.[17] Infectious diseases accounted for 10 percent of the pipeline. Companies with large shares of the industry include Merck and Amgen.

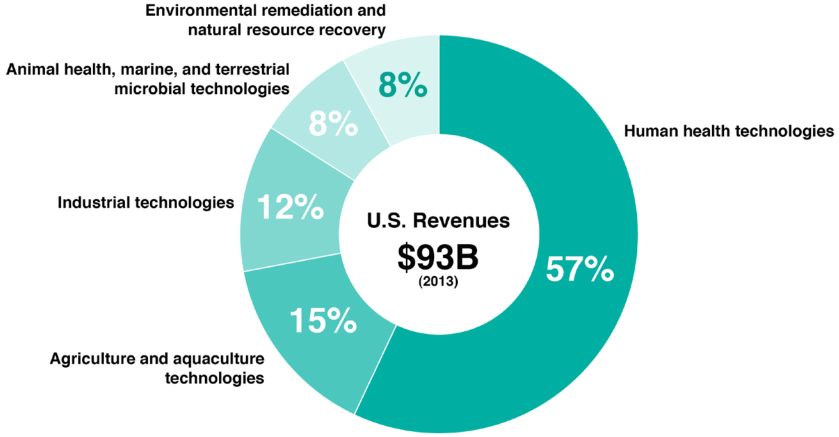


Figure 15. Human health technologies, such as pharmaceuticals, comprise the largest segment of the biotechnology industry. Source: IBISWorld.

Demand

The demand for biotechnology products, especially pharmaceuticals, will grow as the proportion of individuals aged 65 and over increases. The biotechnology industry in the U.S. is expected to grow 8.9 percent from 2013-2018,[18] while brand name pharmaceutical manufacturing will grow 1.9 percent.[19] The smaller growth in pharmaceuticals is partially due to patents expiring, allowing for a greater availability of generic drugs. Research and development (R&D) expenditures in the pharmaceutical industry grew at a compound annual growth rate (CAGR) of 6 percent from $26 billion in 2000 to $50 billion by the end of 2011.[20] Large pharmaceutical companies like Novartis, Roche, Merck, Pfizer, and Johnson & Johnson spent the most on R&D in 2012.[21]

Demand for drugs to treat diseases with effects similar to those resulting from extended space flight is also high. More than one-third of the 100 best-selling drugs in 2012 treat degenerative diseases like arthritis, cancer, multiple sclerosis, osteoporosis, and cardiovascular disease, indicating an increasingly strong market for these drugs in the coming years.[22] By 2030, 19 percent of the U.S. population will be over 65 years of age.[23] Heart disease and cancer are the most common causes of death in the U.S., respectively, and the American Cancer Society estimates that more than 1.6 million new cases of cancer will be diagnosed in the U.S. in 2012.

Spending on stem cell research is also increasing. The National Institutes of Health (NIH) plans to spend nearly $3 billion on stem cell research in both FY 2013 and FY 2014, indicating their increasing importance as potential therapies.[24] The global market for research using adult stem cells is projected to reach $3.2 billion by 2017,[25] which does not include research using embryonic stem cells or non-human stem cells.

Supply

There are no ground-based methods capable of achieving zero gravity. The NASA-developed rotating wall bioreactor can reduce the effects of gravity enough for initial testing and insights in many instances, but tissue growth in microgravity may allow organized three-dimensional tissues to become large enough to enable greater medical advances.[26]

Several commercial space organizations currently host or intend to host microgravity experiments on their vehicles. Bigelow Aerospace intends to market its orbital space modules to tourists, corporations, and scientists, providing the ability to conduct longer-duration experiments. Currently, only SpaceX's Dragon provides the only means of returning substantial cargo and scientific experiments to Earth.[27] However, Sierra Nevada Corporation's Dream Chaser will provide similar capability within a few years. The Cygnus module from Orbital Sciences Corporation. can remain in orbit for up to two years before reentering.[28] Suborbital reusable vehicles such as Blue Origin's New Shepard, Virgin Galactic's SpaceShipTwo, or XCOR's Lynx provide the potential for 3 to 5 minutes of microgravity for experiments. These flights complement ISS investigations by offering researchers additional platforms on which to fly experiments.

Barriers and Uncertainties

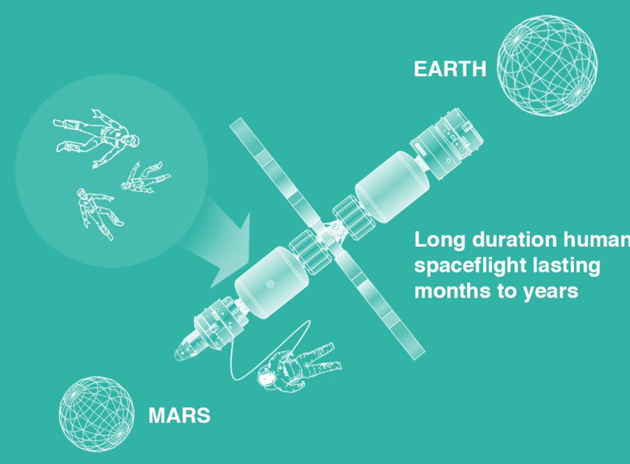
Conducting research and development in space is much more difficult and expensive in comparison to ground based laboratories and is only considered when no terrestrial option is available. In addition, few in-space studies have been done in specific areas of interest to biotech companies (versus the general area e.g. "cancer research" or "tissue engineering") and thus, corporate sponsored space research is still largely exploratory. Further, a number of accommodations are required to make space-based microgravity research more feasible for biotechnology and pharmaceutical industries. These include: 1) accommodating best practices in the field to leverage schedules that meet customers' needs; 2) providing sustained and frequent access to the microgravity environment, including the return of samples to Earth; 3) providing crew support; 4) providing advanced analytical technologies; and 5) supporting exploratory development and basic research with results published in open literature. Some of these accommodations are already in place or becoming available, but attracting paying customers for ISS research will require additional accommodations and support to meet their needs.

Microgravity Research for Biomedical Applications

COMMERCIAL APPLICATION

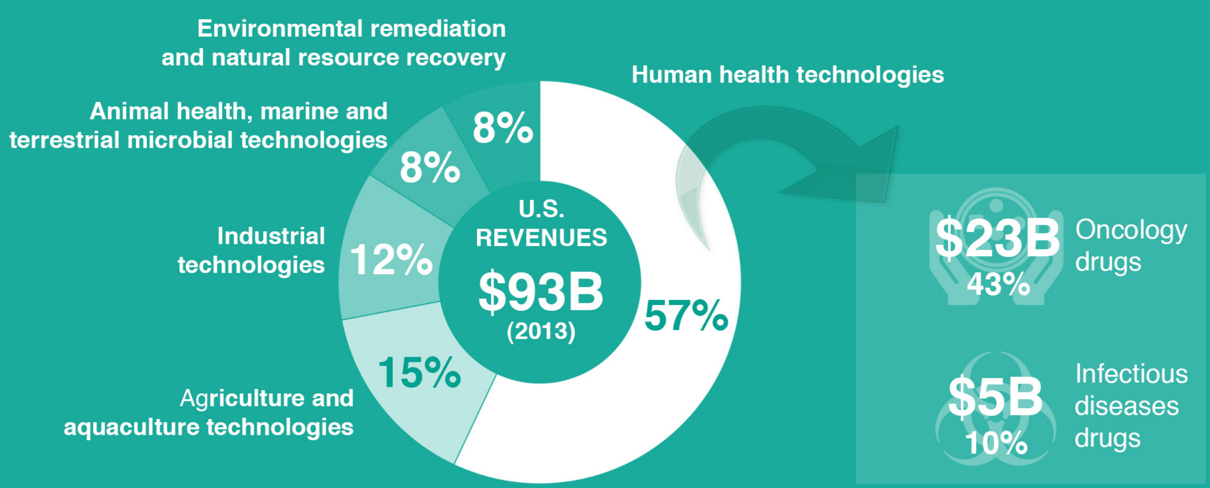
- Drugs for diseases that afflict the elderly
- Drugs for infectious diseases
- Drugs for oncology
- Stem cell research
- Protein crystallization

NASA APPLICATION



MARKET OVERVIEW

U.S. BIOTECHNOLOGY INDUSTRY



POTENTIAL SUPPLIERS (2014-2024)

Suborbital

- **Blue Origin** New Shepard
- **XCOR** Lynx
- **Virgin Galactic** SS2
- **Armadillo** STIG
- **UP Aerospace** SpaceLoft
- **Masten** Xaero
- **ZERO-G**

Orbital

- **Boeing** CST-100
- **NASA** ISS
- **SpaceX** DragonLab
- **Blue Origin** Space Vehicle
- **Orbital Sciences** Cygnus
- **SNC** Dream Chaser
- **Bigelow** BA 330

Microgravity Research Facilitators

- **CASIS**
- **NanoRacks**

MICROGRAVITY RESEARCH

Demand for drugs to treat diseases that mimic the health effects of space flight is high and expected to grow as population over 65 increases

Liquid Rocket Engines for Launch Vehicles

Liquid rocket engines (LREs) are part of the primary propulsion system for launch vehicles and spacecraft. Facilitating the development of safe, reliable, cost effective engines could further position the U.S. to regain some of the launch vehicle market share lost during the past decade. The success of NASA's Commercial Orbital Transportation Services (COTS) effort to enable the development of cost-effective commercial space transportation systems demonstrated the potential of a public-private partnership model. Facilitating the development of safe, reliable, cost effective engines for government and commercial customers could further position the U.S. to gain back launch vehicle market share lost during the past decade.

Commercial Application

LREs are currently being used to power the core stages of the Atlas V (RD-180) and Delta IV (RS-68A), the first and second stages of SpaceX Falcon vehicles (Merlin), the SpaceX Dragon thrusters (Draco), and the first stage of the Orbital Sciences Antares vehicle (AJ26). Aerojet Rocketdyne currently produces the RD-180 (as a partner with Russia's NPO Energomash under joint company RD AMROSS), the RS-68A, the AJ26 (of Russian origin, production licensed), and the RL10 used to power the Atlas V and Delta IV upper stages. Development of simpler, less expensive U.S. LREs is currently underway by a variety of U.S. companies including Aerojet Rocketdyne, Blue Origin, Masten Space Systems, and Orbital Technologies Corporation (ORBITEC). XCOR Aerospace and United Launch Alliance (ULA) are jointly developing a liquid rocket engine featuring a piston pump.

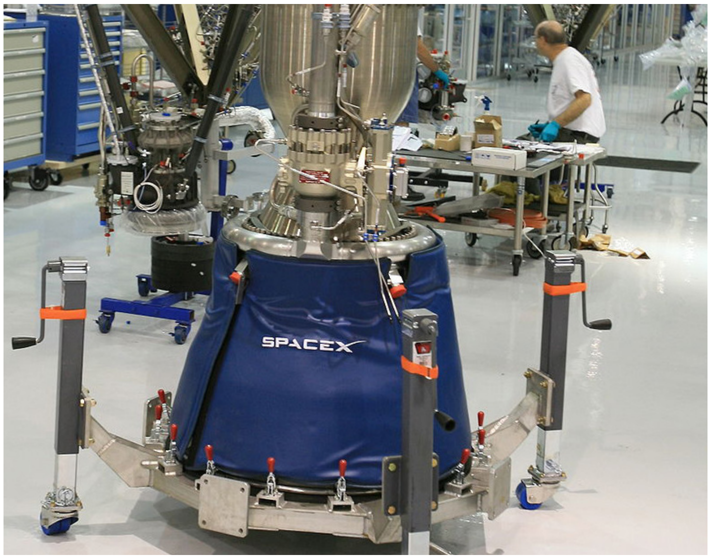


Figure 16. SpaceX's Merlin engine at its factory in Hawthorne, CA. Source: SpaceX.

U.S. launch vehicles like the Atlas V and Antares use foreign-built LREs to power their first stages. India's Geosynchronous Satellite Launch Vehicle and South Korea's Naro-1 use Russian stages featuring LREs.

NASA Application

Through the COTS program, NASA enabled the development of new space transportation systems including launch vehicles and orbital spacecraft. This program helped establish the U.S. as a cost-effective provider of global launch services while helping to regain market share lost to foreign providers. The program resulted in the successful introduction of the SpaceX Falcon 9, powered by the Merlin series of engines, and Orbital Sciences Corporation's Antares, which is powered by Aerojet Rocketdyne's AJ26 engines.

Continued emphasis on cost-effective liquid engines will support NASA as it extends human presence into the solar system. New concepts resulting in lower-cost liquid oxygen (LOX)/hydrocarbon engines, in particular, could help NASA more effectively achieve its interplanetary exploration plans.

New concepts in LREs could reduce costs needed to support NASA's SLS and MPCV exploration programs. NASA has worked with Aerojet Rocketdyne to develop the RS-25E and the J-2X engines for the SLS program. The expendable RS-25E, which is derived from the refurbished Space Shuttle Main Engine (RS-25D), is designed as a less complex and costly engine.[1] The J-2X, which may someday be used to power an improved SLS second stage, features a simplified design as well as parts manufactured using less expensive automated techniques.[2]

NASA is also working with Ball Aerospace to produce a spacecraft thruster using an environmentally friendly propellant to replace the toxic hydrazine commonly used. The new propellant will also provide 50 percent better performance than hydrazine.[3] NASA's Green Propellant Infusion Mission, due to launch in 2015, will be the first to employ and test the new propulsion system.

Market Overview

The commercial launch industry generates annual revenues of approximately $2.5 billion to $3 billion, with an average of 19 commercial launches per year, out of a total average of 77 launches per year.[4] The U.S. has lost market share in commercial launches for several years. In 2008, the U.S. had 21 percent (6 launches) of the market. In 2011, the U.S. had no commercial launches, and in 2012, the U.S. captured 10 percent (2 launches) of the market. Figure 17 shows the the number of commercial launches from 1993 through 2012, with a projection to 2021. Beginning in 2013, the U.S. is expected to increase its market share from an annual average of 13 percent (2008-2012) to 28 percent. SpaceX's commercial satellite launch contracts and flights to the ISS are driving the increase in U.S. market share.

As Orbital Science Corporation and SpaceX continue to attract commercial customers, the U.S. commercial launch market share is expected to grow. At the Satellite 2013 conference, SpaceX's entrance into the commercial launch market was seen as a potential market game-changer by a number of satellite operators.

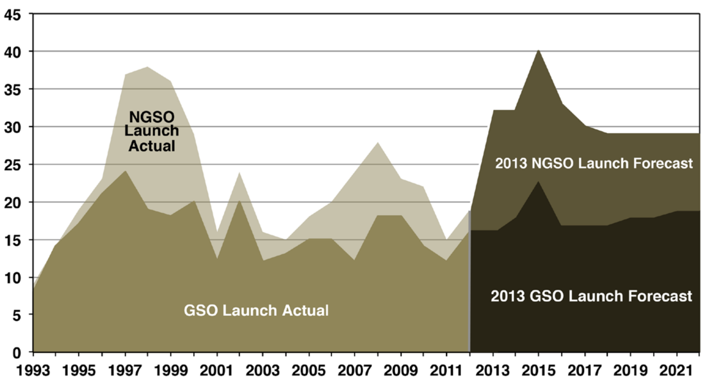


Figure 17. Historical worldwide orbital launches and forecast by geostationary (GSO) and non-GSO (NGSO) (1993-2022).[5]

NASA and the DoD are exploring low-cost alternatives to the expensive Aerojet Rocketdyne RL10 currently used to power the Atlas V and Delta IV upper stages.[6] To eliminate reliance on the Russian RD-180 engine used to power the Atlas V, DoD is seeking a large advanced LRE as a replacement.[7]

Demand

Demand for U.S.-built LREs is currently limited to U.S. launch service providers and spacecraft operators.

Projections for worldwide commercial orbital launch activity show that demand will grow during the next ten years. Figure 17 illustrates the projected number of worldwide commercial orbital launches, with an expected average of 31 launches per year beginning in 2013.

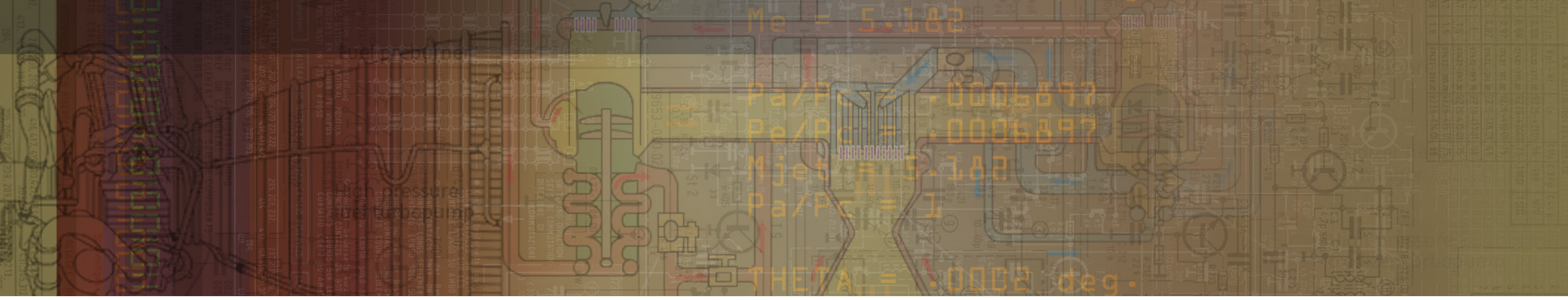
Supply

There are two major manufacturers of advanced LREs in the United States: Aerojet Rocketdyne and SpaceX. Aerojet Rocketdyne, owned by GenCorp, sell engines to NASA, Orbital Sciences Corporation, United Launch Alliance, and some satellite manufacturers. SpaceX does not currently offer its engines commercially.

Aerojet Rocketdyne's RS-68A, which powers the Delta IV, is the largest LRE powered by hydrogen fuel in the world and designed specifically to reduce costs. It is constructed of 80 percent fewer parts than the Space Shuttle Main Engine, an engine with similar capabilities.[8] The new Merlin-1D engine used for both stages of the Falcon is more efficient and reliable than typical LREs, featuring a simpler design and fewer parts.

Another potential advanced LRE is being developed by ORBITEC called the VR-3A Vision. The VR-3A features simpler construction than its competitors. Reducing engine complexity and increasing robustness in reusability are design characteristics that can translate to lower costs. Blue Origin is also developing a large LRE called the BE-3, which will be used to power the company's Reusable Booster System.

Table 7 lists advanced LREs currently in service or under development in the U.S. There are additional development efforts for small LREs for suborbital vehicles. Masten Space Systems and XCOR



Aerospace are developing small, reusable LREs for their suborbital launch systems. Sierra Nevada Corporation continues to develop hybrid liquid-solid engines following successful use of an 88 kN (65,000 lbf) unit used in the SpaceShipOne vehicle to win the Ansari X PRIZE in 2004. Flight tests of the more advanced RocketMotorTwo engine began in 2013 aboard SpaceShipTwo.

Barriers and Uncertainties

The commercial launch market is relatively small with an average of only 19 launches over the past ten years. It is unclear whether this small market can support multiple LRE manufacturers. An aging work force, not being revitalized with young scientists and engineers, is considered a risk factor by a few providers.[9]

The small size of the launch market, approximately 80 launches worldwide of which ~20 are commercial launches, makes it is difficult for multiple companies to become established. The fact that U.S. LRE manufacturers are effectively constrained from selling their engines outside the U.S. amplifies the problem. Additional challenges include vertical integration business models, which inhibit mixing and matching.

Company	Engine	Thrust	Vehicle	Year	Notable Features
Aerojet Rocketdyne	RS-68A	3,123 kN (702,000lbf)	Delta IV	2012	80 percent fewer parts than Space Shuttle Main Engine.[10]
Aerojet Rocketdyne	RS-25E	1,668 kN (375,000 lbf)	SLS core stage	TBD	Based on the reusable Space Shuttle Main Engine with fewer parts.[11]
Aerojet Rocketdyne	AJ26	1,505 kN (338,000 lbf)	Antares first stage	2013	Modified Soviet era NK-33, oxygen kerosene engine. Enhancements include a gimbal block for thrust vectoring capability, new wiring harnesses and electrical circuitry, electromechanical valve actuators, and instrumentation.[12]
Aerojet Rocketdyne	J-2X	1,308 kN (294,000 lbf)	SLS upper stage	TBD	Simpler and more capable version of J-2 engines from the Apollo Program uses 3D manufactured components.[13]
Blue Origin	BE-3	489 kN (110,000 lbf)	Reusable Booster System	TBD	LOX, liquid hydrogen engine used to power Blue Origin's Reusable Booster System.[14]
ORBITEC	VR-3A Vision	133 kN (30,000 lbf)	TBD	TBD	Less complex engine, has fewer parts, is easily scalable and uses an innovative vortex cooling system in the combustion chamber. Potential use may include cryogenic upper stages of the Atlas V, Delta IV, and SLS.[15]
SpaceX	Merlin	654 kN (147,000 lbf)	Falcon 9 and Falcon Heavy	2010	Simple design and automated manufacturing results in lower labor costs.[16]
SpaceX	Raptor/ MCT	TBD	TBD	~2015	Little public information available. Burns methane and LOX. The engine appears to be an upper stage related to journeys to Mars.[17]
XCOR	XR-5K18 XR-5M15 XR-4A3	4 kN (2,900 lbf) 33 kN (7,500 lbf) 0.5 kN (400 lbf)	Lynx TBD EZ Rocket	~2014 TBD 2001	XCOR has been developing LREs for over a decade. It has also developed LRE thrusters like the currently available XR-3N22 and XR-3E17.[18]
XCOR/ULA	LH2 Engine Program	33.9 kN (25,000 lbf)	EELV cryogenic upper stage	TBD	Joint effort to develop a lower-cost, risk-managed LRE the operates with a piston pump instead of a turbopump.[19]

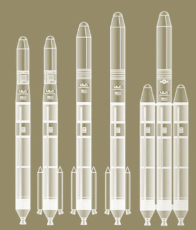
Table 7. Major advanced LREs in service or currently being developed in the U.S., by thrust (at sea level).

Liquid Rocket Engines for Launch Vehicles

COMMERCIAL APPLICATION

EXISTING U.S. LAUNCH VEHICLES USING LRE

Atlas V
1st stage: RD-180 (legacy)
2nd stage: RL10A-4-2 (legacy)

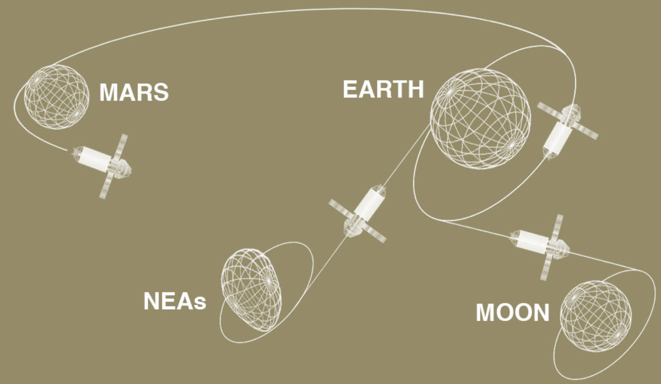


Delta IV
1st stage: RS-68A (new)
2nd stage: RL10B-2 (legacy)

Falcon 9
1st stage: 9 Merlin 1D (new)
2nd stage: 1 Merlin 1D (new)

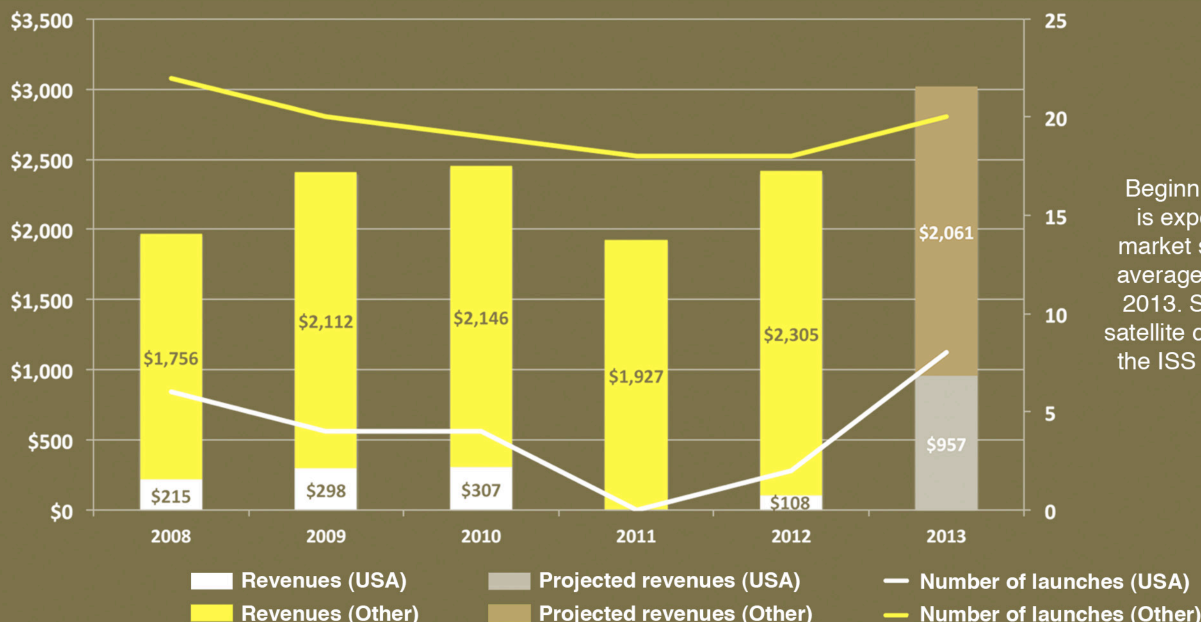
Antares
1st stage: AJ26 (legacy)

NASA APPLICATION



New, more powerful and efficient LREs enable NASA to pursue human missions beyond LEO and to continue robotic missions to the Moon, Mars, and other destinations throughout the solar system.

MARKET OVERVIEW



Beginning in 2013, the U.S. is expected to increase its market share from an annual average of 13% to 28-32% in 2013. SpaceX's commercial satellite contracts and flights to the ISS are driving increase.

Aerojet Rocketdyne	**RS-68A** **J-2X** **AJ26** **RS-25** **RD-180 (RD AMROSS)** **RL10**
SpaceX	**Merlin 1D**

Other major U.S. LRE development efforts

Blue Origin (BE-3)
Masten Space Systems (small, restartable)
ORBITEC (VR-3A)
XCOR Aerospace (small, restartable)

Wireless Power

Wireless power is the capability to transmit power over both short and long distances without wires. Magnetic induction and resonance technologies allow near-field transmission of power to electronic devices within short distances. Achieving long distance power transmission requires power to be beamed as millimeter waves, microwaves, or lasers to a receiver located either on a device, a vehicle to be powered, or to the electric power grid. These technologies would complement military efforts to power unmanned aircraft systems (UAS) wirelessly as well as potential commercial efforts to supply energy through long-distance power beaming. Becoming the global leader in wireless power would give the U.S. a larger share of the over $2 trillion dollar global electricity market. Public-private partnerships could help advance U.S. competitiveness in the growing wireless power market while helping enable NASA's exploration missions.

Commercial Application

Currently, the most widely used form of wireless power is near-field electrical device and vehicle charging. This includes wireless technologies such as magnetic inductors and resonators for mobile device charging mats, beaming power throughout a room to charge electrical devices and appliances, and charging electric vehicles (vehicles that travel on a 'charging' road). In 2012, the World Economic Forum identified wireless powering of electronic devices as one of its top emerging technology areas, stating these technologies were "poised to have as significant an impact on personal electronics as Wifi had on Internet use."[1] Wireless charging of electric vehicles is expected to become another significant application of wireless power as the number of electric vehicles continues to grow.[2]

The most ambitious commercial application of wireless power beaming is providing power to the electric power grid from space. Space-based power beaming remains in an early stage of conceptual and technological development and might never become commercially viable. Nonetheless, wireless power from space remains of interest as a form of clean, sustainable power that could potentially provide electricity to military bases for energy assurance, for emergency power for disaster relief, and to allow nations to become more energy independent. The military is also interested in beaming power from ground-stations to UAS, allowing them to remain permanently aloft. A network of power sources, beamed-energy ground-stations, and UAS could be a more cost-effective form of point-to-point beamed energy transmission than direct wireless power transmission from space.

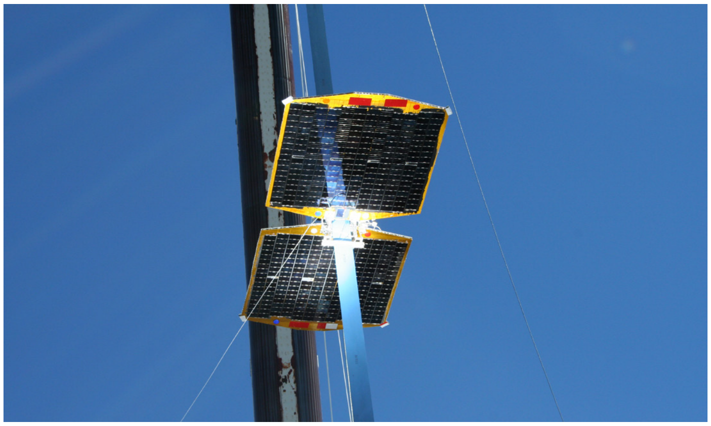


Figure 18. The University of Michigan's MClimber, an entrant into the 2006 Space Elevator Games - Power Beaming competition. The system successfully reached 50-meter mark. Source: Dustin Sensiba.

NASA Application

NASA has studied long distance wireless power transmission for multiple applications including powering rovers in dark craters on planetary surfaces, powering aerospace vehicles and providing launch propulsion. NASA first studied long-distance wireless power transmission from space in the 1970s, and then again in 1996 through 2000. Between 2006 and 2009 NASA conducted the Power Beaming Centennial Challenge that called on competitors to develop a wireless power system that could power a robotic climber to climb a cable one kilometer vertically with ground-based power. Three companies competed and LaserMotive, LLC, won the prize.

In 2011, NASA's Ride the Light project awarded $3 million to six companies to develop low-cost, modular power beaming concepts to provide power and propulsion to aerospace vehicles (including UAS) and study new receiving technologies. NASA's Ames Research Center continues to study beamed energy propulsion through its Millimeter-Wave Thermal Launch System (MTLS). Near-field magnetic resonance power beaming has also been studied for space applications by technologists at Kennedy Space Center.

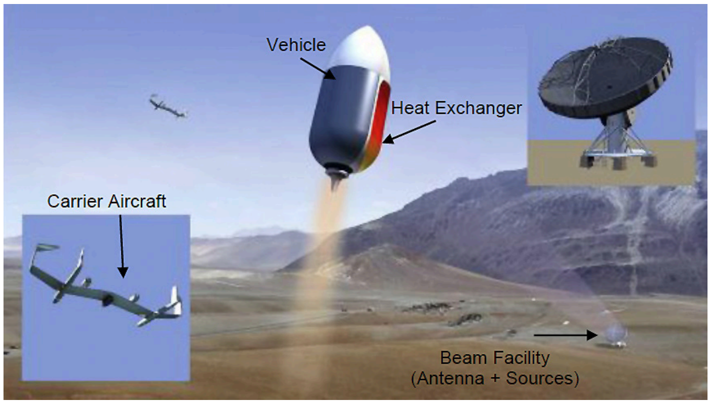


Figure 19. The MTLS concept. Source: NASA/ARC.

Long-range beamed power concepts are also being investigated for applications in space. The Solar Power via Arbitrarily Large Phased Array (SPS-ALPHA) is being explored under the NASA Innovative Advanced Concepts program. An international team will pursue proof-of-concept experiments to determine the feasibility of building massive arrays using thousands of small, remotely operated elements.

The potential to provide wireless power for satellite or spacecraft subsystems is another area of development. NASA is considering concepts related to wireless transmission of data and power for avionics in spacecraft and inflatable habitats. This approach is being pursued to determine if it would facilitate more efficient interaction between crews, vehicles, and equipment.

Market Overview

Each year, the global electricity industry generates over 20 trillion kilowatt (kW) hours of electricity. Leading countries in electricity generation are the U.S., China, Japan, and Russia. In the U.S., electricity generation had over $120 billion in revenue in 2012, while global revenues are predicted to reach over $2 trillion by 2017.[3]

The UAS market continues to be a growing sector of the world aerospace market, with $6.6 billion in revenues in 2012. The U.S. accounts for the majority of sales (55 percent) of UAS as well as the majority of research and development technologies (62 percent).[4] Currently, the U.S. has more than 7,000 UAS.

The wireless charging industry also continues to grow as the number of consumer mobile devices increases. In 2012, the industry reached $1 billion.[5] The consumer electronic devices industry itself was $170 billion.[6] The charging of plug-in electric vehicles is a growing piece of the charging industry. In 2012, there were 120,000 plug-in, electric vehicles globally. However, wireless charging for these vehicles is still in development.

Demand

According to the International Energy Agency's 2002 Energy Outlook report, world electricity demand is projected to double between 2000 and 2030, growing at an annual rate of 2.4 percent.[7] This is faster than any other final energy source. Electricity's share of total final energy consumption will rise from 18 percent in 2000 to 22 percent in 2030.[8] Electricity demand is strongest in developing countries, where it will climb by over 4 percent per year over the projection period, more than tripling by 2030.[8] Consequently, developing countries' share of global electricity demand will jump from 27 percent in 2000 to 43 percent in 2030.[9] In the U.S., total electricity demand is expected to grow 28 percent from 3,839 billion kW hours in 2011 to 4,930 billion kW hours in 2040.[10]

Despite defense cuts, the market for UAS is expected to continue to be strong, having proven to be a high priority asset for the U.S. and other militaries worldwide. The UAS market is forecasted to grow at 12 percent annually between 2013 and 2018, generating $89 billion.[11]

The wireless charging market is expected to grow from $1 billion in 2012 to $6 billion in 2020 due to increasing power requirements for mobile devices and charging hotspots in public places.[12] Additionally, charging capabilities are being added to laptops and automobiles, further increasing demand. Nearly all electric vehicle manufacturers have announced partnerships for wireless charging, with annual sales of 283,000 units of wireless charging equipment for electric vehicles expected by 2020.

Supply

At the 2012 Space Power Symposium in Naples, Italy, engineers and advocates from Russia, China, and Japan presented papers on concepts for delivering power from space. A Russian Federal Space Agency (Roscosmos) representative presented a plan for a 100 kW working prototype power beaming system, but did not announced a launch date. A China Association for Science and Technology representative presented a 100 kW low Earth orbit demonstration system for 2025; with a stated goal of a fully operational system by 2050. A Japanese government representative at the conference revealed plans for a small-scale power beaming test of 160 feet for 2014 and hopes to start generating power from space in 2030. In 2009, U.S. developer Solaren announced the development of a system planned to begin supplying 200 megawatts of power to Pacific Gas and Electric in 2016.[13] However, the latest information available is from 2009, and there is no sign of significant financial investment in any of these initiatives to date.[14]

LaserMotive has demonstrated powering a Lockheed Martin Stalker UAS using their laser power beaming system. Additionally, Teledyne Brown, Aerojet, ATK, LaserMotive, Carnegie Mellon University, Teledyne Scientific, Boeing, and The Aerospace Corporation all participated in NASA's Ride the Light project.

A number of wireless charging technologies are being developed in commercial industry. More than 125 businesses have joined wireless power consortiums to develop a standard for wireless charging and companies like Texas Instruments have begun selling products to integrate wireless charging into the next generation of mobile devices. Many plug-in electric vehicle providers have also partnered with industry to develop wireless charging technologies. Partnerships include: Siemens working with BMW; Witricity and Delphi working with Toyota, Mitsubishi, and Audi; Qualcomm working with Renault and Delta Motorsports; and Evatran is working with SPX Service Solutions, Google, and Hertz Corporation.

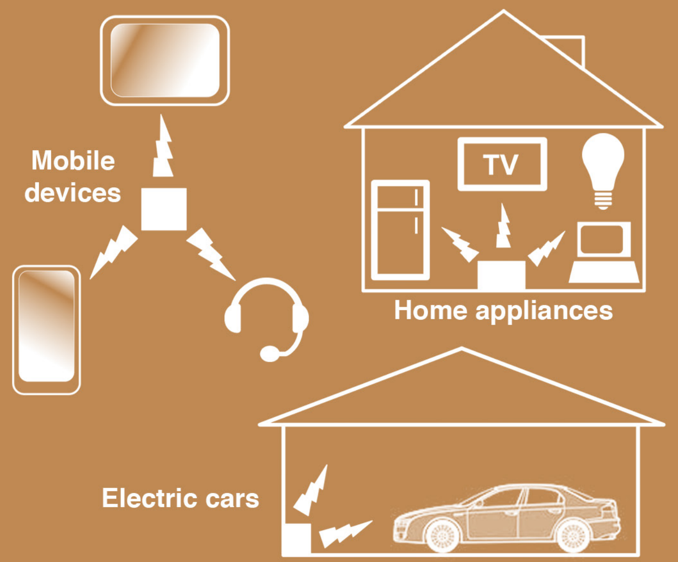
Wireless charging of transit vehicles requires the development of both infrastructure and vehicles. The Korea Advanced Institute of Science and Technology (KAIST) has two wirelessly charged electric vehicles in operation. One is a bus that transports students around the KAIST campus; the second is an amusement park tram in Seoul.[15] In November 2012, Utah State University unveiled a similar technology to wirelessly charge a bus.

Barriers and Uncertainties

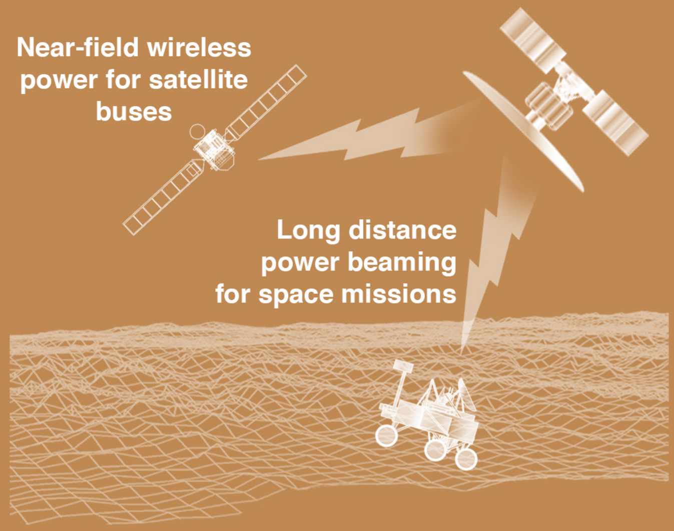
Studies by NASA and the Department of Defense have shown that beaming power from space to the ground is technically feasible. The cost of these systems is estimated to be in the range of $15 to $20 billion. Many experts believe that the costs of space-based solar power prevent the business case from closing.[16] If anticipated advances in technologies for reducing the costs of other terrestrial energy sources come to fruition, space-based solar power may never be economically competitive with other sources, even with major reductions in the cost of access to space.

Wireless Power

COMMERCIAL APPLICATION



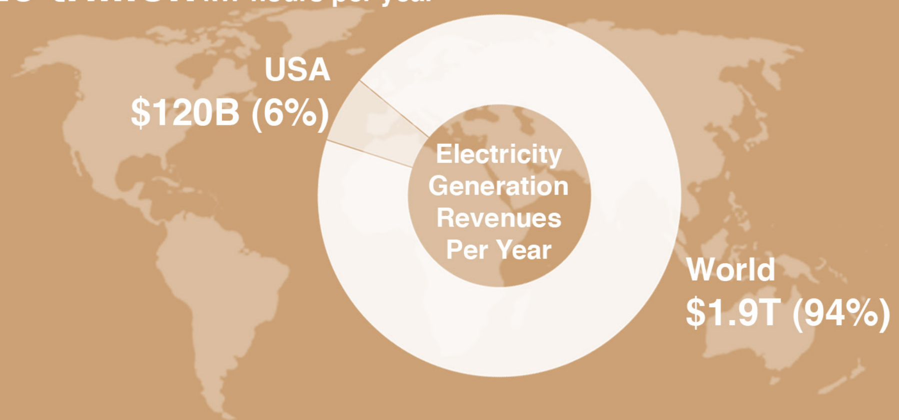
NASA APPLICATION



MARKET OVERVIEW

World energy comsumption:

20 trillion kW hours per year



Major Wireless Power Market Today

Consumer electronics revenue per year

$170B

Wireless charging industry

$1B

DEMAND PROJECTIONS

From **3.8T** kW hours per year

To **4.9T** kW hours per year by 2040

$6B

2020 wireless charging industry revenue projection

ONGOING RESEACH

WIRELESS CHARGING OF ELECTRIC CARS

BMW with Siemens
Toyota, Mitsubishi, and Audi with Witricity and Delphi
Renault and Delta Motorsports with Qualcomm
Evatran with SPX Service Solutions, Google, and Hertz

Centers of research:
USA
Russia
China
Japan

WIRELESS POWER BEAMING TO UANNED AERIAL SYSTEMS

World UAS industry was $6.6B in 2012; Industry projected to be $87B by 2018

Space Communications

Space communication technologies transmit and relay data between satellites, vehicles in space, and assets on the ground. Satellite telecommunications provide vital data links for the global economy and for our national security. NASA made significant contributions to the early satellite telecommunications market by developing capabilities originally designed to support NASA missions, which also supported national recognition of the economic and political importance of satellite telecommunications. NASA's role in satellite telecommunications shifted from overall leader in the 1960s to a niche technology developer in the 1970s. Today, NASA's focus on space communications is to support its missions. As the global demand for bandwidth continues to grow, NASA is working to improve the quality of space communications using advanced technology. The potential exists for NASA to make a significant impact on the U.S. telecommunications market. Public-private partnerships with the U.S. telecommunications industry could increase U.S. market share in the largest commercial space market while increasing NASA's options for space communications.

Commercial Application

Commercial telecommunications companies use space communications for broadcast services; fixed satellite services (FSS) for telephone, television, data (including Internet), and radio signals; and mobile satellite services (MSS) for cellular telephones, maritime, and aircraft services. Laser communication technologies could increase throughput by over 1,000 times through higher data rates and greater frequency reuse while avoiding the problems of highly regulated radio frequency spectrum.

NASA Application

NASA uses space communication technologies to transmit and relay data between satellites, vehicles in space, and assets on the ground for GEO, LEO, cis-lunar space, and deep space activities. Advanced space communications using laser and radio frequency technologies could provide data rates that are 10 to 100 times faster than current state-of-the-art radio frequency systems (e.g., Ka-band) while reducing both retransmissions and data loss.[1,2] Laser communication technologies could decrease the overall mass and power of spacecraft while improving the tracking of interplanetary missions to centimeter-level range accuracy.

NASA tested its first high-data-rate laser communication system, the Lunar Laser Communication Demonstration (LLCD), in 2013. NASA's Laser Communications Relay Demonstration

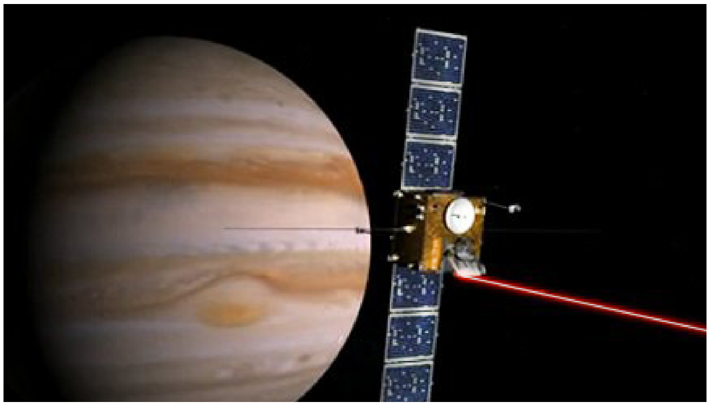


Figure 20. Artist's impression of a laser communications system employed near Jupiter. Source: NASA.

(LCRD) will demonstrate laser communications on a commercial platform in 2017.

Innovative approaches to low-cost telecommunications can also help meet NASA's Exploration communication needs as it expands its activities in cis-lunar space.

Market Overview

The global telecommunications industry generated $4.9 trillion in revenue in 2012.[3] The satellite communications industry is a part of the global telecommunications industry, but in 2012 represented just 4 percent (or nearly $190 billion) of total telecommunications revenues. The satellite industry has four components, as defined by the Satellite Industry Association: satellite services, satellite manufacturing, satellite launch, and ground equipment.

Of the four industry segments, the satellite services segment is by far the largest, generating over $113 billion in global revenue in 2012, a 5 percent increase over 2011.[4]

Within satellite services, consumer services provide satellite television, radio, and broadband Internet. Consumer services are the primary growth driver for the satellite industry, generating $93 billion in revenue in 2012. The FSS segment consists of transponder agreements (purchasing transponder usage from commercial satellite service operators) and end-to-end managed services. FSS is a $16.4 billion industry. MSS companies, which provide data and voice services via satellite, generated $2.4 billion in 2012.[5]

The satellite telecommunications market has grown between 5 percent and 15 percent over the past six years, outpacing world and U.S. economic growth.[6]

NASA has made significant contributions to the satellite telecommunications market. NASA launched the Signal Communication by Orbiting RElay satellite in 1958, which provided the first voice-radio transmission from space. NASA and commercial partners also launched the first privately sponsored communications satellite (Telstar 1 in 1962) and TIROS 1 in 1960, which sent the first television images from space. NASA and commercial partners also launched Syncom 2 in 1963, the first geosynchronous satellite, which transmitted live coverage of the 1964 Olympic Games in Tokyo to stations in North America and Europe. NASA's Applications Technology Satellite (ATS)

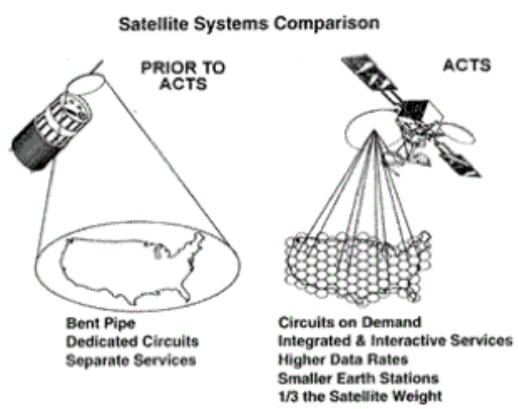


Figure 21. Satellite systems before and after ACTS. Source: NASA.

series from 1966-1974 demonstrated communications technologies, carrying more signal traffic than any satellite before them and pioneering Ka-band communications. ATS-1 was the first satellite to take independently uplinked signals and convert them for downlink on a single carrier.[7] NASA's Advanced Communications Technology Satellite (ACTS), launched in 1993, pioneered the use of Ka-band and spot beam technologies introducing a major shift in how commercial satellite communications are designed.

The U.S. telecommunications industry can once again leverage NASA's innovations and expertise to ensure that data rates provided by U.S. satellite telecommunications providers do not lag behind those of other countries.

Demand

Global demand for bandwidth has grown in the past decade and is expected to continue to grow through 2020. In 2002, providers provided 1.4 terabits per second and are expected to provide more than 1,000 terabits per second by 2020.[8] Due to the limited number of slots in GEO, this increase in demand will not be met with a significant increase in launches, but rather through more capable satellites. About 18 commercial telecommunication satellites per year are expected to launch for the next 10 years.[9]

The U.S. Government, primarily the DoD, obtains over 80 percent of its telecommunications needs from commercial satellites,[10] and spends over $1 billion annually on commercial satellite capacity.[11]

Supply

There are approximately 50 satellite operators globally. In 2012, there were 20 commercial fixed satellite service operators with over $100 million in annual revenue. The "big four" operators are Intelsat, SES, Eutelsat, and Telesat. These four operators generate approximately 45 percent of all fixed satellite service revenues, and 40 percent of the market of fixed and mobile services when taken together.[12]

New companies and services in this sector include O3b, which aims to provide affordable and high-quality Internet connectivity across emerging markets via satellites in medium Earth orbit. United Kingdom-based O3b launched its first four satellites into space in 2013. SES, Google, and HSBC Bank are among O3b's financial backers.[13] LightSquared, a U.S. company, has proposed to offer a U.S. 4G-LTE wireless broadband network via satellite, and reported that they had raised more than $2.3 billion in debt and equity financing, although the company is currently in the process of a voluntary bankruptcy restructure after the Federal Communications Commission blocked its network over interference concerns.[14]

Government agencies are currently the main suppliers of in-space communications. However, commercial industry has begun in-space communication services within LEO. Inmarsat offers Broadband Global Area Network service to LEO users at ~500 kbps downlink rate today with 5th Generation Global Express capability planned to offer 50 Mbps down by 2015.

The predominant space communication technology is radio, which will likely remain the case for the next decade. However, as the demand for bandwidth increases, organizations are investigating alternatives to radio communications to increase bandwidth and provide continuously high data rates. For example, NASA, the European Space Agency (ESA), the German Aerospace Center (DLR), and the U.S. DoD are investing in laser communications.[15,16,17,18] These investments by the U.S. and Europe however are for competing designs that are currently not interoperable. The DoD's space communications programs include the Near Field Infrared Experiment (NFIRE) satellite, which is equipped with a laser communication terminal.

Outside of the government, Planetary Resources has identified deep space laser communication as a critical technology for its asteroid mining and is planning to invest in laser communications on the ARKYD satellite. Additional companies interested in laser communications include service providers like Inmarsat, and satellite manufacturers Ball Aerospace, Northrop Grumman, Lockheed Martin, Space Systems Loral, and Boeing.

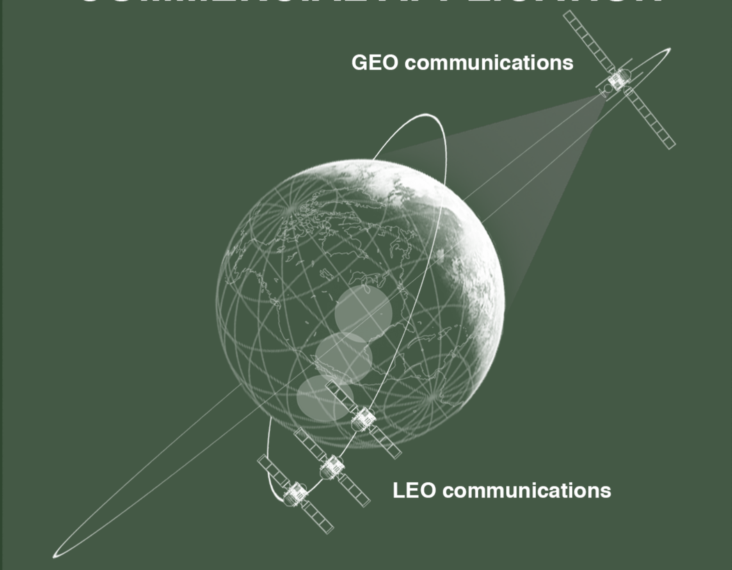
Europe is also investing in laser communications. ESA launched the ARTEMIS satellite to GEO in 2001, which included a laser communication system that has been used to communicate with the SPOT-4 remote sensing satellite and an aircraft at cruising altitude. ARTEMIS is considered a precursor mission to the European Data Relay Satellite (EDRS), a GEO-based, hosted payload system that will feature laser relay capability between satellites, aircraft, and ground stations. The first EDRS payload will be launched in 2014 aboard Eutelsat's Eurobird 9B satellite. In cooperation with ESA and CNES, Inmarsat launched Alphasat on July 25, 2013, built jointly by Thales Alenia and EADS Astrium, which will demonstrate a laser communications payload. In the U.S., NASA's LCRD will be a hosted payload on a Space Systems Loral satellite in 2017, which will have a laser communications terminal.[19,20] Other space agencies in China, Canada, Europe, and India regularly assist their domestic telecommunications satellite manufacturers through research and development funding and support.

Barriers and Uncertainties

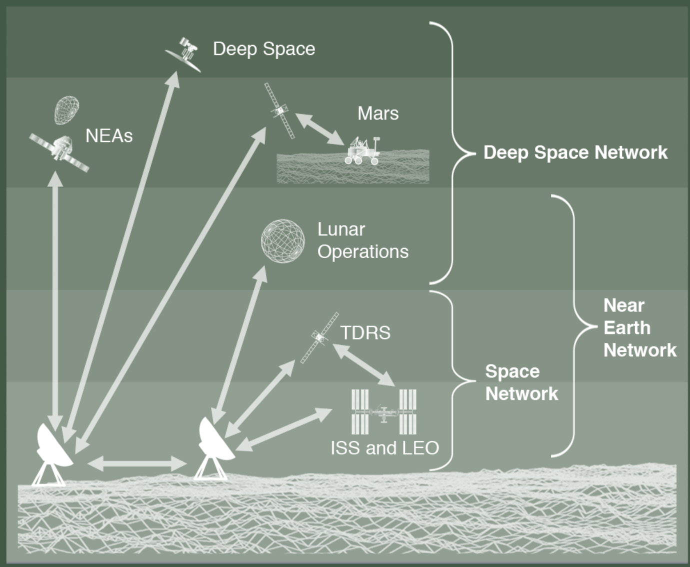
NASA is not a consumer of commercial satellite capacity. Although the U.S. government is the single largest buyer of satellite capacity, its purchases represent less than 10 percent of satellite services revenues. NASA and commercial telecommunication industry needs and objectives are not completely aligned which may make it difficult to find partnering opportunities.

Space Communications

COMMERCIAL APPLICATION



NASA APPLICATION



MARKET OVERVIEW

Global Satellite Industry Revenues
($ Billions)

Satellite Services
Television, radio, broadband, fixed, mobile, remote sensing
$113.5B

Satellite Manufacturing
$14.6B

Launch Services
$6.5B

Ground Equipment
GPS devices, satellite TV dishes, VSATs, network gateways
$54.8B

DEMAND

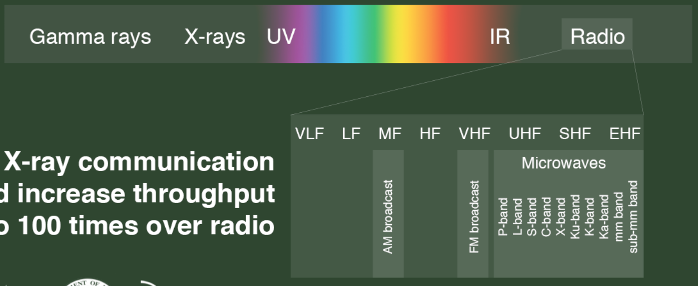
1.4 terabits per second
Demand for bandwidth (2002)

1,000 terabits per second
Demand for bandwidth (2020)

Global growth of satellite services from 2011 to 2012

7%

RESEARCH AND DEVELOPMENT



Optical and X-ray communication technologies could increase throughput by 10 to 100 times over radio

NASA
DoD
European Space Agency
DLR

Organizations currently investigating optical (laser) communications systems.

Earth Observation Data Visualization

There are hundreds of instruments (sensors and cameras) on satellites in orbit and on airborne platforms observing the Earth and collecting data. These data include visible light images; infrared images; radar and laser pulses; and thermal imaging, among others. Earth observation data is used extensively for scientific, civil, humanitarian, and commercial applications. For customers to benefit from geographic data, tools and technologies provided by the geospatial services industry are needed to support integrating, managing, analyzing and displaying information. Geospatial tools enable users to view, understand, question, interpret, and visualize data in many ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts that aid decision making.

The massive volume, complexity, and diversity of data collected through satellite Earth and airborne observations qualify it as “big data”. Understanding and using this data requires innovative approaches to data analysis and visualization.

Diversity of Earth observation data fused with data from other sources is creating an explosion of user applications from tracking weather to resources to tracking artifacts. Public-private partnerships that combine NASA’s unique expertise in Earth science data collection, processing, and visualization with capabilities of U.S. data analysis companies could improve national efforts to study planet Earth, promote innovations, and facilitate commercial applications.

Commercial Application

Earth observation data are collected continuously from both government and commercial satellites. These data have become powerful tools in helping industry better understand resources, develop products and services, and manage markets. Data are used by companies as diverse as retail stores seeking to understand peak business times, to agribusinesses monitoring crop growth, to the weather industry collecting information on impending storms. Other uses of Earth observation data include monitoring oil and gas pipelines, managing natural resources, monitoring crops and pollution, identifying sites for mining, obtaining competitive intelligence, and commercial weather services. Earth observation data can also be used to support homeland security, monitor infrastructure, and help predict disease outbreaks.

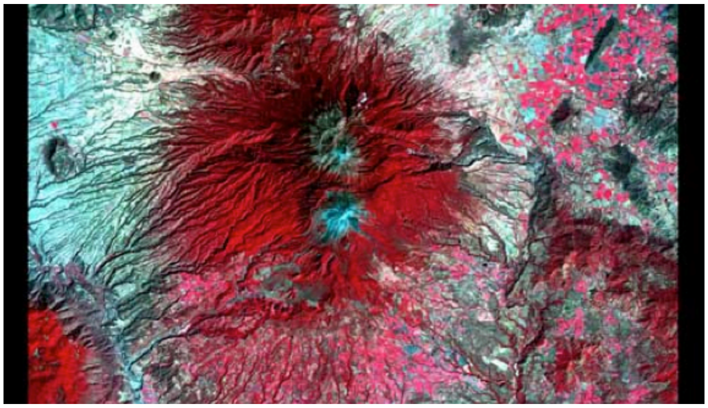


Figure 22. Image of Colima Volcan from NASA's Terra satellite. The image is part of the U.S. Geological Survey Earth Resources Observation and Science (EROS) Center “Earth as Art” image gallery. Source: USGS.

NASA Application

One of NASA’s goals is to understand the Earth as a system. NASA data improves prediction of climate, weather and natural hazards. Twelve NASA-sponsored data centers provide routine, standardized Earth science data, information, and services to research scientists, applied researchers, applications users, students, and the public. NASA works with other U.S. government agencies and academia to understand the effects of natural and human-induced changes to the Earth. NASA’s understanding of the data allows it to form unique partnerships with user-communities like wildland firefighters and developing nations. California firefighters use NASA data to identify areas with prevalent dry-vegetation that are susceptible to wildfires. NASA’s SERVIR program is a joint venture with the U.S. Agency for International Development (USAID), providing satellite-based data and practical applications to help developing nations in Central America, East Africa and the Himalayas improve their environmental decision-making. In addition to the Earth Science data centers, NASA works with a variety of commercial partners, such as Google and Amazon to help manage Earth science data. Many commercial companies are also using Landsat data.[1]

Market Overview

In 2011,the U.S. geospatial industry generated approximately $73 billion in revenues and comprised at least 500,000 high-wage jobs.[2] This includes tools, technologies, and services for individuals and organizations to use location-based information. Satellite imagery is an important part of the market. Demand will likely grow due to increasing use of data. Technologies for making use of geospatial information will become increasingly important to companies and organizations in the near term. End-user markets, such as those listed under commercial applications, are multi-million if not billion dollar markets.

Demand

Growth in the geospatial services industry is expected to be robust. Diverse data products and widespread use in industries including increasing adoption of the technology in oil and gas distribution, electric power, and government sectors drive this growth. There is investment and acquisition interest in companies that create products using earth observation data, such as The Climate Corporation, which received investment from Google Ventures and others to build an online platform for agriculture insurance using earth science data and models, and which was acquired in 2013 for $930 million.[3]

Experts in the remote sensing industry expect the amount of available imagery data to increase in the coming years. Space agencies like NASA and the European Space Agency (ESA) will deliver more data, including more imagery data. Space-based remote sensing products are expected to grow. About nine million scenes from Landsat (built by NASA and operated by the U.S. Geological Survey) were downloaded in 2012.[4] More broadly, over 636 million data products were downloaded in 2012 from NASA's Earth Observation System Data and Information System (EOSDIS).[5] In FY 2013, EOSDIS had a total archive volume of about 9.8 petbytes (PB).[6] Demand for additional processing capabilities and services are expected to grow in the future to meet the need for climate data records. Demand for space-based, climate change data is expected to reach over 350 PB in 2030.[7]

"Indeed, data is the next big thing. And it's not because, according to IBM, the digital universe will grow to eight zetabytes by 2015. The real impetus is the potential insights we can derive from this new, vast, and growing natural resource."

Perry Rotella
Forbes Magazine

There is currently a steady demand for commercial remote sensing satellites. Launches of remote sensing satellites account for 7 percent of the launch market, and have had a steady demand for one or two dedicated launches per year.[8] A 2011 survey of nearly 250 firms in the industry indicated that the international market for U.S. remote sensing firms was expanding, with the percent of business activities undertaken by U.S.-based organizations in foreign areas projected to increase from 7.5 percent in 2010 to 10 percent by 2020.[9]

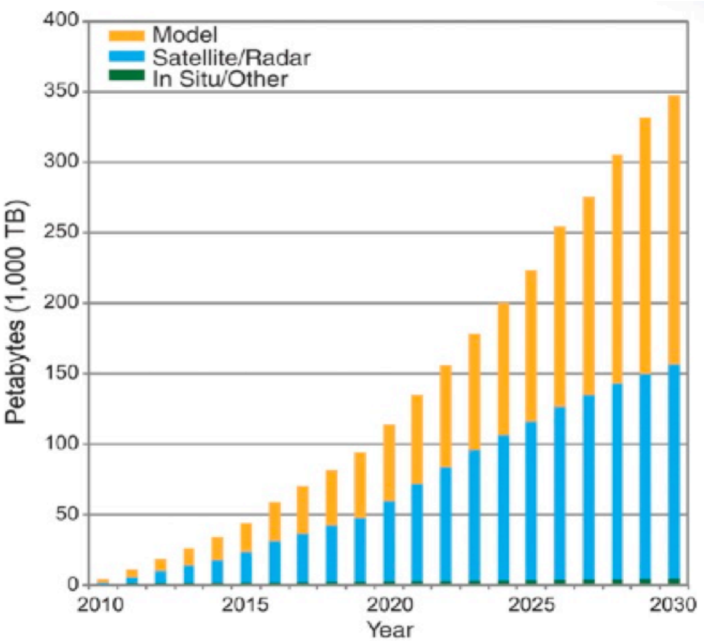


Figure 23. Climate change data is projected to grow nearly 350 PB by 2030. Source: NASA.

Supply

U.S. companies providing geospatial services include: ESRI, Intergraph, MapInfo, Global Information Systems, Inc., New Century Software, TerraGo Technologies, and SharedGeo. Data analytics companies interested in Earth Observation products include IBM, Cray, Cisco and Google. ESRI and IBM recently worked together to link information about customers of communication's company KDDI, with ESRI's geographic information to provide data to firms for marketing campaigns.

NASA, the Department of Defense, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey operate dozens of remote sensing satellites, including the Landsat series. The U.S. Government works closely with the international community and other countries' space agencies, through Committee on Earth Observation Satellites and the intergovernmental Group on Earth Observatories to coordinate and share Earth observation data. This data is also publicly available.

U.S. commercial satellite Earth observation companies include: Digital Globe, Planet Labs, and Skybox. In 2012, Skybox raised over $90 million from venture capital firms, and launched its first satellite in December 2013 aboard a Russian Dnepr vehicle.[10] To date, Planet Labs has raised $65 million from venture capital firms and launched its Flock-1 constellation of 28 satellites in January 2014 aboard an Orbital Sciences Corp. Antares vehicle.[11]

A U.S. company, PlanetIQ, plans to launch a small satellite constellation to commercially provide GPS Radio Occultation (GPS-RO) measurements. The provision of remote sensing satellite manufacturing worldwide is very competitive; satellite providers include companies in China, South Korea, Japan, Europe and India.

Barriers and Uncertainties

U.S. regulations currently limit commercial satellite remote sensing companies to selling imagery with a 50-centimeter resolution to non-U.S. government customers. This restricts U.S. competitiveness, as foreign companies are introducing data products with a resolution greater than 50 centimeters. The U.S. Government is currently reviewing the policy, which is expected to be relaxed in 2014 to enable U.S. companies to provide imagery with 25 centimeter resolution.[12]

Several new remote sensing satellite companies will begin providing imagery products and services in 2014. These companies plan to use constellations of very small, inexpensive satellites to obtain imagery of the Earth with revisit times measured in hours. Large, established players like DigitalGlobe operate satellites with revisit times measured in days. It is uncertain if there is a large enough market for near real-time imagery.

The use of unmanned aircraft systems (UAS) to obtain high resolution imagery is anticipated. It is unclear how this will impact the the market for satellite imagery.

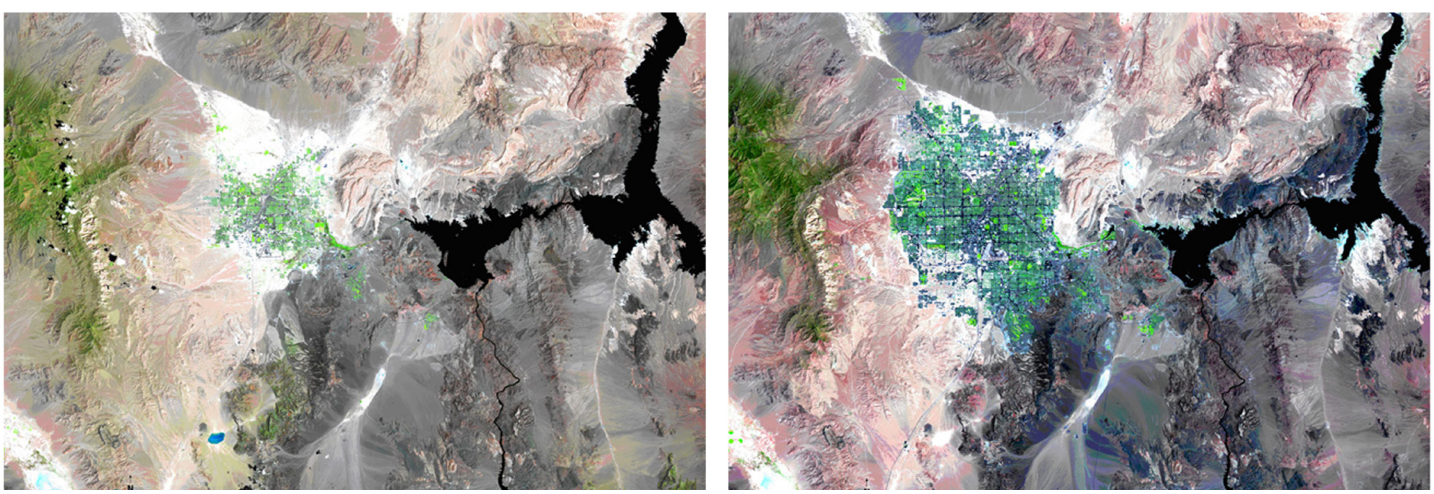


Figure 24. Landsat images showing the urban growth of Las Vegas, with the city as it appeared in 1984 (left) and in 2007 (right). Source: USGS.

Earth Observation Data Visualization

COMMERCIAL APPLICATION

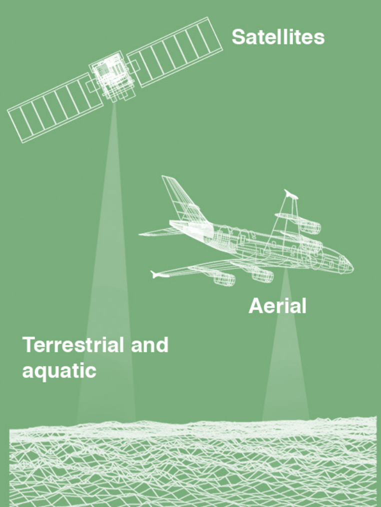
NASA APPLICATION

NASA focuses primarily on Earth science missions

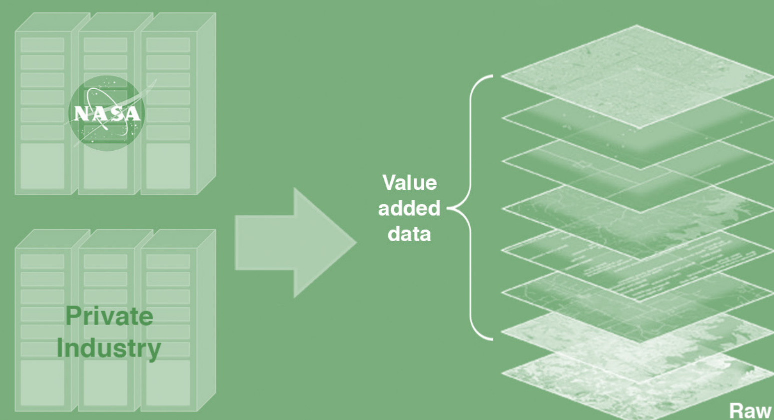
NASA developed systems to manage, process, store, archive, distribute, and visualize data products, partnering with Cray and Cisco, among others

MARKET OVERVIEW

RAW IMAGE ACQUISITION



GEOSPATIAL INDUSTRY SERVICES



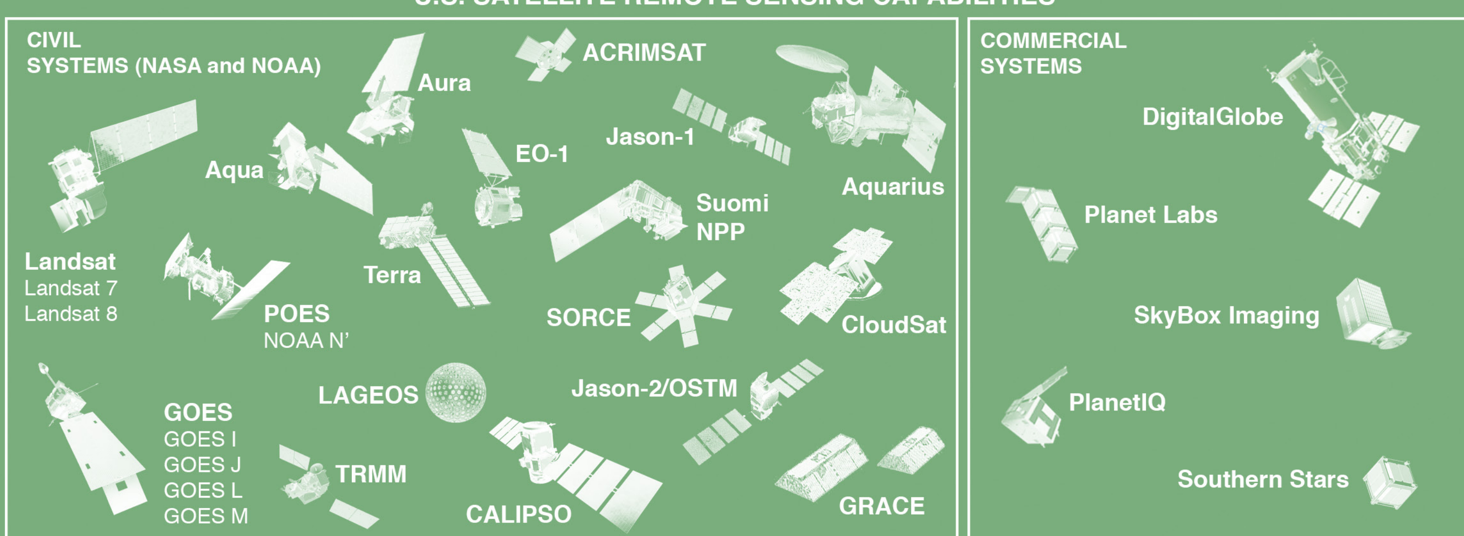
$73B
2011 estimated total worldwide revenue

500K
2011 estimated total high-wage jobs

Management of imagery from various sources, initial processing, and data transport

Climate change annual data volume projected to be over 350 petabytes by 2030

U.S. SATELLITE REMOTE SENSING CAPABILITIES



Conclusion

The topics explored within this report are areas for potential partnership that could result in supporting NASA's Mission as well as provide U.S. economic benefits. Research into these areas displayed positive private-sector indicators and alignment with NASA interests. Using a standardized method to explore each area provided a framework to investigate publicly available data beyond what is often traditionally considered.

Although the primary objective of the report is to provide general economic intelligence on promising areas for partnerships, the study also found that:

1. Economic analysis and market evaluation are valuable additions to the Agency's strategic decision-making and acquisition processes for program formulation;
2. Public-private partnerships deserving of particular attention are those that have attracted private capital, have technical merit, contribute to achieving NASA's overall Mission, and are in the national interest; and,
3. The development of strategies and architectures for space exploration that include public-private partnerships should be encouraged.

As NASA develops its deep space exploration strategy, identification of options for leveraging private investment and contributing to U.S. economic competitiveness in the process will be critical to establishing a sustainable path. NASA will continue to drive advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality, and stewardship of Earth. However, NASA will also continue to be fiscally constrained given the current economic conditions while trying to engage in tasks of extraordinary risk, complexity, and national priority. Having the capability to consider non-traditional approaches such as partnerships will be essential to NASA achieving its overall mission. We hope the information in this report shows the value that economic intelligence and economic analysis can contribute to our ability to plan for the future. We also hope that this analysis will lead to broader recognition that by leveraging public-private partnerships as a regular part of the agency's approach to space capability development, NASA's programs can be a fundamental driver of U.S. economic growth in the 21st century

National Aeronautics and Space Administration

Satellite Servicing

Interplanetary Small Satellites

Robotic Mining

Microgravity Research for Biomedical Applications

Liquid Rocket Engines for Launch Vehicles

Wireless Power

Space Communications

Earth Observation Data Visualization

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