Mega-Drivers to Inform NASA Space Technology Strategic Planning

Melanie L. Grande,[1] Matthew J. Carrier,[1] William M. Cirillo,[2] Kevin D. Earle,[2] Christopher A. Jones,[2] Emily L. Judd,[1] Jordan J. Klovstad,[2] Andrew C. Owens,[1] David M. Reeves,[2] and Matthew A. Stafford[3]
NASA Langley Research Center, Hampton, VA, 23681, USA

The National Aeronautics and Space Administration (NASA) Space Technology Mission Directorate (STMD) has been developing a new Strategic Framework to guide investment prioritization and communication of STMD strategic goals to stakeholders. STMD's analysis of global trends identified four overarching drivers which are anticipated to shape the needs of civilian space research for years to come. These Mega-Drivers form the foundation of the Strategic Framework. The *Increasing Access* Mega-Driver reflects the increase in the availability of launch options, more capable propulsion systems, access to planetary surfaces, and the introduction of new platforms to enable exploration, science, and commercial activities. *Accelerating Pace of Discovery* reflects the exploration of more remote and challenging destinations, drives increased demand for improved abilities to communicate and process large datasets. The *Democratization of Space* reflects the broadening participation in the space industry, from governments to private investors to citizens. *Growing Utilization of Space* reflects space market diversification and growth. This paper will further describe the observable trends that inform each of these Mega Drivers, as well as the interrelationships between them within STMD's new Strategic Framework.

I. Nomenclature

AI = Artificial Intelligence
ARM = Asteroid Redirect Mission
ARMD = Aeronautics Mission Directorate
CMOS = Complementary Metal Oxide Semiconductor
COTS = Commercial Orbital Transportation Services
COTS = Commercial Off-The-Shelf
CSLI = CubeSat Launch Initiative
DARPA = Defense Advanced Research Projects Agency
DLR = German Aerospace Center
ELaNa = Educational Launch of Nanosatellites
EP = Electric Propulsion
ESA = European Space Agency
FAA = Federal Aviation Administration
FAR = Federal Acquisition Regulation
FCC = Federal Communications Commission
FY = Fiscal Year
GEO = Geostationary Orbit, or Geosynchronous Equatorial Orbit
GPS = Global Positioning System
GSO = Geosynchronous Orbit
HEOMD = Human Exploration and Operations Mission Directorate
HST = Hubble Space Telescope
HTS = High Throughput Satellites

---

[1] Student Trainee (Engineering), Space Mission Analysis Branch, MS 462, 1 N. Dryden Street, Hampton, VA, Student Member.
[2] Aerospace Engineer, Space Mission Analysis Branch, MS 462, 1 N. Dryden Street, Hampton, VA, Member.
[3] Electronics Engineer, Systems Integration & Test Branch, MS 462, 21 Langley Boulevard, Hampton, VA, Non-Member.

ICCS = ISS Commercial Cargo Services
IMAP = Interstellar Mapping and Acceleration Probe
ISS = International Space Station
JPL = Jet Propulsion Laboratory
JWST = James Webb Space Telescope
LADEE = Lunar Atmosphere and Dust Environment Explorer
LEO = Low-Earth Orbit
MarCO = Mars Cube One
MEDICI = Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation
NASA = National Aeronautics and Space Administration
OCST = Office of Commercial Space Transportation
OSTP = Office of Science and Technology Policy
PSLV = Polar Satellite Launch Vehicle
SAA = Space Act Agreement
SBIR = Small Business Innovation Research
SMD = Science Mission Directorate
SpaceX = Space Exploration Technologies
SPI = Strategic Planning and Integration
SSO = Sun Synchronous Orbit
STEM = Science, Technology, Engineering, and Mathematics
STEREO = Solar TErrestrial RElations Observatory
STMD = Space Technology Mission Directorate
STTR = Small Business Technology Transfer
ULA = United Launch Alliance
WFIRST = Wide Field InfraRed Survey Telescope

II. Introduction

The National Aeronautics and Space Administration (NASA) Space Technology Mission Directorate (STMD) is developing a Strategic Framework to ensure technology development investments are aligned with trends in the space industry and provide a vision for the future of space technology [1]. The goal is to reframe STMD strategy to focus investment prioritization and communication on impacts, outcomes, and challenges first; and on technologies and systems second. The Framework will enable STMD to respond to new challenges in a dynamic global environment. At the highest level of the Framework, STMD identified overarching trends that have shaped, are shaping, and will shape the space industry over many years. These overarching trends informed the definition of four Mega-Drivers:

1) Increasing Access
2) Accelerating Pace of Discovery
3) Democratization of Space
4) Growing Utilization of Space

The Mega-Drivers represent the beginning of a top-down approach to analyzing the Mission Directorate's strategic goals, and they are a step towards focusing on the most high-impact investments for Agency strategic goals in science and exploration.

III. The Process

The structure of the STMD Strategic Framework approach was modeled after one successfully pioneered by NASA's Aeronautics Research Mission Directorate (ARMD) over the past five years, incorporating lessons learned and changes where appropriate [2]. At its highest level, this Strategic Framework, shown in Fig. 1, includes Mega-Drivers informed by overarching trends in the space industry and a dynamic global environment. The identification of these trends involved detailed industry research, literature review, and analysis of forecasted impacts based on current space technology developments. In addition, conversations with STMD customers (e.g., the Human Exploration and Operations Mission Directorate (HEOMD), Science Mission Directorate (SMD), U.S. space industry, and other government agencies) as well as industry review were critical to trend identification. Subject matter experts, STMD Principal Technologists, and members of the Strategic Planning and Integration (SPI) team within STMD identified four Mega-Drivers through the consolidation of these identified trends and current technology developments.

Following the Mega-Drivers research, a handful of Strategic Thrusts were crafted to address key avenues of investment for STMD. Each of the Strategic Thrusts have a set of Outcomes, which are measurable achievements STMD would like to see accomplished over the next few decades. As community-level goals, the Outcomes involve and respond to STMD's customers and other entities in the space industry. The Strategic Framework is described in more detail in Ref. [1].

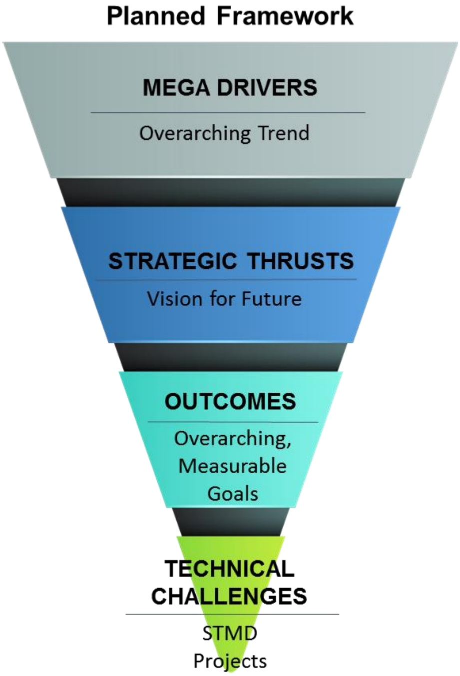


Fig. 1: STMD's Planned Strategic Framework.

IV. Mega-Driver 1: Increasing Access

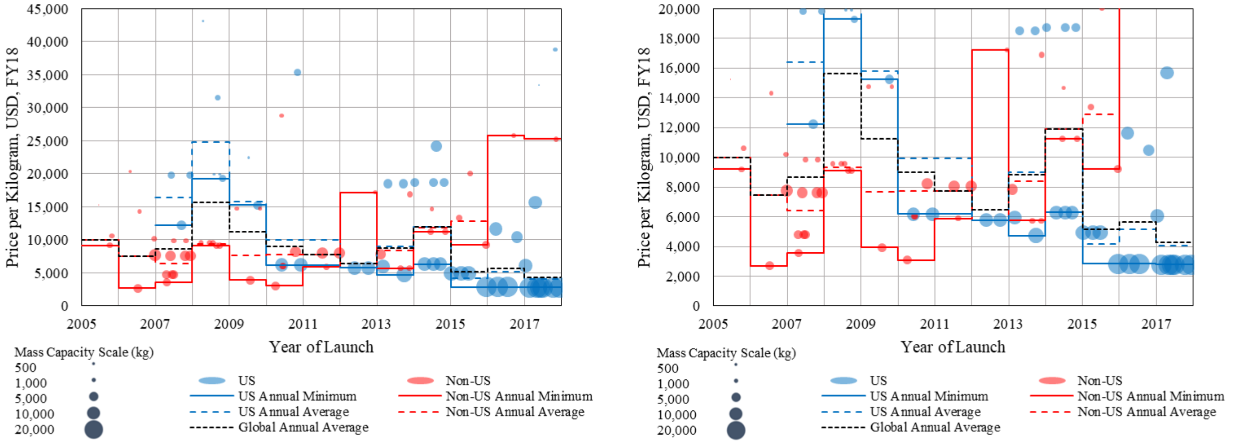
Over the past two decades, space has become increasingly accessible, and it has become easier for both traditional and new players to launch assets into space, move around in space, and land and operate on other planetary surfaces. The first Mega-Driver, *Increasing Access*, reflects the combination of an increase in the availability of a broad range of launch options, more capable and efficient propulsion systems, access to planetary surfaces, and new platforms to enable exploration, science, and commercial activities at reduced cost and risk of those platforms over time.

A. Launch Price Reductions over Time

The price of access to space drives prices across the space industry. Several factors have influenced the cost to launch: increased competition in the international and private sectors, higher launch rates, technology development, and regulation changes. Launch providers have benefitted from reusable rockets, additive manufacturing techniques, improved propellants, modular systems, and other advancements. Diversifying launch architectures, the expansion of the rideshare market, and smaller/lighter satellites are also driving down launch prices [3].

Additionally, new launch vehicles introduced in the private sector create increased competition that reduces launch prices. Within the United States, a few companies have dominated within the past 30 years: Boeing with its Delta II and IV and Lockheed Martin with the Athena and Atlas V, both companies now working together in the United Launch Alliance; Orbital with the Pegasus, Taurus, Minotaur-C, and Antares; and SpaceX with their Falcon 1, 9, and Heavy variants. International competition has also increased; since 1980, Israel, India, Japan, Iran, Italy, South Korea, and New Zealand have demonstrated launch capabilities to join Russia, the United States, Ukraine, China, and the European Space Agency (ESA). The increased competition has driven lower-priced launch vehicles, with SpaceX publically claiming the goal of lowering launch prices by an order of magnitude [4]. The company has benefited from many new development and manufacturing techniques, such as 3D printing, simplified production of engines, increased usage of composite materials, and a focus on reusability.

As displayed in Fig. 2, while the global minimum launch price per unit mass has not changed over the last decade the average price per unit mass showed a decreasing trend. Further, although the global minimum has not changed, the launch vehicle capacity for the equivalent price per unit mass has increased significantly. This behavior can be attributed entirely to the introduction of the Falcon 9 vehicle, as prior to Falcon 9 there were no commercial launches on a launch vehicle with capability greater than 10,000 kg. When considering solely domestic launch vehicles there is a clear decreasing trend in the last decade. Lastly, there was a related trend that in the last few years there simply more launches and payloads, signifying a fundamental change in the LEO market. Correspondingly, Fig. 3 presents the launch price per unit mass for commercial Geostationary Earth Orbits (GEO), which shows there was an increase from 2005–2009 but that there has been a steady downward trend after 2009. This trend holds for both domestic and international launch vehicles. As with LEO launches, Falcon 9 is driving down the price per unit mass of commercial GEO launches, particularly in the domestic market.



(a) **(b)**

Fig. 2 Commercial launch prices per kilogram to LEO, (a) total range and (b) zoomed-in, with the annual minimum and the annual average by US and non-US launches and the global annual average, all sized by launch mass capacity [5]–[53].

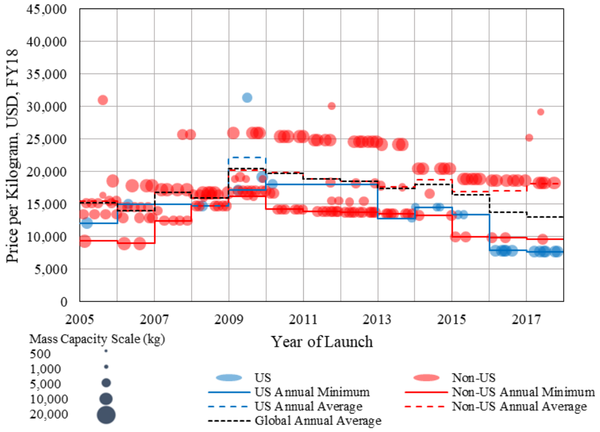


Fig. 3 Commercial launches to GEO with the annual minimum and the annual average by US and non-US launches and the global annual average, all sized by launch mass capacity [5]–[53].

B. Increase in Launch Availability and Options

A key aspect of *Increasing Access* is the increasing availability of launch vehicles, including the growth and diversification of vehicle options. On the government and military side, there has been fluctuation over the years of the number of launches per year; however, the 2010s have seen some stabilization to a near constant rate [54]. The number of commercial launches per year, on the other hand, has grown in the 2000s, especially in the last few years.

Bloomberg reported that more commercial orbital launches were planned for 2017 and 2018 than in any year in the previous decade [54]–[55]. This growth in availability has a significant impact on the space industry as a whole.

Much of the growth comes from new launch services entering the market, which represent a variety of classes of vehicles, service options, and launch architectures. One increasingly prevalent launch option in today's launch services sector is a secondary payload. Since the 1960s, secondary payloads have been manifested on a rocket with a primary payload (primarily for military purposes) to allay the launch costs for both the primary and secondary customers. In the early 2010s, this secondary payload market began to be dominated by CubeSats [55]. In 2013, after five straight years with 30 or more secondary payloads, a record-setting 115 secondary payloads were manifested, nearly three times the previous record of 36 set in 2009 [56]. This number has continued to grow. Nearly 350 SmallSats were launched in 2017, with the Russian Soyuz alone scheduled to fly 120 small spacecraft, including 72 on one launch [57]–[65]. In 2017, an Indian Polar Satellite Launch Vehicle (PSLV) launched a record-breaking 104 satellites on a single vehicle. Unsurprisingly, many launch providers have responded accordingly and entered the rideshare market. Arianespace's Vega Rocket will begin a Small Spacecraft Mission Service in 2019 with a new SmallSat adapter that can accommodate up to 15 small spacecraft or CubseSat deployers [58]. These ride-along spacecraft aspire to operate similar to airline passengers, with the entrance of "payload aggregator" companies like Spaceflight Industries, whose tagline is "Buy a seat, not a rocket." Spaceflight Industries boasts a network of providers including the SpaceX Falcon 9, Russian Soyuz, Arianespace Vega, Virgin Orbit Launcherone, Rocket Lab Electron, Indian PSLV, and others [59].

In addition to rideshare options, new launch vehicles are under development in a variety of classes—small, medium, heavy, and super heavy. SpaceX's Falcon Heavy launched successfully in February 2018 and is the first new super heavy rocket since the Delta IV Heavy's first successful flight in 2007, and before that, the U.S. Space Shuttle debut in 1981. The Space Angels investment group has identified 13 maiden flights of small launch vehicles planned for 2018–2021, including Vector's Vector-R, Virgin Orbit's LauncherOne, Firefly's Alpha, and the now-successful Electron (launched by Rocket Lab in January 2018) [60]. A total of 30 small launchers were listed as "under development" in 2016 from the U.S., Spain, United Kingdom, New Zealand, China, and others [60], and more start-ups sought investment since then. With access to space increasing, the demand from industry accelerating, and the market diversifying worldwide; (discussed in additional Mega-Drivers) a multitude of launch options will continue to be developed and will continue to have an immense impact on the space industry.

C. Emergence of SmallSat Markets

Miniaturization of satellite components has led to the development of small, affordable platforms for mini-, micro-, and nanosatellites. Though originally used in academia, these types of satellites have found an array of applications ranging from remote sensing to telecommunications [3][64]–[65]. As of 2017, NASA had 71 CubeSats missions either launched or in-development for science, technology, exploration, and STEM purposes [66]. Components that were originally made for large space programs like integrated circuits and solar cells have been adopted for terrestrial use and produced in large volume, thereby lowering their cost and making them affordable for use in small satellites [67]–[68]. With the increasing availability of additive manufacturing and other advanced manufacturing techniques, satellite firms can incorporate specialized components into their designs at a faster pace without being forced to scale production to recoup costs [67]–[69]. This shift has introduced new developmental and operational models characterized by rapid design iterations, lower design life and performance, higher risk acceptance, and use of constellations [70]–[71].

These developments have lowered the entry barrier for small commercial players and non-traditional nations. Growth in CubeSats and other small satellites has been a driver for new start-ups with business models centered around or related to small satellites, with examples including Accion, Cape Analytics, Enview, Rocket Lab, and Planet Labs [72]. In total, over 200 SmallSats have been launched since 2012 [65]. The emergence of the small satellite market has led to *Increasing Accessibility* of space and a diversification of space utilization apart from the traditional uses.

D. Increasing Availability of High Efficiency and Scalable In-Space Transportation Systems

Increasing Access also refers to the ability to access destinations within the solar system and beyond. There is a significant demand to expand human and robotic operations in deep space in the coming years, and a demand from certain portions of the science community to push deeper into our solar system. These mission objectives create a high demand for high efficiency and scalable in-space transportation systems. For human class missions, in-space propulsion technology is slowly advancing under the demand to move tens to hundreds of tons of mass through high energy maneuvers, e.g. for human exploration of Mars.

The maturation of electric propulsion (EP) systems is enabling missions into deep space as well as in-orbit transfer and maintenance maneuvers. These EP systems can reduce the required launch mass due to their high propulsive efficiency. As seen in Fig. 4, EP has been used in more government and commercial missions each year since its introduction [62]. Additionally, development of scalable propulsion systems has been an important driver for a range of robotic and human mission concepts. For example, EP can be used for a large robotic mission to an asteroid, in the case of NASA's Asteroid Redirect Mission (ARM) concept, or scaled down to take the first interplanetary CubeSats to Mars, in the case of Mars Cube One (MarCO). The MarCO Micro Propulsion System is a self-contained cold gas thruster system that was developed by the Jet Propulsion Laboratory (JPL) and launched with the InSight Mars rover in May 2018 [63].

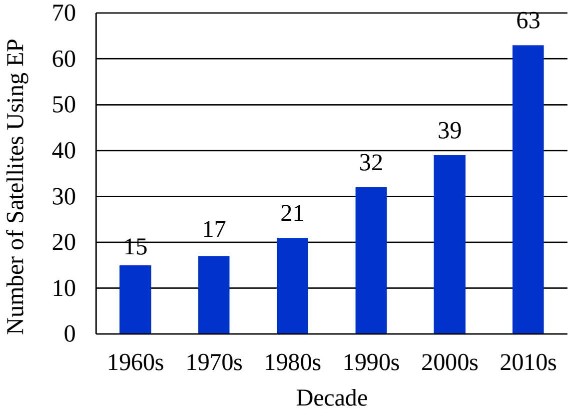


Fig. 4 Number of spacecraft using electric propulsion over the years [62].

E. Increasing Accessibility to Planetary Surface Destinations

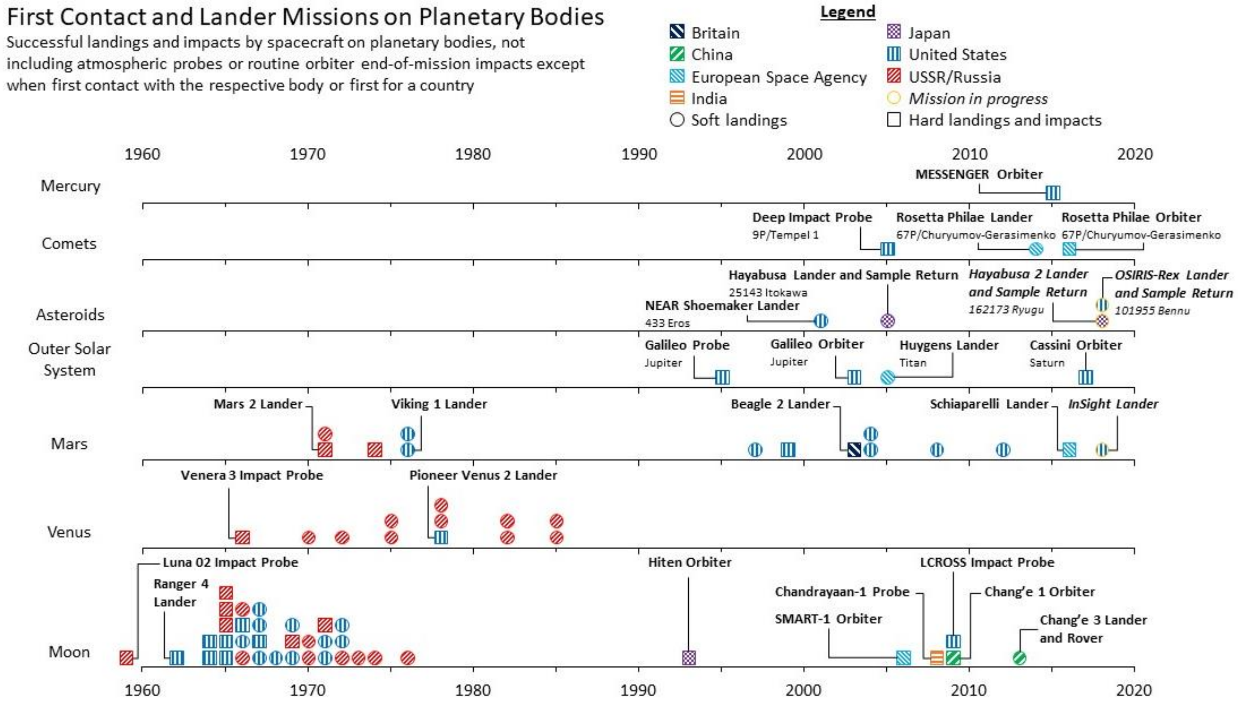


Fig. 5 First contact and lander missions on planetary bodies [73]–[148].

As seen in Fig. 5, as technology has improved, more challenging destinations have become accessible to spacecraft, from the Martian surface to probes in the atmospheres of the outer planets [73]–[148]. Additionally, more complex missions have become possible, as demonstrated by an evolution from fly-by or orbiting spacecraft to landers, rovers, and ascent vehicles for sample return. Technological feats, such as landing on comets and asteroids and attempting sample returns, have increased the knowledge of bodies within the solar system. Several ongoing missions plan to return samples from asteroids, such as Japan's Hayabusa 2 and NASA's OSIRIS-Rex. In addition to new destinations, there are also new participants as additional countries continue to become involved with these endeavors, including relative newcomers to planetary surface operations like India and Japan. Newer participants in the space industry have also performed exploration of the Moon and Mars. In the near term, NASA plans to extend to more challenging destinations, including a planned mission to Europa to continue the search for life another Martian lander, InSight, launched in May of 2018, and the planned Mars 2020 rover [149]. Thus, access is not only increasing in the form of new destinations but also in the expanding presence on established destinations by new and traditional players alike.

F. Changes in Regulation of Access to Space over Time

Growing commercialization of space and shifts in technology have been driving changes to federal and state regulation in the United States. The FAA oversees federal regulation regarding launch licensing, a process which has significantly improved since the early 1980s when multiple agencies were involved [150]–[155]. Furthermore, the DARPA Launch Challenge is seeking technological innovation regarding quick and repeatable access to space [156], which could result in more launches and put pressure on FAA launch regulations to become more flexible. Growth in small satellites has also impacted federal policy and regulation. The FCC, which regulates non-government use of radio communications in space, is seeking input on a new process to streamline licensing procedure for small satellites [157]. Developing commercial space enterprises require new regulations [158], which will pave the way for future companies and markets to develop.

G. Shift in Procurement Models

In February 1988, President Reagan issued a policy directive stating, “Federal agencies will procure existing and future required expendable launch services directly from the private sector to the fullest extent feasible” [155]. This marked a change in how NASA would do business, shifting from purchasing products to procuring services.

In 2005, the ISS Commercial Cargo Services (ICCS) program was formed to meet this intent and evolved into the Commercial Orbital Transportation Services (COTS), with the goal of moving away from the Federal Acquisition Regulation (FAR) typically used for procurement and instead using the Space Act Agreement (SAA) to form commercial partnerships and develop commercial launch systems [159]. NASA’s Phase 1 COTS program started in 2006 and selected Space Exploration Technologies (SpaceX) and Rocketplane Kistler to develop capabilities to transport cargo and crew to low-Earth Orbit [160]. In 2007, NASA ended work with Rocketplane Kistler, and in 2008, initiated an SAA with Orbital Sciences Corporation (now part of Northrop Grumman) to develop cargo transportation capabilities [160]. Commercial Resupply Services contracts were awarded to SpaceX and Orbital to resupply the ISS; since then, the number of commercial resupplies has risen from one in 2012 to a peak of seven in 2017, as shown in Fig. 6 [161]–[162]. Overall, a change in how NASA procures expendable launch services helped the development of new commercial launch vehicles, and it is expected that those vehicles will continue to increase the *Accessibility of Space*.

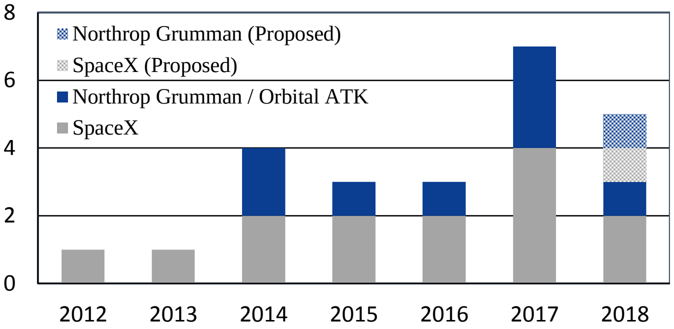


Fig. 6 Commercial Resupply Services launches by SpaceX and Northrop Grumman Innovation Services [161]–[162]

V. Mega-Driver 2: Accelerating Pace of Discovery

Accelerating Pace of Discovery reflects the desire of the space community to explore more remote and challenging destinations with humans and robotics, which also creates an increased demand for the capability to downlink and process large datasets. Increased data accessibility, in combination with sensing and computing advances, have increased the volume of data returned from space. At the same time, advances in data processing, the use of mathematical models, machine learning, and artificial intelligence (AI) are allowing for an increased pace of discovery from this data.

A. Science Goals are Driving Exploration Deeper into Space

One of the key drivers of change is the science community’s continuous push deeper into our solar system and beyond. The decadal surveys set science goals for the coming years, and the Planetary Science 2013–2022 Decadal Survey highlighted missions to planetary surfaces and moons that humanity has never explored before, including Europa as well as Uranus and its moons [163]. Furthermore, expansive exploration of Mars, including with a new rover, has been at the forefront of planetary exploration for many years. In fact, the cumulative entry mass on Mars is increasing exponentially, as seen in Fig. 7 [164]–[165].

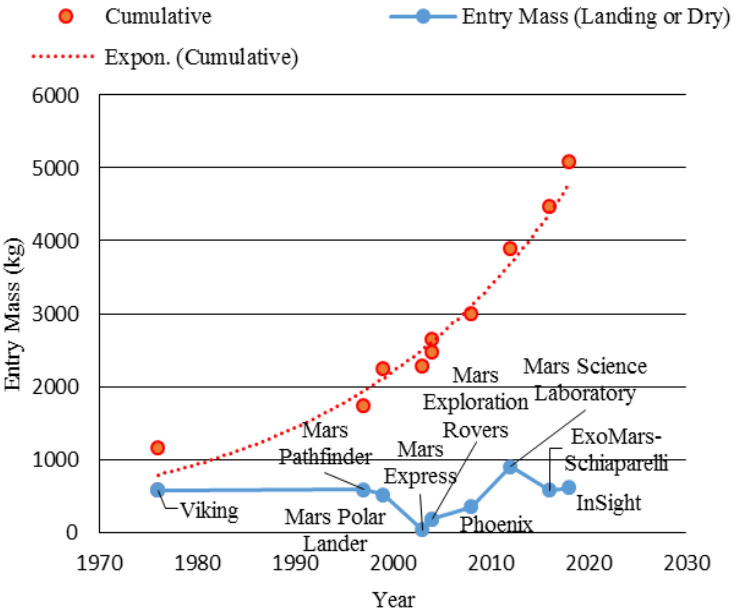


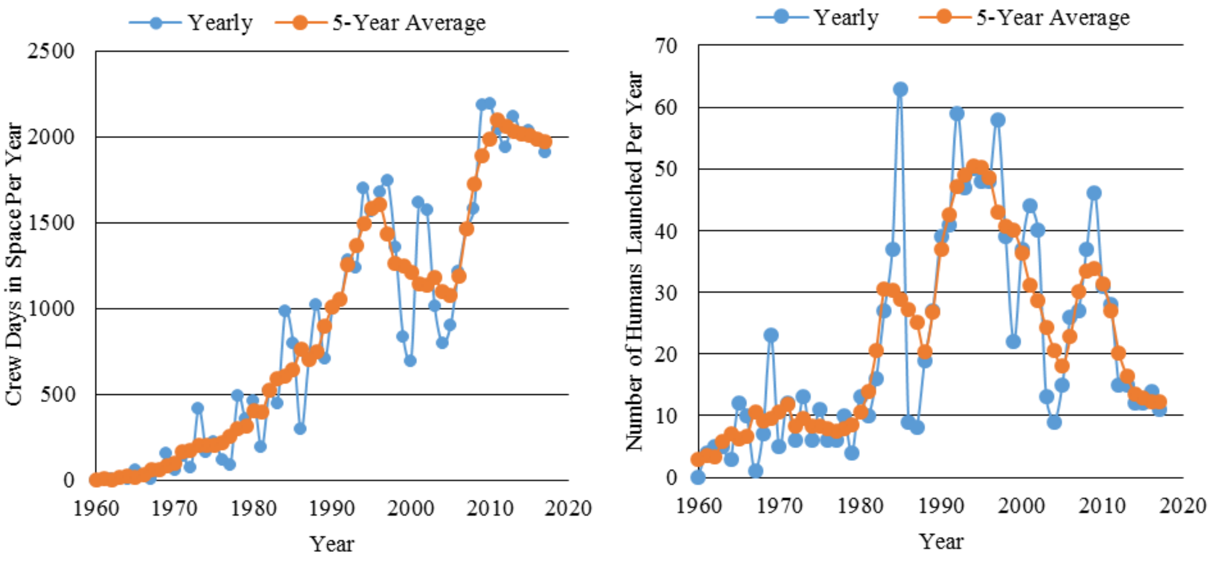
Fig. 7 Mars mission entry mass over time [164]–[165].

The motivation to design and fly more aggressive missions is supported by the many highly successful missions over the past 30 years. The Hubble Space Telescope, Chandra X-ray Observatory, Solar TErrestrial RElations Observatory (STEREO), Lunar Atmosphere and Dust Environment Explorer (LADEE), Cassini-Huygens mission to Saturn, Mars Science Laboratory, and New Horizons mission to Pluto are a few examples. In the coming decades, astrophysics will focus on deeper observations to find more exoplanets and to achieve higher fidelity measurements. Two new astrophysics missions are the James Webb Space Telescope (JWST), which will use cryo-cooled mid-infrared detectors, unfolding mirror segments, and a five-layer deployable sunshield to surpass Hubble's capabilities; and the Wide Field InfraRed Survey Telescope (WFIRST), which will perform a microlensing survey of exoplanets, dark energy, and infrared astrophysics. Key planned missions include the Interstellar Mapping and Acceleration Probe (IMAP), which will examine the protective boundary of the heliosphere around our solar system and the generation of cosmic rays, and the Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI). These are the top solar-terrestrial probe science targets recommended by the National Research Council's Committee on a Decadal Strategy for Solar and Space Physics [166]. Many planned astrophysics and heliophysics missions seek to take advantage of "quieter" regions beyond LEO that allow uninterrupted views of deep space and a constant power source (i.e. no eclipse cycles), which can only be enabled by developing technologies.

B. Expanding Presence of Humans in Space

Discovery is accelerating in human exploration and presence in space as well. In the United States, the National Aeronautics and Space Administration Transition Authorization Act of 2017 outlined a Human Exploration Roadmap which directs human exploration to expand to cis-lunar space and then to the surface of Mars [167]. Human spaceflight activities have been a sustained part of the NASA budget, and this trend is expected to continue [168]. Humanity's interest in reaching new destinations is supported by Congressional directives, investments by space entrepreneurs, copious research studies, and public media. Spaceflight has galvanized people to reframe themselves as part of a single, global society that exists on one fragile planet. This has been the impetus for multiple movements; from protecting and repairing Earth's environment to expanding human settlements beyond Earth [169].

The number of crew days in space per year, as shown in Fig. 8(a), is dominated by the presence and occupation of a space station. The drop in the early 2000s corresponds to the retirement of Mir and only increases again with the completion of the ISS. The number of humans launched per year on the other hand is dominated by the Space Shuttle. The connection to the Space Shuttle is clearly seen in Fig. 8(b), showing its introduction in the mid-1980s, drops following the Challenger and Columbia disasters in 1986 and 2003 respectively, an increased flight rate in the mid to late-1990s, and finally the retirement in 2011.



(a) **(b)**

Fig. 8 (a) Crew days in space per year, 1960–2018. (b) Number of humans launched per year worldwide, 1960–2018.

C. Increase in Volume of Data

Heightened demands from the science and exploration communities led to the development of technologies increasing the ability to acquire and return more data. For example, optical imagery technique resolution has improved over time, (e.g., 266% resolution improvement from 1999 to 2014 for DigitalGlobe Earth observation satellites [3]). This trend is not limited to large satellites, which by comparison to small satellites are not as constrained by physical size (impacting aperture size and signal-to-noise ratios) or by power supply (impacting transmission capability). Instead, "small satellites using COTS optical payloads are improving at more than three times the rate of larger satellites using custom optics as a result of the faster rate of technological advancement in COTS components” [3]. Additionally, increasing amounts of data are being acquired due to the previously discussed increased human and robotic mission durations, including operational and health data from space.

This increasing data acquisition capability is also driving increased data return capability. New and developing communications platforms, including optical/laser communications, are facilitating greater data return capabilities. While radio frequency communications continues to be leveraged heavily, especially for command and control, High Throughput Satellites (HTS) have entered the market, with twenty-seven in orbit as of 2014 [3]. Additionally, the number of ground stations to receive and process data is increasing, as ground stations are spreading around the world to new international operators and established at universities.

D. Advances in Data Processing

Increases in data produced by human and robotic missions also requires more streamlined data management. Interest in developing advanced data processing and analytical tools is demonstrated by both ESA and NASA. For Earth Observation (EO) alone, NASA had an average daily archive growth of 1.7 terabytes per day in 2011 and ESA had archived a total 1.5 petabytes of data by 2013. Following this milestone, ESA estimated their archive would be over 2 petabytes within the next few years [170]; however, in July 2017, the German Aerospace Center (DLR) reported that their Earth Observation Center (EOC) had processed over 4.2 petabytes within only three years from ESA’s three Sentinel satellites [3]. For comparison, one of the EOC’s longest-duration projects had processed data over the course of ERS-1, ERS-2, and Envisat (1995–2012), totaling 800 terabytes. In three years, the accumulated processed data of these new satellites had exceeded the entire 26-year lifetime of the ERS/Envisat project by more than a factor of five [171].

Advances in Earth science applications will continue in the next decade due to the evolution of more sophisticated processing and analysis systems. These are enabled in part by increased computer power, which leads to forecast model systems of much higher fidelity in physical process representation, increased temporal and spatial resolution, larger ensembles, and longer lead times [172]. Increased computer power and improved software engineering will enable data assimilation systems and forecasting models to move steadily towards exascale computing with commensurate higher fidelity, wider range of physical processes representation, increased temporal and spatial resolution, increased number of high resolution ensembles, and longer lead times [172]. Other sectors of the space industry and the global economy as a whole will benefit from and in turn contribute to more sophisticated data management systems.

Advances in mathematical models and system modeling will explore and predict behaviors to inform future scientific exploration of our solar system and the universe. Currently, companies such as Google, Facebook, Apple, and Microsoft in the United States, and Baidu in China that rely on being able to manage large quantities of data are investing heavily in advancing machine learning, especially for automated image recognition [3]. Even Moore's Law—which states that the number of transistors on a computer chip doubles every year or two—is impacting the space industry while it continues to hold, as it is allowing for more computational capability in a given volume. This results in an increased capability to handle data on the ground as well as perform on-board processing. The future application and economic values of these trends in difficult to predict but has a high potential and could easily be seen as disruptive [3].

E. Increase in Number of Space Papers Published

As a result of the compounding effects of technology evolution for data acquisition and analysis, the world has seen an influx of research papers by new participants on space topics. Since the launch of the Hubble Space Telescope in 1990, the publication rates and number of unique authors of papers with the keywords "satellite" or "astronomy" have significantly grown, including a sharp spike in the total publications per year by a factor of 12 from 1991 to 1998 [3][173]. Emerging countries like Brazil, Iran, Malaysia, Turkey, South Africa, and Indonesia had few to no publications with the keywords "satellites" or "astronomy" until around 2000; some countries have increased the number of such publications by a factor of ten in less than a decade [3]. New authors from all over the world are taking advantage of technology advancements and availability of discoveries to change the face of the global space industry and continuing to drive the ever increasing demand for space-based data.

VI. Mega-Driver 3: Democratization of Space

The *Democratization of Space* reflects the broadening participation in the space industry, from national governments to private investors to individual citizens, which has been greatly influenced by the lowered barrier to entry resulting from the reduction in costs to access space. Several trends explain the Democratization, including new and sustained modes of investment as well as engaging programs for academia and citizens.

A. Growth in Private Investment in Space

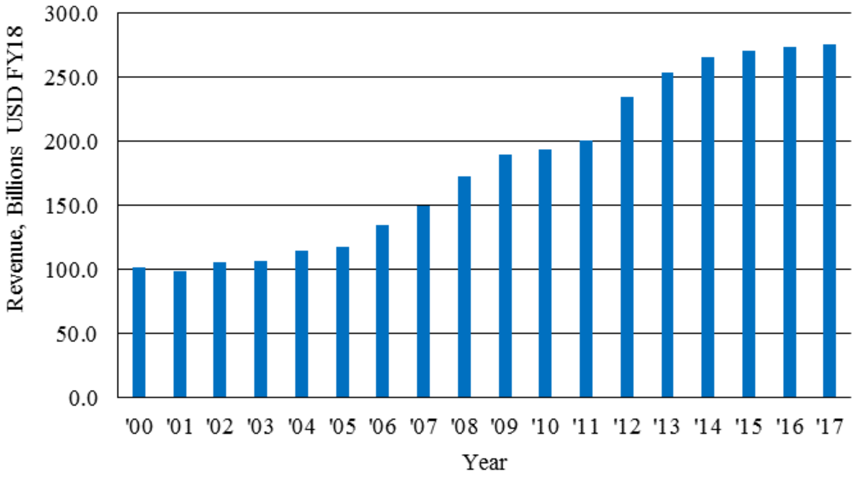


Fig. 9 Global satellite industry revenues, in FY18 USD [174].

Over the last 40 years, nationally and internationally, there has been an increasing shift towards the privatization of services and the use of public-private partnerships (e.g. prisons, education, air transportation). Over the past 20 years, the funding sources for the space industry have shifted from primarily government-driven to more of a balance of government spending and commercial services. In the global space economy, commercial revenues from privately-funded space enterprises, particularly in the communications and navigation sector, are now on par with government spending. In fact, the commercial satellite sector, which dominates the global space industry, has grown 42% from just 2010 to 2016, approximately $81.7 billion [175]; see Fig. 9. As seen in Fig. 10, individual sectors worldwide have seen an average 2.2% yearly growth, with commercial remote sensing and satellite radio particularly outpacing the rest in terms of yearly percentage growth despite being comparatively smaller markets [175]–[176]. As shown in Fig.

11, the growth of the satellite industry has also outpaced global and U.S. economic growth most of the past decade, though the percentage growth in recent years has come down significantly [175]–[176].

The emergence of heavy investment from private actors can be seen as part of the shift to procurement models that encourage competition and provide private enterprises more freedom while shifting risk burden. Public-private partnerships in the aerospace industry stem from a 2006 reemergence of the Space Act Agreement (SAA), where NASA formed partnerships in the private sector to develop specific technologies [177]. NASA continues to use SAAs to create private-public partnerships, such as with United Launch Alliance (ULA) in 2014 [174] and with Bigelow Aerospace in 2018 [178]. The key difference in the COTS awards was that the award funding was enough to incentivize milestones in which NASA was interested, without fully funding the projects. Private companies would therefore need to secure private sources of funding and assume some risk burden [179]. Space Exploration Technologies (SpaceX), for example, has been remarkably successful in doing just that, raising over $1.6 billion in venture capital while still partnering with government agencies to develop launch capabilities [180]. NASA has also used private-public partnerships in HEOMD’s NextSTEP Broad Area Announcement and STMD’s Tipping Point solicitations.

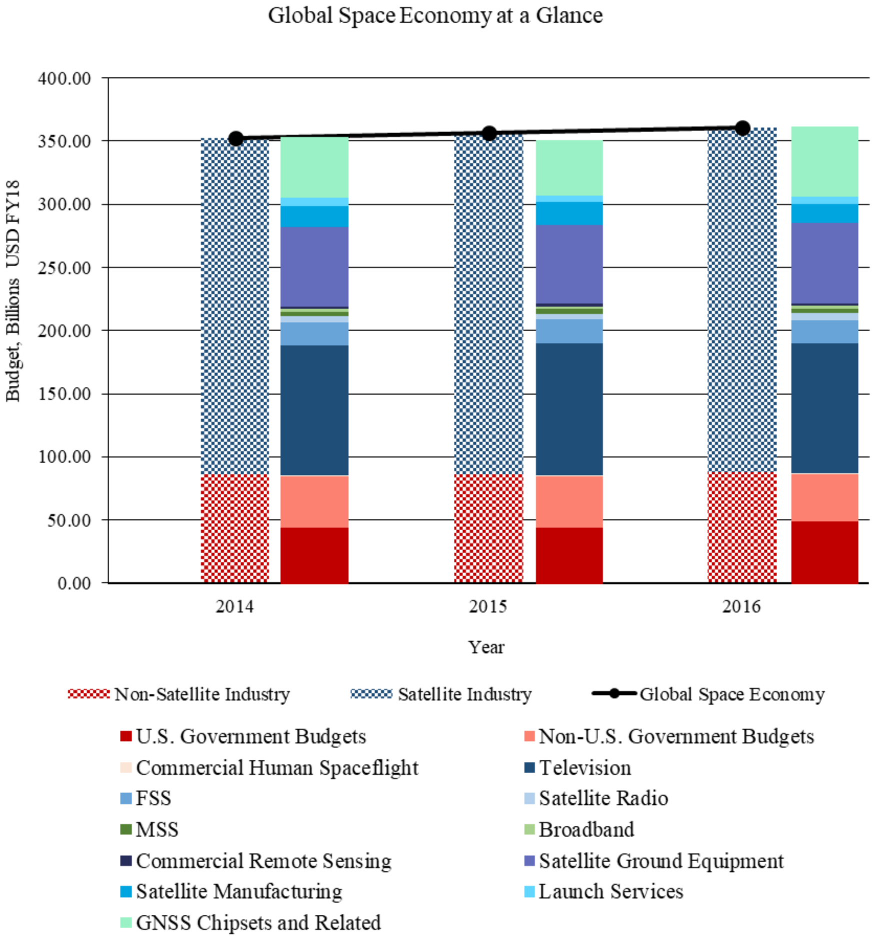


Fig. 10 Global space economy at a glance.[*]

The Space Angels, an angel and venture capital fund focused exclusively on the entrepreneurial space sector, reported that 2017 saw records set in the amount of investment, number of venture capital investors, and number of new privately funded companies [54]. The *Start-Up Space* report by Bryce Space & Technology has found that the number of space start-ups created each year have, on average, grown from four in the early 2000s to nearly 19 in the past six years. The biggest spike in the number of space ventures founded each year was a 270% increase from 2008 to 2014. However, this excludes firms that haven’t secured investment yet, which the Bryce team reports to be many—

---

[*] Data obtained from private communication with Bryce Space and Technology, LLC (April 2018).

implying the 2017 reported value may be quite conservative [72]. The Space Angels 2017 Q4 report corroborates this significant rise, counting 303 space companies receiving equity investment totaling over $12.8 billion between 2009 and 2017 [54].

Most importantly, the magnitude and types of investment available to space ventures today have risen rapidly in the last ten years. Including venture capital, seed financing, private equity, acquisitions, mergers, and debt financing, investment in start-up space between 2000 and 2017 was recorded to be $18.4 billion [72]. Then, in the first quarter of 2018 alone, another $1 billion of equity investment was added to that sum [60]. These investment numbers are the result of a significant increase in the number of investors, from an average of only eight in 2000–2005 to an average of 110 in 2012–2017. Nearly 60% of the investment has occurred since 2015, and 80% of investment since 2015 was seed financing and venture capital [72].

Investment in space ventures has increased interest coming from non-traditional actors in the industry as well, including established businesses such as Coca-Cola, SoftBank, Google, Monsanto, Apple, and Japan Airlines [181]–[186]. For example, SoftBank invested approximately $1 billion in 2016 into OneWeb, a satellite internet company dedicated to providing internet and global communications to all parts of the globe via a constellation in low-Earth orbit (LEO). Many of these investments are targeted. Softbank is making investments that enable global communication [181]. Agricultural companies like Monsanto are investing in companies that use machine learning and other complex algorithms to analyze satellite imagery and provide useful data in return. Monsanto paid approximately $930 million to acquire the Climate Corporation, a data-based insurance company, in 2013 [184]. It then sold off the crop insurance portion of its company to AmTrust, retaining satellite data and analytics [185]. The huge increase in venture capitalist investment in space has been referred to as the Dawn of the Entrepreneurial Space Age, aptly reflecting numerous record years in investment statistics, the number of start-ups being founded, and the diverse commercial playing field of the space industry.

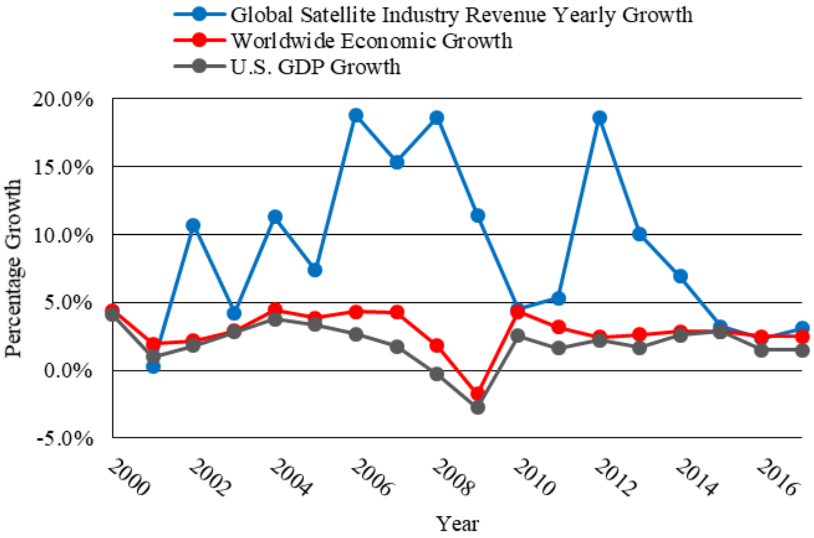


Fig. 11 Global satellite industry revenue growth compared to worldwide and U.S. economic growth [175][176].

B. Sustained Government Expenditures in Space

Apart from the rise in available private capital, the federal budget for civilian space programs is a significant aspect of worldwide progress in space. In the United States, government budgets for space have been tracked by the Aeronautics and Space Report of the President [187], the Space Foundation [188], and Bryce Space and Technology

[189]. Fig. 12 shows that NASA's budget, the primary funder of government civilian space in the U.S., has been sustained since the early 1990s.

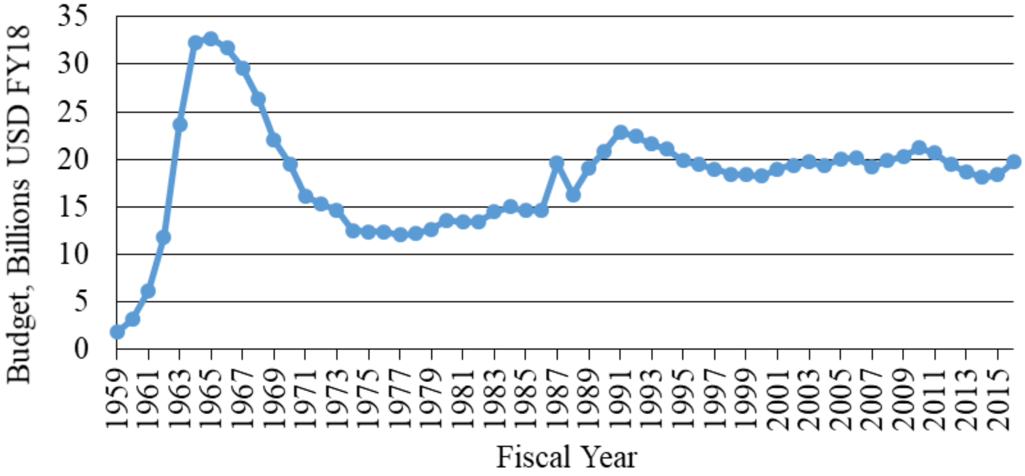


Fig. 12 **NASA space expenditures, FY1959–FY2016 [187].**

Fig. 13 shows international civilian space budgets over a shorter time scale, but nonetheless there is the same trend of sustained funding [188]. Additionally, many new players are included in the "Other" category, including Brazil, China, India, South Korea, and individual European countries' funds aside from European Space Agency (ESA) contributions.

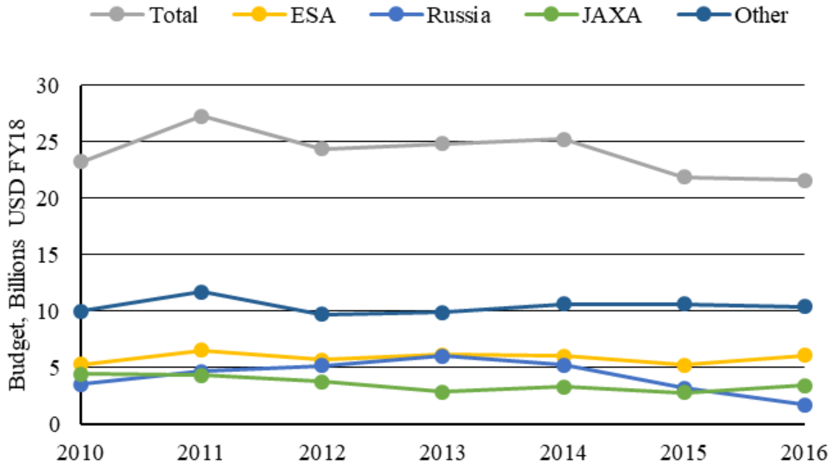


Fig. 13 **International civilian space budgets [188].**

C. Growth in Number of Space-Faring Nations

The number of space-faring nations has been on a steady increase since the 1940s. Each decade, the democratization of space is visible as new governments form official programs or develop a range of capabilities in space, as seen in Fig. 14. The Australian Space Agency, founded in May 2018, cited “major changes in the economics of market entry” as the trigger for the creation of the world’s most recent government space program [190]. Worldwide connectivity, security, and a global space economy expected to triple have driven more nations to invest in space.

These space-faring nations are becoming involved in a full range of activities, from nanosatellites to flying astronauts onboard ISS to landing on other worlds. As of August 2017, 88 operational Earth satellites had multinational operators/owners, with 25 different countries participating in collaborative missions, as seen in Fig. 15 [191].

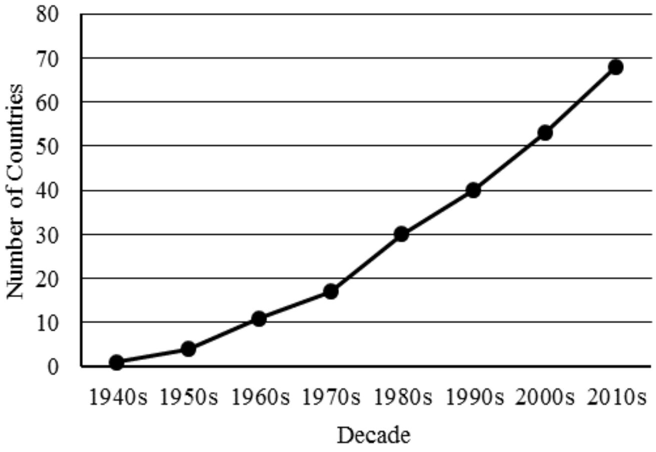


Fig. 14 Countries with government space programs.

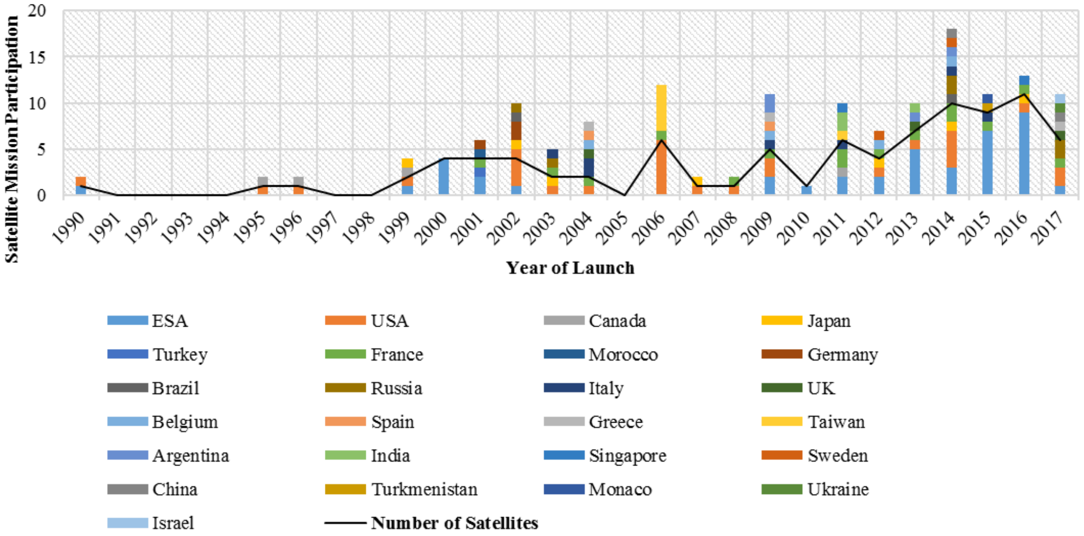


Fig. 15 Number of currently operational Earth satellites with multinational collaboration [191].

The number of countries with astronauts is increasing steadily. As of June 2018, 37 countries now have citizens that have flown in space, with 556 astronauts and cosmonauts that have flown above the Karman line at 100 km altitude. Some astronauts had dual citizenship, such as Soviet and Russian cosmonauts from countries including Azerbaijan, Belarus, Georgia, Kazakhstan, and Ukraine, and astronauts who are naturalized U.S. citizens from countries such as Iran, Costa Rica, India, Peru, Australia, Hungary. The demographics of space are changing every year, as players from all over the world become involved not just as astronauts but as satellite manufacturers, operators, and entrepreneurs [192]–[194].

D. Growth in Spending on Programs for Academia, Small Businesses, and Other New Participants

The federal budgets for space activities are helping to accelerate the democratization by creating programs for academia, small businesses, and other new participants to become involved. Examples of this within the U.S. are the Small Business Innovation Research (SBIR), Small Business Technology Transfer (STTR), and Tipping Point programs managed by STMD for NASA. In the 1970s, with increasing globalization and a growing concern for U.S. commercial space to remain competitive, the SBIR and STTR programs were founded in 1982 and 1992, respectively. These programs fund innovative business proposals for space technology development that would also achieve Agency goals. The 2017 National Defense Authorization Act renewed both programs [195], and funding has been steady over the past decade, representing 28–30% of the STMD budget [196]. NASA additionally runs the Flight Opportunities Office, whose mission is to stimulate the growth of the U.S. commercial spaceflight industry while providing “affordable access to relevant test environments”. Since its founding in 2010, over 100 payloads have participated and been delivered on a range of launch platforms [197]. Funding has been sustained around these government programs; funding has also been available through academic and public engagement opportunities with offices such as the Office of Education. As democratized space becomes ever more prevalent, it is expected that this support from governments will continue.

E. Growth in Academic and Public Engagement

Thanks to the emergence of CubeSats lowering the barrier to entry to new players—as discussed in Mega-Driver 1: *Increasing Access*—public participation in space has increased substantially. Academia and individual citizens are becoming engaged through an increased number of university programs or challenges to build and launch CubeSats, crowdsourced project fundraisers, and collaborative software that enables distributed communities to self-organize. Prizes and challenges such as the NASA’s Educational Launch of Nanosatellites (ELaNa), CubeSat Launch Initiative (CSLI), and Cube Quest Challenge have been instrumental in this regard. From 2011 to April 2017, NASA’s ELaNa/CSLI program launched 49 CubeSats and had manifested an additional 47 for the following year [66]. In the NASA Cube Quest Challenge, $5.5 million in prize money was made available for competitors who could design and operate small satellites in the lunar vicinity. In the first round of the competition in 2015, there were five industry, seven university, and one high school participants, and the winners are planned to launch on EM-1 [198]. Other foreign organizations, such as the India Space Research Organization (ISRO), are starting to engage in similar programs and are supporting involvement by academic institutions to create satellites and payloads while processing data from space [199].

Global sourcing and crowdsourcing are also enabling a large number of individuals to collaborate on space projects or CubeSat designs. A number of “citizen science” projects are run by NASA each year. By 2014, “more than 1.2 million people from 80 countries [had] participated in NASA’s citizen science projects,” including Be a Martian (1.23 million participants), International Space Apps Challenge (2,083 participants from 17 countries), and Stardust at Home (30,649 participants from 2006–2012) [200]. Small communities of passionate individuals have formed as a result of these opportunities and increased accessibility to knowledge; self-organized groups like the Mars Society, Mars Academy USA, and the Space Generation Advisory Council are able to collaborate to develop highly capable systems and concepts.

There are so many new players in the global space economy, from government programs to academic competitors to non-traditional entrepreneurs. These new players are creating new sectors of the market and new ways in which to invest. The cycle of broadening participation and market growth and diversification is one of the most important drivers of the global space economy.

VII. Mega-Driver 4: Growing Utilization of Space

Growing Utilization of Space reflects space market diversification and growth, including space-based solutions to address growing global challenges and solutions enabling space exploration and settlement. This Mega-Driver builds upon the supply and accessibility drivers as well as the cycle of broadening participation and interests. *Increasing Access* and the *Democratization of Space* Mega-Drivers are based on the emerging strategies from private companies to drive low-cost, effective solutions for increasing access to space, as well as unique strategies to enable popular ideas such as large-scale habitation or resource prospecting. These strategies are part of the growth in private investments in new space ventures and the increasing number of nations with space programs or assets. The pressure on technologies for science and exploration is part of the cycle of demand, too, as explained by *Accelerating Pace of Discovery*. By lowering the barrier to entry and increasing the pressure on governments to deliver more with flat or reduced budgets, the space industry is seeing growth and diversification.

A. Substantial Growth in Existing Space Sectors

An increasing reliance on space-based assets worldwide complements the substantial growth in existing space sectors. Global-based telecommunications, GPS positioning and timing, and space-based Earth imaging are providing essential services to an increasing number of users around the globe. The utilization of these capabilities includes GPS maps, ATMs using GPS-based timing signals, weather satellites that inform insurance agencies and disaster planning, agriculture management and crop-tracking, and urban mapping. The global satellite industry almost tripled its revenues in this century, from $101 billion in 2000 to $275 billion in 2017, shown in Fig. 9, as companies have moved to keep up with demand [176].

The demand is growing in part because of new platforms in the existing markets of geospatial data-based analytics and services [3]. In the past decade, there has been an increase in the number of geospatial analytics space start-ups developing or deploying their own satellites, such as PlanetiQ, Planet, Iceye, Terra Bella, and Spire, among others. There has also been an increase in the number of space start-ups that provide geospatial analytics platforms using commercially available satellite imagery, including Descartes Labs, SpaceKnow, Orbital Insight, Ursa Space Systems. Including ground services, the satellite industry currently comprises 79% of the total space economy with 48% of the satellite industry revenue coming directly from satellite services [189].

B. Growth in New and Diversified Markets

With new players, platforms, and strategies, the space industry is evolving over time. Recent years have seen an emergence of novel markets, such as space tourism, resource prospecting, and in-space manufacturing; see Table 1. Blue Origin, founded in 2000, has been developing a reusable launch vehicle for private crewed suborbital launches and recently, in December 2017, completed a successful flight of Crew Capsule 2.0—on a rocket which flew successfully for the seventh time [201]. Also in space tourism, Bigelow Aerospace has produced concepts and hardware mock-ups of expandable habitats which private users could lease. Bigelow Aerospace proposed in 2015 that users could live in space for up to 60 days at a price of $25–51 million [202].

Made In Space was founded to initiate in-space manufacturing capabilities to support human exploration, such as enabling reusability of plastic product waste through additive manufacturing. However, Made In Space is also targeting terrestrial markets with their new efforts to produce optical fibers in microgravity. ZBLAN fiber optic cables are part of a market worth billions of dollars, and production of the cables in microgravity results in “higher degrees of purity, quality, and most importantly, commercial value” [203]. Furthermore, markets that were previously closed are opening up for business. Spire is a company founded in 2012 that became the first commercial entity contracted to deliver space-based weather data, which until a bill in April 2017, was forbidden to all but the government. Spire’s focus is to provide global, near-realtime coverage 24/7, especially from remote locations, for maritime, weather, and aviation applications [204].

Other new markets are expected to emerge based on growing concerns for the future. Space debris has been internationally recognized as a growing challenge due to the current rate of growth and the predicted increase in orbiting objects and debris. The *Growing Utilization of Space* and *Increasing Access* trends support this prediction, but business models have yet to be proposed for enabling a space debris clean-up service. Space-related technology investments are also contributing to non-space industries. Technology transfer and spin-offs have produced the Complementary Metal Oxide Semiconductor (CMOS) image sensor now used in digital image and video cameras and cellphones [205]; the Neurala Brain artificial intelligence neural network software that was originally a NASA contract for rovers and now for drones and self-driving cars [206]; and Ferrofluid, which was originally developed for rocket fuel transfer and now is being applied to for loudspeakers and semiconductor chip manufacturing [207]. Many of these developments are a result of STTR or other technology transfer programs and represent a positive contribution to the global economy.

Table 1 New and existing space markets in Q4 2017, with number of companies and total investment [54].

Market	Satellites	Launch	Media & Education	In-Space Biosphere	In-Space Industrials	Information & Research	Planetary Markets	In-Space Logistics
Number of Companies	170	60	30	17	8	7	6	5
Total Investment	$5,323M	$6,562M	$9.97M	$505.2M	$115.9M	$74.5M	$55.6M	$154.9M

C. Constrained Global Resources

Global overuse of water resources, water quality degradation, population growth, climate change, and other factors are contributing to increasing constraints on terrestrial resources. This has a two-fold effect on the utilization of space assets. First, inventories of assets and global monitoring can be accomplished using remote measurements from satellites. From space-based data, models and visualizations will be needed to forecast demand and inform decision making. Technologies will be needed to address water stress and other escalating terrestrial resource challenges. Monsanto is just one example of an agricultural company already investing in space-based data analytics for similar applications [184]. Second, the implications of the technology and model developments may benefit resource assessment, extraction, and processing methods in extraterrestrial environments. Sustained access to essential resources in space has continually presented significant technical challenges to human and robotic space exploration.

Efforts to address global resource constraints on Earth may present significant potential for leveraging partnerships for exploration agencies or organizations.

VIII. Conclusion

NASA STMD has developed a Strategic Framework for prioritizing investments in the emerging global space economy. Trends and activities in spaceflight were analyzed along with input from NASA program leads, technical experts, and STMD customers. These were distilled into four overarching trends referred to as Mega-Drivers:

1) *Increasing Access*: Trends that have already occurred and are expected to continue include reductions in launch price, increases in the number of launch options, increases in launch availability, shifts in procurement models, and the emergence of small, micro-, and nanosatellite markets. Increases in highly-efficient and scalable transportation systems, increases in accessibility to planetary surfaces, and changes in regulation are expected to lead to *Increasing Access* of space and other planetary destinations in the near future.
2) *Accelerating Pace of Discovery*: Increases in demand for data downlink, increases in data processing, and advances in data connectivity are leading to an *Accelerating Pace of Discovery*. This rate is expected to grow as robotic systems and humans continue to explore deeper into space with increasing detail.
3) *Democratization of Space*: In addition to traditional governments and corporations sustaining a presence in space, growth in private investment and the number of space-faring nations means there are more participants in the global space economy than before, with the number expected to grow. Growth in spending for academia, small businesses, and new players incentivizes their involvement in space as well. *Increasing Accessibility* to low-cost platforms (e.g. micro- and nanosatellites) mean that more people can participate in space.
4) *Growing Utilization of Space*: Advances in satellite technology are enabling more widespread personal and commercial applications, for example, the many uses of GPS in mobile devices. Geospatial analytics companies are providing increasing amounts of data to a diverse set of users, including farmers, commodities traders, and more. Recent participants in commercial and industrial space are creating companies that focus on the new, diverse ways to utilize space, like space tourism, resource prospecting, and space manufacturing.

These Mega-Drivers create the basis for a Strategic Framework containing goals, outcomes, and capabilities related to the future of spaceflight. NASA STMD is using the Mega-Drivers and the associated trend analysis to determine which goals to pursue relative to spaceflight, the measurable outcomes associated with those goals, and the capabilities required to achieve those outcomes. NASA STMD can then strategically invest in technologies that deliver a portfolio of capabilities to be integrated into mission architectures that enables NASA to achieve its goals, such as returning to the Moon, sending humans to Mars, and understanding humanity's place in the universe.

Acknowledgments

The authors would like to thank NASA STMD senior leadership and the Strategic Planning and Integration office for support and funding for this work. Insights and data from Raphael Perrino, Stephanie Booth, and John Nelson from Bryce Space and Technology were greatly appreciated.

References

[1] Earle, K., Carrier, M., Cirillo, W., Grande, M., Jones, C., Judd, E., Klovstad, J., Owens, A., Reeves, D., and Stafford, M., "Strategic Framework for NASA's Space Technology Mission Directorate", AIAA Space and Astronautics Forum, 17 Sep 2018.

[2] *NASA Aeronautics: Strategic Implementation Plan 2017 Update*, National Aeronautics and Space Administration, Washington, DC, NP-2017-01-2352-HQ.

[3] Lal, B., Sylak-Glassman, E. J., Mineiro, M. C., Gupta, N., Pratt, L. M., and Azari, A. R., *Global Trends in Space Volume 2: Trends by Subsector and Factors that Could Disrupt Them*, Institute for Defense Analyses, Science & Technology Policy Institute, IDA Paper P-5242, Vol. 2, Washington, DC, June 2015.

[4] "Capabilities & Services", SpaceX, URL: https://www.spacex.com/about/capabilities [retrieved 30 July 2018].

[5] "Commercial Space Transportation: 2005 Year In Review", Federal Aviation Administration, January 2006, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2005_YIR_FAA_AST_0206.pdf [retrieved 2 August 2018].

[6] "Commercial Space Transportation: 2006 Year In Review", Federal Aviation Administration, January 2007, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2006YIR.pdf [retrieved 2 August 2018].

[7] "Commercial Space Transportation: 2007 Year In Review", Federal Aviation Administration, January 2008, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2007_Year_In_Review_Jan_2008.pdf [retrieved 2 August 2018].

[8] "Commercial Space Transportation: 2008 Year In Review", Federal Aviation Administration, January 2009, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/year_in_review_2009.pdf [retrieved 2 August 2018].

[9] "Commercial Space Transportation: 2009 Year In Review", Federal Aviation Administration, January 2010, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/year_in_review_2009.pdf [retrieved 2 August 2018].

[10] "Commercial Space Transportation: 2010 Year In Review", Federal Aviation Administration, January 2011, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2010%20Year%20in%20Review.pdf [retrieved 2 August 2018].

[11] "Commercial Space Transportation: 2011 Year In Review", Federal Aviation Administration, January 2012, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2012_YearinReview.pdf [retrieved 2 August 2018].

[12] "Commercial Space Transportation: 2012 Year In Review", Federal Aviation Administration, January 2013, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/Year_in_Review_2012_Commercial_Space_Transportation_FAA_AST_January_2013.pdf [retrieved 2 August 2018].

[13] "Commercial Space Transportation: 2013 Year In Review", Federal Aviation Administration, January 2014, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/FAA_YIR_2013_02-07-2014.pdf [retrieved 2 August 2018].

[14] "Commercial Space Transportation: 2014 Year In Review", Federal Aviation Administration, February 2015, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/FAA_YIR_2014_02-25-2015.pdf [retrieved 2 August 2018].

[15] "The Annual Compendium of Commercial Space Transportation: 2012", Federal Aviation Administration, February 2013, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/Annual_Compendium_of_Commercial_Space_Transportation_2012_February_2013.pdf [retrieved 2 August 2018].

[16] "The Annual Compendium of Commercial Space Transportation: 2013", Federal Aviation Administration, February 2014, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2014-02-04_FAA_2013_Compendium.pdf [retrieved 2 August 2018].

[17] "The Annual Compendium of Commercial Space Transportation: 2014", Federal Aviation Administration, February 2015, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/FAA_Annual_Compendium_2014.pdf [retrieved 2 August 2018].

[18] "The Annual Compendium of Commercial Space Transportation: 2016", Federal Aviation Administration, January 2016, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2016_Compendium.pdf [retrieved 2 August 2018].

[19] "The Annual Compendium of Commercial Space Transportation: 2017", Federal Aviation Administration, January 2017, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2017_AST_Compendium.pdf [retrieved 2 August 2018].

[20] "The Annual Compendium of Commercial Space Transportation: 2018", Federal Aviation Administration, January 2018, URL: https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf [retrieved 2 August 2018].

[21] Krebs, G., "Antares-120", Gunter's Space Page, URL: http://space.skyrocket.de/doc_lau_det/antares-120.htm [retrieved 30 Jul 2018].

[22] Steinmeyer, J. and Frick, W., "Antares: Medium-Class Space Launch Vehicle", Northrop Grumman, 31 May 2018, URL: http://www.northropgrumman.com/Capabilities/Antares/Documents/Antares_Factsheet.pdf [retrieved 30 Jul 2018].

[23] “Ariane 5 ECA”, European Space Agency, URL: https://m.esa.int/Our_Activities/Space_Transportation/Launch_vehicles/Ariane_5_ECA2 [retrieved 30 Jul 2018].
[24] “Ariane 5 GS”, European Space Agency, URL: https://m.esa.int/Our_Activities/Space_Transportation/Launch_vehicles/Ariane_5_GS [retrieved 30 Jul 2018].
[25] “Ariane 5 Generic”, European Space Agency, URL: https://m.esa.int/Our_Activities/Space_Transportation/Launch_vehicles/Ariane_5_Generic2 [retrieved 30 Jul 2018].
[26] “Atlas V”, United Launch Alliance, URL: https://www.ulalaunch.com/rockets/atlas-v [retrieved 30 Jul 2018].
[27] “Comparison of orbital launch systems”, Wikipedia, 27 Jul 2018, URL: https://en.wikipedia.org/wiki/Comparison_of_orbital_launch_systems [retrieved 30 Jul 2018].
[28] “Delta II”, SpaceFlight Insider, URL: http://www.spaceflightinsider.com/hangar/delta-ii/ [retrieved 30 Jul 2018].
[29] “Delta IV Launch Services User’s Guide: June 2013”, United Launch Alliance, 4 Jun 2013, URL: https://web.archive.org/web/20140710005717/http://www.ulalaunch.com/uploads/docs/Launch_Vehicles/Delta_IV_Users_Guide_June_2013.pdf [retrieved 30 Jul 2018].
[30] Blau, P., “Dnepr Launch Vehicle Information”, Spaceflight 101, URL: http://www.spaceflight101.net/dnepr-launch-vehicle-information.html [retrieved 30 Jul 2018].
[31] Messier, D., “Russia to End Rockot Launches”, Parabolic Arc, 7 Apr 2017, URL: http://www.parabolicarc.com/2017/04/07/russia-rockot-launches/ [retrieved 30 Jul 2018].
[32] “Electron”, Rocket Lab USA, URL: https://www.rocketlabusa.com/electron/ [retrieved 30 Jul 2018].
[33] “Falcon 9 Overview”, Space Exploration Technologies, 2010, URL: https://web.archive.org/web/20101222155322/http://www.spacex.com/falcon9.php [retrieved 30 Jul 2018].
[34] “Falcon 1 Overview”, Space Exploration Technologies, 2008, URL: https://web.archive.org/web/20080831221242/http://www.spacex.com:80/falcon1.php [retrieved 30 Jul 2018].
[35] “Falcon 9 Full Thrust”, Wikipedia, 27 Jul 2018, URL: https://en.wikipedia.org/wiki/Falcon_9_Full_Thrust [retrieved 30 Jul 2018].
[36] “Falcon 9”, SpaceX, 2013, URL: https://web.archive.org/web/20140805175724/http://www.spacex.com/falcon9 [retrieved 30 Jul 2018].
[37] “Kosmos-3M”, Wikipedia, 22 Dec 2017, URL: https://en.wikipedia.org/wiki/Kosmos-3M [retrieved 30 Jul 2018].
[38] “Long March 2D”, Wikipedia, 4 Jun 2018, URL: https://en.wikipedia.org/wiki/Long_March_2D [retrieved 30 Jul 2018].
[39] “Long March 3B”, Wikipedia, 29 Jul 2018, URL: https://en.wikipedia.org/wiki/Long_March_3B [retrieved 30 Jul 2018].
[40] Brunschwyler, J. and Frick, W., “Minotaur-C: Ground-Launched Space Launch Vehicle”, Northrop Grumman, 31 May 2018, URL: http://www.northropgrumman.com/Capabilities/Minotaur/Documents/Minotaur-C_Factsheet.pdf [retrieved 30 Jul 2018].
[41] “Pegasus (rocket)”, Wikipedia, 11 Jul 2018, URL: https://en.wikipedia.org/wiki/Pegasus_(rocket) [retrieved 30 Jul 2018].
[42] “Proton-M”, Wikipedia, 22 Jul 2018, URL: https://en.wikipedia.org/wiki/Proton-M [retrieved 30 Jul 2018].
[43] “Polar Satellite Launch Vehicle”, Wikipedia, 9 Jun 2018, URL: https://en.wikipedia.org/wiki/Polar_Satellite_Launch_Vehicle#Variants [retrieved 30 Jul 2018].
[44] “Rokot”, Wikipedia, 29 Apr 2018, URL: https://en.wikipedia.org/wiki/Rokot [retrieved 30 Jul 2018].
[45] “Soyuz: The Medium Launcher”, Arianespace, URL: http://www.arianespace.com/vehicle/soyuz/ [retrieved 30 Jul 2018].
[46] “Soyuz (rocket)”, Wikipedia, 10 Jun 2018, URL: https://en.wikipedia.org/wiki/Soyuz_(rocket) [retrieved 30 Jul 2018].
[47] “Soyuz-2”, Wikipedia, 21 Jun 2018, URL: https://en.wikipedia.org/wiki/Soyuz-2 [retrieved 30 Jul 2018].
[48] Blau, P., “Soyuz 2-1B – Launch Vehicle”, Spaceflight 101, URL: http://www.spaceflight101.net/soyuz-2-1b.html [retrieved 30 Jul 2018].
[49] “Start-1”, Wikipedia, 27 Jul 2018, URL: https://en.wikipedia.org/wiki/Start-1 [retrieved 30 Jul 2018].
[50] “Vega: The Light Launcher”, Arianespace, URL: http://www.arianespace.com/vehicle/vega/ [retrieved 30 Jul 2018].
[51] “Volna”, Wikipedia, 11 Nov 2017, URL: https://en.wikipedia.org/wiki/Volna [retrieved 30 Jul 2018].
[52] “Zenit-3SL”, Wikipedia, 25 Jan 2018, URL: https://en.wikipedia.org/wiki/Zenit-3SL [retrieved 30 Jul 2018].
[53] “Zenit-3SLB”, Wikipedia, 24 Nov 2017, URL: https://en.wikipedia.org/wiki/Zenit-3SLB [retrieved 30 Jul 2018].
[54] Kilian, J., Patel, R., *Space Investment Quarterly: Q4 2017*, Space Angels, 18 Jan 2018, URL: https://www.spaceangels.com/information-central [retrieved 1 Jun 2018].
[55] Vance, A., "The Tiny Satellites Ushering in the New Space Revolution." Bloomberg Businessweek, 29 June 2017, URL: https://www.bloomberg.com/news/features/2017-06-29/the-tiny-satellites-ushering-in-the-new-space-revolution [retrieved 20 Jul 2018].
[56] Swartwout, M., “Secondary Payloads in 2014: Assessing the Numbers”, IEEE Aerospace Conference, AERO.2014.6836390, 2014, URL: https://ieeexplore.ieee.org/document/6836390/ [retrieved 24 Jul 2018].
[57] Foust, J., “Rideshare demand grows despite development of small launch vehicles”, Space News, 23 Jun 2017, URL: https://spacenews.com/rideshare-demand-grows-despite-development-of-small-launch-vehicles/ [retrieved 24 Jul 2018].
[58] Clark, S., “Spaceflight reserves two rideshare missions on Vega rocket”, Spaceflight Now, 18 Apr 2018, URL: https://spaceflightnow.com/2018/04/18/spaceflight-reserves-two-rideshare-missions-on-vega-rocket/ [retrieved 24 Jul 2018].
[59] “Launch Services”, Spaceflight Industries, 2017, URL: http://spaceflight.com/services/launch-services/ [retrieved 24 Jul 2018].
[60] Space Angels, *Space Investment Quarterly: Q2 2018*, Space Angels, 10 Jul 2018, URL: https://www.spaceangels.com/information-central [retrieved 18 Jul 2018].

[61] Niederstrasser, C., Frick, W., "Small Launch Vehicles – a 2016 State of the Industry Survey", International Astronautical Congress 2016, IAC-16-B4.5.10, Orbital ATK.

[62] "List of spacecraft with electric propulsion", Wikipedia, 22 Jul 2018, URL: https://en.wikipedia.org/wiki/List_of_spacecraft_with_electric_propulsion [retrieved 26 Jul 2018].

[63] "JPL MarCO Micro CubeSat Propulsion System", CubeSat Propulsion Systems, VACCO Industries, 2012, URL: http://www.cubesat-propulsion.com/jpl-marco-micro-propulsion-system/ [retrieved 26 Jul 2018].

[64] Doncast, B., Williams, C., Shulman, J., "2017 Nano/Microsatellite Market Forecast", SpaceWorks, Inc., Atlanta, GA, USA, 2017, URL: http://www.spaceworkscommercial.com/wp-content/uploads/2018/01/SpaceWorks_Nano_Microsatellite_Market_Forecast_2017.pdf, [retrieved 27 Jul 2018].

[65] Bok, C.B., Comeau, A., Dolgopolov, A., Halt., T., Juang, C., Smith, P., "Smallsats by the Numbers 2018", Bryce Space and Technology, Alexandria, VA, USA, Mar 2018, URL: https://brycetech.com/downloads/Bryce_Smallsats_2018.pdf, [retrieved 27 Jul 2018]

[66] Baker, C., Hunter. R., Agasid, E., Cockrell, J., Yost, B., Kepko, L., Millar, P.S., Norton, C.D., Martinez, A., Skrobot, G., "NASA Town Hall", *Small Satellite Conference 2017*, National Aeronautics and Space Administration, Logan, Utah, slides 37-38, 7 Aug 2017, URL: https://www.nasa.gov/sites/default/files/atoms/files/smallsatelliteconference2017nasatownhall_0.pdf [retrieved 25 May 2018].

[67] Lal, B., Sylak-Glassman, E. J., Mineiro, M. C., Gupta, N., Pratt, L. M., and Azari, A. R., *Global Trends in Space Volume 1: Background and Overall Findings*, Institute for Defense Analyses, Science & Technology Policy Institute, IDA Paper P-5242, Vol. 1, Washington, DC, June 2015.

[68] Peters, B., "Ardusat Space Program: Training the Next Generation of Satellite Scientists and Engineers", *Small Satellite Conference 2016*, AIAA/USU, Logan, Utah, Aug 2016, URL: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3419&context=smallsat

[69] Christensen, C., Smith, P., Dolgopolov, A., Doom, T., "New Kids on the Block: How New Start-Up Space Companies Have Influenced the U.S. Supply Chain", Bryce Space and Technology, Alexandria, VA, USA, Nov 2017, URL: https://brycetech.com/downloads/Start_Up_Space_Supply_Chain_2017.pdf, [retrieved 27 Jul 2018].

[70] Butler, D., "Many eyes on Earth", Nature Vol. 505, Macmillan Publishers, Jan 2014, pp 143-144.

[71] Rivers, T., "Small Satellites – Evolving Innovation for the Entire Market", 31st Space Symposium, Technical Track, Colorado Springs, CO, USA, April 2015, URL: http://2015.spacesymposium.org/sites/default/files/downloads/T.Rivers_31st_Space_Symposium_Tech_Track_paper.pdf.

[72] Bryce Space and Technology, "Start-Up Space: Update on Investment in Commercial Space Ventures", 2018, URL: https://brycetech.com/downloads/Bryce_Start_Up_Space_2018.pdf [retrieved 30 Jul 2018].

[73] Williams, D., "Luna 2", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1959-014A [retrieved 30 Jul 2018].

[74] Williams, D., "Ranger 4", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1962-012A [retrieved 30 Jul 2018].

[75] Williams, D., "Ranger 6", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1964-007A [retrieved 30 Jul 2018].

[76] Williams, D., "Ranger 7", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1964-041A [retrieved 30 Jul 2018].

[77] Williams, D., "Luna 5", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1965-036A [retrieved 30 Jul 2018].

[78] Williams, D., "Luna 7", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1965-077A [retrieved 30 Jul 2018].

[79] Williams, D., "Luna 8", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1965-099A [retrieved 30 Jul 2018].

[80] Williams, D., "Ranger 8", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1965-010A [retrieved 30 Jul 2018].

[81] Williams, D., "Ranger 9", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1965-023A [retrieved 30 Jul 2018].

[82] Williams, D., "Venera 3", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1965-092A [retrieved 30 Jul 2018].

[83] Williams, D., "Luna 9", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1966-006A [retrieved 30 Jul 2018].

[84] Williams, D., "Luna 13", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1966-116A [retrieved 30 Jul 2018].

[85] Williams, D., "Surveyor 1", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1966-045A [retrieved 30 Jul 2018].

[86] Williams, D., "Surveyor 2", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1966-084A [retrieved 30 Jul 2018].

[87] Williams, D., "Surveyor 3", NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1967-035A [retrieved 30 Jul 2018].

[88] Williams, D., “Surveyor 4”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1967-068A [retrieved 30 Jul 2018].

[89] Williams, D., “Surveyor 5”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1967-084A [retrieved 30 Jul 2018].

[90] Williams, D., “Surveyor 6”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1967-112A [retrieved 30 Jul 2018].

[91] Williams, D., “Surveyor 7”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1968-001A [retrieved 30 Jul 2018].

[92] Williams, D., “Apollo 11”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1969-059C [retrieved 30 Jul 2018].

[93] Williams, D., “Apollo 12”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1969-099C [retrieved 30 Jul 2018].

[94] Williams, D., “Luna 15”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1969-058A [retrieved 30 Jul 2018].

[95] Williams, D., “Luna 16”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1970-072A [retrieved 30 Jul 2018].

[96] Williams, D., “Luna 17”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1970-095A [retrieved 30 Jul 2018].

[97] Williams, D., “Venera 7”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1970-060A [retrieved 30 Jul 2018].

[98] Williams, D., “Apollo 14”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1971-008C [retrieved 30 Jul 2018].

[99] Williams, D., “Apollo 15”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1971-063C [retrieved 30 Jul 2018].

[100] Williams, D., “Luna 18”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1971-073A [retrieved 30 Jul 2018].

[101] Williams, D., “Mars 2”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1971-045D [retrieved 30 Jul 2018].

[102] Williams, D., “Mars 3”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1971-049F [retrieved 30 Jul 2018].

[103] Williams, D., “Apollo 16”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1972-031C [retrieved 30 Jul 2018].

[104] Williams, D., “Apollo 17”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1972-096C [retrieved 30 Jul 2018].

[105] Williams, D., “Luna 20”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1972-007A [retrieved 30 Jul 2018].

[106] Williams, D., “Venera 8”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1972-021A retrieved 30 Jul 2018].

[107] Williams, D., “Luna 21”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1973-001A [retrieved 30 Jul 2018].

[108] Williams, D., “Luna 23”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1974-084A [retrieved 30 Jul 2018].

[109] Williams, D., “Mars 6”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1973-052A [retrieved 30 Jul 2018].

[110] Williams, D., “Venera 10”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1975-054D [retrieved 30 Jul 2018].

[111] Williams, D., “Venera 9”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1975-050D [retrieved 30 Jul 2018].

[112] Williams, D., “Luna 24”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1976-081E [retrieved 30 Jul 2018].

[113] Williams, D., “Viking 1”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1975-075C [retrieved 30 Jul 2018].

[114] Williams, D., “Viking 2”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1975-083C [retrieved 30 Jul 2018].

[115] Williams, D., “Pioneer Venus 2”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1978-078D [retrieved 30 Jul 2018].

[116] Williams, D., “Venera 11”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1978-084D [retrieved 30 Jul 2018].

[117] Williams, D., “Venera 12”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1978-086C [retrieved 30 Jul 2018].

[118] Williams, D., “Venera 13”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1981-106D [retrieved 30 Jul 2018].

[119] Williams, D., “Venera 14”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1981-110D [retrieved 30 Jul 2018].
[120] Williams, D., “Vega 1”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1984-125E [retrieved 30 Jul 2018].
[121] Williams, D., “Vega 2”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1984-128E [retrieved 30 Jul 2018].
[122] Williams, D., “Hiten”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1990-007A [retrieved 30 Jul 2018].
[123] Williams, D., “Galileo Probe”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1989-084E [retrieved 30 Jul 2018].
[124] Williams, D., “Mars Pathfinder”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1996-068A [retrieved 30 Jul 2018].
[125] Williams, D., “Mars Polar Lander”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1999-001A [retrieved 30 Jul 2018].
[126] Williams, D., “NEAR Shoemaker”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1996-008A [retrieved 30 Jul 2018].
[127] Williams, D., “Beagle 2”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2003-022C [retrieved 30 Jul 2018].
[128] Williams, D., “Galileo”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1989-084B [retrieved 30 Jul 2018].
[129] Williams, D., “Opportunity”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2003-032A [retrieved 30 Jul 2018].
[130] Williams, D., “Spirit”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2003-027A [retrieved 30 Jul 2018].
[131] Williams, D., “Deep Impact”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2005-001Aretrieved 30 Jul 2018].
[132] Williams, D., “Hayabusa”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2003-019A [retrieved 30 Jul 2018].
[133] Williams, D., “Huygens”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1997-061C [retrieved 30 Jul 2018].
[134] Williams, D., “SMART-1”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2003-043C [retrieved 30 Jul 2018].
[135] Williams, D., “Chandrayaan-1”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2008-052A [retrieved 30 Jul 2018].
[136] Williams, D., “Phoenix”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2007-034A [retrieved 30 Jul 2018].
[137] Williams, D., “Chang’e 1”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2007-051A [retrieved 30 Jul 2018].
[138] Williams, D., “LCROSS”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2009-031B [retrieved 30 Jul 2018].
[139] Williams, D., “Curiosity”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2011-070A [retrieved 30 Jul 2018].
[140] Williams, D., “Chang’e 3”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2013-070C [retrieved 30 Jul 2018].
[141] Williams, D., “Philae”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2004-006C [retrieved 30 Jul 2018].
[142] Williams, D., “MESSENGER”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2004-030A [retrieved 30 Jul 2018].
[143] Williams, D., “Rosetta”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2004-006A [retrieved 30 Jul 2018].
[144] Williams, D., “Schiaparelli”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2016-017A [retrieved 30 Jul 2018].
[145] Williams, D., “Cassini”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1997-061A [retrieved 30 Jul 2018].
[146] Williams, D., “Hayabusa 2”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2014-076A [retrieved 30 Jul 2018].
[147] Williams, D., “InSight”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=INSIGHT [retrieved 30 Jul 2018].
[148] Williams, D., “OSIRIS-Rex”, NASA Space Science Data coordinated Archive, 21 Mar 2017, URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2016-055A [retrieved 30 Jul 2018].
[149] “Mars 2020 Mission Overview”, NASA, URL: https://mars.nasa.gov/mars2020/mission/overview/ [retrieved 30 Jul 2018].

[150] "The launch of Conestoga 1," Space Services Inc of America, 9 Sept 1982, URL: http://www.spaceservicesinc.com/conestoga-1 [retrieved 18 May 2018].
[151] State of the Union Addresses by Ronald Reagan, *Electronic Classics Series*, the Pennsylvania State University, Hazleton, PA 18201-1291, 2003, pp. 37, URL: http://www.tiltright.com/page/dl/SUaddressRReagan.pdf [retrieved 18 May 2018].
[152] Executive Order 12465, "Commercial expendable launch vehicle activities", Federal Register, 24 Feb 1984, URL: https://www.archives.gov/federal-register/codification/executive-order/12465.html [retrieved 18 May 2018].
[153] Commercial Space Launch Act, H.R. 3942, 98th Congress, Sept 1983, URL: https://www.congress.gov/bill/98th-congress/house-bill/3942 [retrieved 18 May 2018].
[154] Bromberg, J. L., *NASA and the Space Industry*, The Johns Hopkins University Press, Baltimore, 1999, pp. 128.
[155] "The President's Space Policy and Commercial Space Initiative to Begin the Next Century," Feb. 1988. http://aerospace.wpengine.netdna-cdn.com/wp-content/uploads/2018/03/National-Space-Policy-Fact-Sheet-Feb88.pdf [retrieved 18 May 2018].
[156] "DARPA Launch Challenge: Qualification Guidelines", Defense Advanced Research Projects Agency (DARPA), Rev. 1, 21 May 2018, URL: https://www.darpalaunchchallenge.org/2018%2005%2021%20Launch%20Challenge%20Guidelines.pdf, [retrieved 1 Aug 2018].
[157] "Streamlining Licensing Procedures for Small Satellites", [Notice], 83 FR 24064, (proposed May 24, 2018) (to be codified at 47 CFR 2 and 47 CFR 25).
[158] "FACT SHEET: Harnessing the Small Satellite Revolution to Promote Innovation and Entrepreneurship in Space", The White House: Office of the Press Secretary, 21 Oct. 2016, URL: https://obamawhitehouse.archives.gov/the-press-office/2016/10/21/fact-sheet-harnessing-small-satellite-revolution-promote-innovation-and, [retrieved 1 Aug 2018].
[159] Lyndon B. Johnson Space Center Staff, *Commercial Orbital Transportation Services: A New Era in Spaceflight,* National Aeronautics and Space Administration, Government Printing Office, NASA/SP-2014-617, May 2014
[160] Lyndon B. Johnson Space Center Staff, Commercial Orbital Transportation Services: A New Era in Spaceflight, National Aeronautics and Space Administration, Government Printing Office, NASA/SP-2014-617, May 2014.
[161] "CRS Mission History", Orbital-ATK, URL: https://www.orbital.com/space-systems/human-space-advanced-systems/commercial-resupply-services/docs/CRS%20Mission%20History.pdf [retrieved 23 May 2018].
[162] "Launch Manifest". SpaceX. http://www.spacex.com/missions. Accessed 23 May 2018.
[163] *Vision and Voyages for Planetary Science in the Decade 2013-2022,* National Research Council, Committee on the Planetary Science Decadal Survey, Washington, DC: National Academies Press, 7 Mar 2011, URL: https://solarsystem.nasa.gov/resources/598/vision-and-voyages-for-planetary-science-in-the-decade-2013-2022/ [retrieved 23 Jul 2018].
[164] "Program & Missions", National Aeronautics and Space Administration, URL: https://mars.nasa.gov/programmissions/missions/ [retrieved 23 Jul 2018].
[165] "List of missions to Mars", Wikipedia, 20 Jul 2018, URL: https://en.wikipedia.org/wiki/List_of_missions_to_Mars [retrieved 23 Jul 2018].
[166] *Solar and Space Physics: A Science for a Technological Society*, Chapter: Summary, pp. 7, National Research Council, Committee on a Decadal Strategy for Solar and Space Physics (Heliophysics), Washington, DC: National Academies Press, 2013, URL: https://www.nap.edu/read/13060/chapter/2#7 [retrieved 20 Jul 2018].
[167] National Aeronautics and Space Administration Transition Authorization Act of 2017, S. 442, 115th Congress, 2017.
[168] "Budget Documents, Strategic Plans, and Performance Reports", National Aeronautics and Space Administration, 2 May 2018, URL: https://www.nasa.gov/news/budget/index.html [retrieved 20 Jul 2018].
[169] *Benefits Stemming from Space Exploration*, International Space Exploration Coordination Group, 2013.
[170] Zhang, W., Wang, L., Liu, D., Song, W. Ma, Y., and Chen, D., "Towards Building a Multi-Datacenter Infrastructure for Massive Remote Sensing Image Processing," Concurrency and Computation: Practice and Experience, Vol. 25, No. 12, 2013, 1798-1812.
[171] Hahmann, T., Fischer, P., "For 26 years a successful ERS/Envisat D-PAF/D-PAC", German Aerospace Center, 4 Jul 2017, URL: https://www.dlr.de/eoc/en/desktopdefault.aspx/tabid-11932/20674_read-49632/ [retrieved 20 Jul 2018].
[172] *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observations from Space*, National Academies of Sciences, Engineering, and Medicine, Washington, DC, 2017, pp. 3-26, URL: https://essp.nasa.gov/essp/files/2018/02/2017-Earth-Science-Decadal-Survey.pdf [retrieved 23 Jul 2018].
[173] "HST Publication Statistics" [online database], Barbara A. Mikulski Archive for Space Telescopes, 15 March 2018, URL: https://archive.stsci.edu/hst/bibliography/pubstat.html [retrieved 23 Jul 2018].
[174] McAlister, P.R. and Reising, D., "Collaborations for Commercial Space Capabilities", National Aeronautics and Space Administration, SAA-QA-14-18884, 18 Dec 2014, URL: https://www.nasa.gov/sites/default/files/atoms/files/saa-qa-14-18884-ula-baseline-12-18-14-redacted_3.pdf [retrieved 5 July 2018].
[175] World Bank, *GDP growth (annual %)* [online database], URL: https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG [retrieved 6 June 2018].
[176] Bryce Space & Technology, "2017 State of the Satellite Industry Report," Satellite Industry Association, 20th Edition, June 2017.
[177] Lyndon B. Johnson Space Center Staff, Commercial Orbital Transportation Services: A New Era in Spaceflight, National Aeronautics and Space Administration, Government Printing Office, NASA/SP-2014-617, May 2014.

[178] Shireman, K.A. and Bigelow, R., “Nonreimbursable Space Act Agreement Between the National Aeronautics and Space Administration Lyndon B. Johnson Space Center and Bigelow Space Operations for Non-Reimbursable to Low-Earth Orbit Commercial Development”, National Aeronautics and Space Administration, OZ-18-27253, 28 Mar 2017, URL: https://www.nasa.gov/saa/domestic/27253_SAA_27253_Final_Approved_Sigs.pdf [retrieved 5 July 2018].
[179] Michael D. Griffin, interview by Rebecca Wright, January 12, 2013, transcript, C3PO OHP, URL: https://www.jsc.nasa.gov/history/oral_histories/C3PO/GriffinMD/GriffinMD_1-12-13.htm [retrieved 27 June 2018].
[180] Equidate, “Buy and Sell SpaceX Pre-IPO Stock”, URL: https://equidateinc.com/company/space-exploration-technologies [retrieved 27 Jun 2018].
[181] Caleb Henry, “SoftBank interested in more satellite, OneWeb-related investments”, SpaceNews, 6 Feb 2018, URL: http://spacenews.com/softbank-interested-in-more-satellite-oneweb-related-investments [retrieved 28 Jun 2018.].
[182] Peter B. de Selding, “OneWeb’s Powerful Partners in Their Own Words”, SpaceNews, 26 Jun 2015, URL: http://spacenews.com/onewebs-partners-in-their-own-words [retrieved 28 Jun 2018].
[183] Ellen Huet, “Google Buys Skybox Imaging -- Not Just For Its Satellites”, Forbes, 10 Jun 2014, URL: https://www.forbes.com/sites/ellenhuet/2014/06/10/google-buys-skybox-imaging-not-just-for-its-satellites/#65cca8099739 [retrieved 28 Jun 2018]
[184] Bruce Upbin, “Monsanto Buys Climate Corp For $930 Million”, Forbes, 2 Oct 2013, URL: https://www.forbes.com/sites/bruceupbin/2013/10/02/monsanto-buys-climate-corp-for-930-million/#360ed097177a [retrieved 28 Jun 2018].
[185] “The Climate Corporation Sells Crop Insurance Business to Amtrust Financial Services Inc.”, Climate Fieldview, 31 July 2015, URL: https://climate.com/newsroom/climate-sells-crop-insurance-to-amtrust/13 [retrieved 28 Jun 2018].
[186] Werner, D., “Descartes Labs raises $30 million for data refinery”, SpaceNews, 24 Aug 2017, http://spacenews.com/descartes-labs-raises-30-million-for-data-refinery/ [retrieved 28 Jun 2018].
[187] Aeronautics and Space Report of the President: Fiscal Year 2016 Activities, National Aeronautics and Space Administration, URL: https://history.nasa.gov/presrep2016.pdf [retrieved 10 July 2018].
[188] “Annual Economy Overviews”, The Space Report Online [online database], Space Foundation, Colorado Springs, CO, URL: https://www.thespacereport.org/resources/economy/annual-economy-overviews [retrieved 26 April 2018].
[189] Bryce Space & Technology, “2018 State of the Satellite Industry Report,” Satellite Industry Association, June 2017, URL: https://brycetech.com/downloads/SIA_SSIR_2018.pdf [retrieved 17 July 2018].
[190] *Review of Australia’s Space Industry Capability*, Australian Government, Department of Industry, Innovation and Science, Mar 2018, URL: https://industry.gov.au/industry/IndustrySectors/space/Documents/FINAL_ERG-Review-Report_10-May_accessible.pdf [retrieved 5 Jun 2018].
[191] Union of Concerned Scientists, UCS Satellite Database [online database], Cambridge, MA, 31 August 2017, URL: https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database [retrieved 14 June 2018].
[192] “Astronauts & Cosmonauts: List of Names by Nationality”, World Space Flight, 13 August 2017, URL: https://www.worldspaceflight.com/bios/nation_names.php [accessed 7 Aug 2018].
[193] “List of astronauts”, Encyclopædia Britannica, URL: https://www.britannica.com/topic/list-of-astronauts-2020968 [accessed 7 Aug 2018].
[194] “List of space travelers by nationality”, Wikipedia, 20 July 2018, URL: https://en.wikipedia.org/wiki/List_of_space_travelers_by_nationality [accessed 7 Aug 2018].
[195] “Tutorial 5: The History of the SBIR and STTR Programs”, Course 1: Program Basics, Small Business Administration, URL: https://www.sbir.gov/tutorials/program-basics/tutorial-5 [retrieved 5 June 2018].
[196] Yang, R., “Small Business Innovative Research (SBIR) and Small Business Technology Transfer (STTR) Programs, April 2015, URL: https://www.nasa.gov/sites/default/files/atoms/files/byang_sbir_and_sttr.pdf [retrieved 5 June 2018].
[197] Hall, L., “About Flight Opportunities”, National Aeronautics and Space Administration, August 2017, URL: https://www.nasa.gov/directorates/spacetech/flightopportunities/about [retrieved 29 June 2018].
[198] Petro, A., Small Satellite Conference 2015: NASA Town Hall Meeting, National Aeronautics and Space Administration, 10 Aug 2015, URL: https://www.nasa.gov/sites/default/files/atoms/files/nasa_town_hall_small_sat_conf_2015.pdf [retrieved 25 May 2018].
[199] “University / Academic Institute Satellites”, India Space Research Organization, Department of Space, URL: https://www.isro.gov.in/spacecraft/university-academic-institute-satellites [retrieved 5 June 2018].
[200] Emerging Space Report, National Aeronautics and Space Administration, 2014, p.29, URL: https://www.nasa.gov/sites/default/files/files/Emerging_Space_Report.pdf
[201] Etherington, D., “Blue Origin flies its Crew Capsule 2.0 for the first time”, TechCrunch, Dec 2017, URL: https://techcrunch.com/2017/12/13/blue-origin-flies-its-crew-capsule-2-0-for-the-first-time/ [retrieved 13 June 2018].
[202] “Astronaut Flight Costs”, Bigelow Aerospace, Oct 2015, URL: https://web.archive.org/web/20151007192151/http://bigelowaerospace.com/about/opportunities-pricing-services/ [retrieved 13 June 2018].
[203] Gilbert, J., “Made In Space: How space manufacturing is becoming a reality”, Cleantech News, Nov 2017, URL: https://www.cleantech.com/made-in-space-how-space-manufacturing-is-becoming-a-reality/ [retrieved 13 June 2018].
[204] “Company”, Spire, 2018, URL: https://spire.com/company/ [retrieved 13 June 2018].
[205] “CMOS Sensors Enable Phone Cameras, HD Video”, NASA Technology Transfer Program, 2017, URL: https://spinoff.nasa.gov/Spinoff2017/cg_1.html [retrieved 15 June 2018].

[206] “Planet-Navigating AI ‘Brain’ Helps Drones and Cars Avoid Collisions”, NASA Technology Transfer Program, 2018, URL: https://spinoff.nasa.gov/Spinoff2018/it_1.html [retrieved 15 June 2018].
[207] “Ferrofluid Technology Becomes a Magnet for Pioneering Artists”, NASA Technology Transfer Program, 2018, URL: https://spinoff.nasa.gov/Spinoff2018/cg_3.html [retrieved 15 June 2018].