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THE ECONOMICS OF SPACE: AN INDUSTRY READY TO LAUNCH

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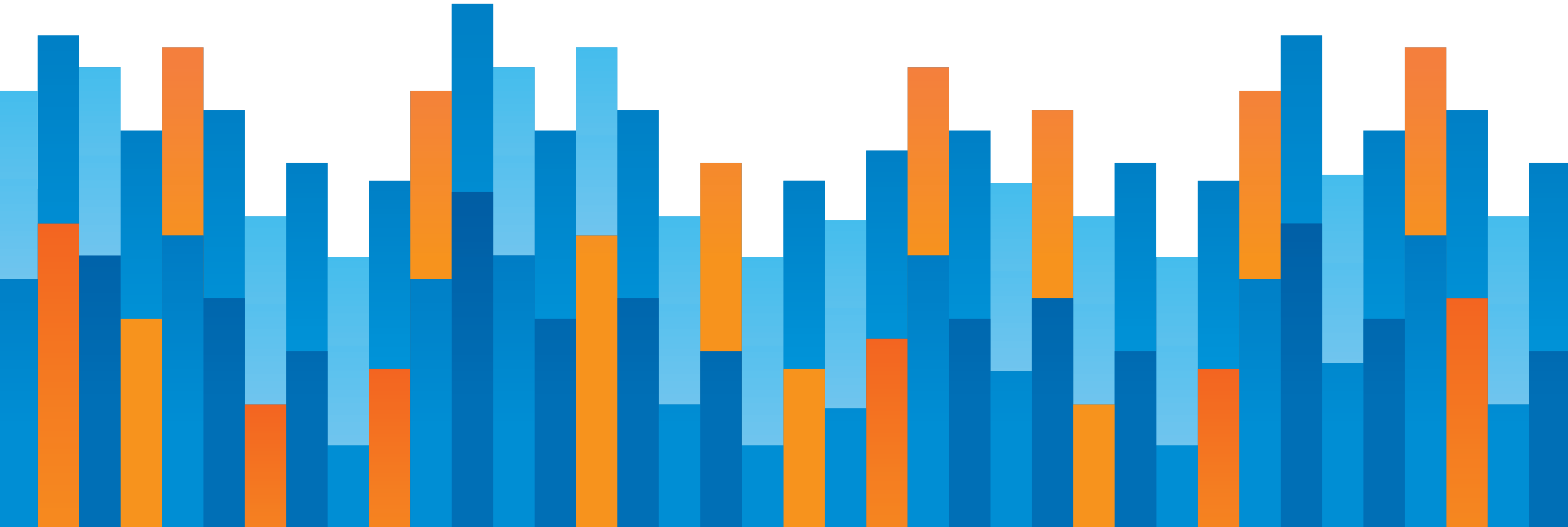
June 2019



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EXECUTIVE SUMMARY

America's future success in space depends on restructuring our approach for financial sustainability. While NASA has contracted with the private sector for innovation and cost savings, it continues to use the same antiquated and constraining structure that was first developed for exploring space. This carries an opportunity cost that slows the private sector's plans to harness space's many viable materials and properties, compared to the pace it could attain with a more market-friendly approach. Such activities could help solve Earth's most pressing problems and foster a space industry that sustains itself financially.

Many space-based activities have commercial potential. For example:

- tapping space-based clean energy sources
- mining asteroids for useful raw materials
- developing safe venues for scientific experiments
- upcycling/sequestering hazardous but valuable debris currently in space
- tapping sources of water already in space, to decouple into oxygen and hydrogen for space fuels and oxidizers, and to provide radiation shielding mass
- using the low-gravity, low-temperature and other properties of space for many activities, including manufacturing and research

These endeavors—as well as our current use of space for communication, navigation, defense, etc.—argue for a change in our approach to space from the current exploration paradigm to one of commercialization. Transportation infrastructure will create the environment for private players to develop space-based industries that use commerce to greatly increase quality of life and decrease cost of living. The history of developing frontiers, such as the open seas via shipping practices and the American West via railroads, demonstrates the effects of this evolution in public role.

The basic infrastructure needed should be attainable in 10 to 20 years within the same budget currently appropriated to NASA, with the following features:

- Fuel depots (essentially gas stations) in an appropriate orbit
- Fuel (from water) and water itself
- A shuttle for travel to the lunar surface
- Lunar facilities, for resupply and water and aluminum mining for construction in space
- Orbital facility complex

While this list sounds ambitious, it is technologically feasible currently and would allow the private sector to develop pragmatic use for space's assets much faster than government provision. This creates a sustainable market-based economy in space that our current approach obstructs. A commerce-based structure, much like we have with the seas and airspace, in which government provides a legal framework where the private sector can flourish, would greatly advance our use of the space environment, maximizing our potential to pursue these activities. Allowing the private sector to continue to advance private launch vehicle technology, and instead spending public funds on infrastructure, not only drives efficiency but creates a financially self-sustaining commercial industry. A great deal of low-hanging fruit is available if (and only if) we make a whole-hearted decision to turn from a merely scouting and near-offshore use of space to being a spacefaring nation.

This can all happen within the current NASA budget. In a commerce-based approach, the private sector develops the space industry and NASA and other government parties buy transport and other key services, such as on-orbit facilities, as customers of the private providers. NASA has already begun buying some space transportation in this manner, just as we currently do with other transportation systems. Extending this good start and making it more consistent is the only way, within the current NASA budget, that leads to comprehensive advancement in space.

This approach does not fault NASA, the Air Force, or the other government agencies in charge of American space launch. Almost all the approaches used by cutting-edge companies like SpaceX and Blue Origin were well known to aerospace engineers and had been thoroughly discussed in aerospace engineering forums for decades. Furthermore, the decision-makers at the top of the relevant government agencies were for the most part intelligent and experienced engineering managers. This study finds the fault lies primarily in the structure of the current system itself, especially the interplay between Congress, the contractor companies, and the agencies charged with maintaining America's space capabilities. The current structure ties space development to conflicting political requirements and fails to fund projects adequately, making for suboptimal decisions by managers, administrators, and politicians. In contrast, changing to a commerce paradigm, in which government funds infrastructure, lays the foundation for a sustainably funded space industry.

Given a functioning transportation infrastructure, as the private sector develops space industry, government's role changes to fostering that industry. What space commerce needs from government is a legal framework in which to operate that defines and defends property rights, and research (especially on human health in space) that leads to more diverse space activities. Taking cues from agreements on the way various nations regard the bounty of the seas, government can ensure a sustainable and equitable free market environment. With models from other frontier exploration, government should focus on creating the legal framework to allow commerce and private endeavor to flourish.

We cannot imagine how profoundly, comprehensively and quickly technological advancement—when it is commercialized—changes our everyday lives. Every single time, and by orders of magnitude, we underestimate its power to improve ordinary people's lives once it becomes widely used through commercialization. For example, we cannot each own a jet, but today almost all of us can afford a plane ticket. This is due to the tangible effects of the synergy of technology and commerce. These effects occur so universally that any discussion of new technological frontiers should assume a blind but well-grounded expectation of manifold global rewards, if only we have the foresight to encourage its proliferation. Examples from sea, land and air transportation, the Digital Age and countless other endeavors prove that technology combined with commerce triggers comprehensive advancement at lower cost. America's future success in space depends on restructuring our approach to accommodate such a vision.

COMMERCIALIZATION CREATES A SELF-SUSTAINING SPACE INDUSTRY

Despite the best current efforts of the private sector in this direction, it's not yet an industry. Yet, launch companies have managed to create a profitable service focusing on occasional launches of very high-value payloads at very high prices. For example, the geosynchronous orbital position for telecommunications is so valuable that even our current highly inefficient way of accessing it is profitable.

SpaceX's Falcon 9 launch success at one-third the price of a traditional NASA-contracted launch demonstrates private-sector capability to fulfill many current NASA functions at a fraction of the cost. Such achievement frees up NASA to concentrate on its core research and exploration missions in space, and allows the private sector to invest in self-sustaining space-based industry. Developing the industry depends on a certain amount of infrastructure, which can pay for itself by freeing up funds currently used for NASA's SLS (Space Launch System)/Orion program.

This redistribution of current NASA funding is the key to paradigm change, although there are political problems with terminating the current SLS/Orion program in closely contested states in the 2020 presidential elections—states like Alabama and Florida. A compromise solution might be to push for increased spending on commercial service purchase, while SLS proceeds to flight status, since the SLS will run out of surplus Shuttle engines by the early 2020s.

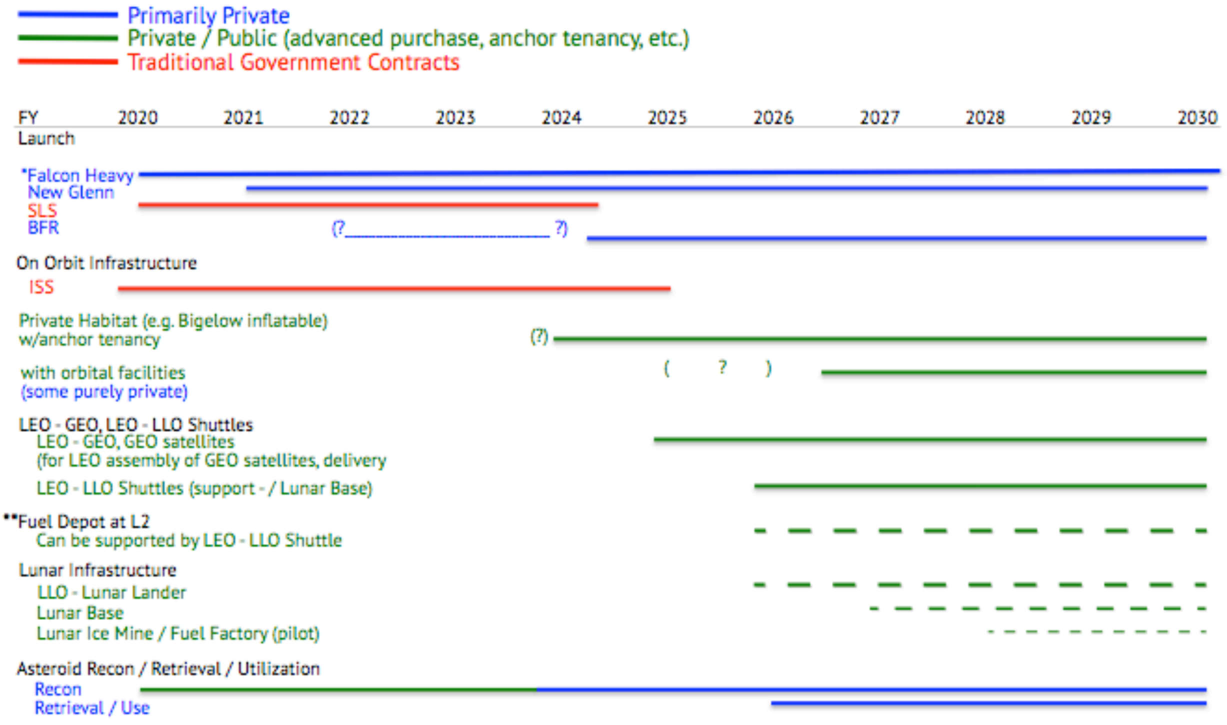
Moving our funding of space activity from solely the exploration function to a mixture of privately funded commercial industry and publicly funded research is signaled by the private sector's current capabilities, and the commercial-quality resources already identified in space that the current paradigm prevents us from harnessing. Also, changing to a commercial approach allows for efficiencies such as mass production of equipment and standardized designs that can carry cargo or humans with few modifications—which is much cheaper and more effective than what we do now. No matter how much money Congress sinks into status-quo space activities now, utility will continue to decline, making funding increasingly ineffective, and keeping the U.S. space program confined. The first step in progress is systemic change, beginning with policy change. Every single change that makes space operations more like airline operations bears fruit in lower costs, and those changes in turn trigger further reduction in costs.

TRIGGERING LARGE-SCALE ADVANCEMENT IN SPACE WITHOUT ADDITIONAL FEDERAL FUNDING

Private sector launch allows the market to exploit every available efficiency to develop the cheapest, most effective means of space travel. When NASA becomes a paying customer of such transportation, it fosters the development of simpler and vastly cheaper launch and vessels, which are now the most expensive, difficult and complicated part of space activity. With cheaper launch comes more launch—for the same or less cost. This allows the private sector to exploit its best uses and NASA to do the same, for more NASA emphasis on research and less on transportation.

With NASA as an anchor tenant on a privately contracted space station, funding is available for infrastructure such as orbital facilities, which expands current space activities and makes them better and cheaper to accomplish. Much like the move to railroads did for U.S. exploration and settlement of the American West, transportation infrastructure levers progress in all sectors, usable for commercial, scientific and military pursuits—without increasing NASA's space activity budget. By redirecting funds, space infrastructure would likely be available by the mid-late 2020s.

FIGURE ES1: TIMELINE FOR TRANSITION TO PRIVATE SPACE PARADIGM



* Falcon Heavy has been in service since 2018

**Technologies for a fuel depot at L2 are proven feasible but development has not begun.

The potential exponential cost reduction and technological advancement of such a paradigm shift cannot be precisely quantified. This is especially true in a frontier like space, where we have only begun to identify caches of resources and uses of physical and material properties of space. This study gives rough order of magnitude cost and timeline estimates based on our current technological capability, knowledge of space resources and current costs, with firm estimates in the near future—through about 2025, when infrastructure would be complete enough to support a fully commercial space industry. From that point, estimates are less firm, as depicted by dotted lines in Figure ES1, as we cannot know which technologies will dominate and which additional resources and efficiencies will proliferate. New ideas will be tested and many will fail. Some companies will fold and others rise up with new perspectives. Such a pattern and outcome is consistent with past technology leaps and acquisition of frontiers. But we know from history that transportation infrastructure catalyzes economic advancement, and that industries are created and sustained through private investment and commerce.

This study examines our current radical transformation in space transport as private actors and market forces have slashed the costs of accessing space. These advancements have already greatly reduced costs for not only NASA, but also civilian (mostly satellite) and military space transport as well. These cost reductions, especially for classified military applications, cannot be quantified within the current available budget breakdowns, but are likely to follow similar cost reductions to NASA's. As with other transportation industries, increasing efficiencies continue to drive down costs, but order of magnitude efficiencies come with infrastructure that can sustain a space-faring industry, where NASA and military and civilian companies become customers on private space transport, as we have seen with shipping and rail industries and even with Antarctic exploration. We argue for shifting to an approach based on our current reality of new private launch capability at a fraction of the cost of government procurement, whereby government invests in infrastructure and allows the private sector to innovate to develop efficient transportation and financially sustainable use of space resources.

POLICY RECOMMENDATIONS TO CONGRESS

To set NASA and the U.S. space sector on the right path, we make the following recommendations:

LEGAL/SECURITY RECOMMENDATIONS:

The U.S. government should continue active planning as begun by the current Administration for the defense and internal policing of U.S.-flagged spacecraft, space stations, and extraterrestrial facilities, including consideration of creating a Coast-Guard-like constabulary service for space. The U.S. government should also create a working group, including representatives of the space development community, to examine and make recommendations on the space treaties and international legal environment as they affect the U.S. space sector. Upon its reporting, the U.S. government should give due consideration to its recommendations regarding interpreting, modifying, and/or withdrawing from existing and pending space treaties and agreements. The U.S. should begin discussions with other market-oriented, space-using nations on a multilateral agreement within or without the framework of the Outer Space Treaty, recognizing each other's property claims on space assets.

Congress should create legislation establishing U.S. recognition of transferable resource rights, analogous to private property rights, based on first capability of reaching space resources, and transferable rights to keep-away zones around space objects, consistent with international law. It should, furthermore, create safe-harbor provisions for buying, selling, and hypothecating such rights on open markets or exchanges and in commercial and financial contracts under U.S. jurisdiction without risk of prosecution for fraud, provided that such rights are appropriately registered and verified by the U.S., consistent with international law.

PROCUREMENT POLICY RECOMMENDATIONS:

The U.S. government should declare a policy of reliance on the private sector for launch operations and in-space facilities on terms and conditions similar to those of private sector users, starting with commercial resupply and crew transportation to ISS. The baseline future scenario for an ISS should be the government's letting of anchor-tenant contracts for research space in an orbital facility or facilities.

NASA missions of any sort, including science and exploration missions, should be performed whenever possible by issuing purchase orders for results, such as data gathered from specific targets under specific conditions, rather than contracting for the development of means of obtaining such data. Evidence of market failure, judged by an agency external to NASA, should be required before permitting NASA contracting for construction or operation of spacecraft.

The U.S. government should establish a working group that includes representatives of the space development community to recommend procedures and mechanisms to ensure that NASA's spaceflight and space operations research supports private sector research and development in the same way NASA and its predecessor, the N.A.C.A., support the aviation industry.

POLICY IMPLEMENTATION RECOMMENDATIONS:

The U.S. government, in an agency external to NASA, should establish criteria to determine when the U.S. private sector capabilities in heavy-payload launch become sufficiently reliable that NASA should establish a timetable for exiting the development of large-payload launch vehicles and winding down existing large-payload vehicle launch operations.

The government should select NASA's future exploration missions (crewed and uncrewed) so they can take on propellant from an on-orbit facility, establish advance purchase contracts that are financially trustworthy for the purchase of that propellant and, with private industry, develop standard interfaces and interconnects for the delivery of that propellant. Industry should be allowed innovative freedom to find the best delivery mechanism. Such a pilot on-orbit refueling facility should be a 10-year objective, including a government open purchase order for delivery of water to an orbital fueling facility at a fixed price equal to the effective price of fuel launched from Earth, which should be unlimited for the first 10 years of operation.

NASA, in its periodic setting of solar system research and exploration priorities, should give preference to dual-purpose probes—i.e., those that serve both scientific research goals and also provide useful scouting data for space resource harvesting, and further possible economic uses of space and its properties.

TABLE OF CONTENTS

TABLE OF FIGURES AND TABLES

PART 1

INTRODUCTION

From the Industrial Revolution to the fairly recent technological explosion that birthed the modern Information Age, only one thing remains constant: we cannot imagine how profoundly, comprehensively and quickly technological advancement changes our everyday lives. These advancements began with single prototypes that took much labor and hand-crafting to build and perfect. Because of this, their initial costs were so great that only the very wealthy could afford to buy them. But as they commercialized, they standardized to take advantage of assembly line manufacture, interchangeable parts, economies of scale, and cost-efficient materials and designs. Simultaneously, they diversified in style and price in response to diverse demand. Soon they evolved into products that became part of ordinary people's daily lives, greatly changing the face of commerce and employment. As they proliferated, their price dropped until most anyone could buy them. We cannot each own a jet, but today almost all of us can afford a plane ticket. These are the tangible effects of the synergy of technology and commerce.

Examples from sea, land, and air transportation, the Digital Age, and countless other endeavors prove that technology combined with commerce is like that: nearly every time, and by orders of magnitude, we underestimate its power to improve our lives through commercialization. This occurs so universally that any discussion of new technological frontiers should assume a blind but well-grounded expectation of manifold global rewards, if only we have the foresight to encourage its proliferation.

America's future success in space depends on restructuring our approach to accommodate such a vision. Our current system uses the antiquated and constraining structure of an exploration-based paradigm. While NASA has contracted with the private sector for innovation and cost savings, it continues to use the same structure that was first developed for exploring space. This carries an opportunity cost that slows the private sector's plans to harness space's many viable materials and properties, compared to the pace it could attain with a more market-friendly approach. Such activities could help solve Earth's most pressing problems and foster a space industry that sustains itself financially.

A commerce-based structure, much like we have with the seas and airspace, whereby government provides a legal framework in which the private sector can flourish, would greatly advance our use of the space environment. Maximizing our potential ranges from harvesting tangible raw materials to using the physical properties of space such as low gravity and weightlessness, to finding new energy alternatives and other benefits yet to be discovered. This could all happen within the current NASA budget. In a commerce-based approach, the private sector develops the space industry and NASA and other government parties buy transport and other key services, such as on-orbit facilities, as customers of the private providers. NASA has already begun buying some space transportation in this manner, just as we currently do with other transportation systems. Extending this good start and making it more consistent is the only way, within the current NASA budget, that leads to comprehensive advancement in space, ensuring that our reach always exceeds our grasp.

With this long-range and open-ended vision in mind, this study examines and analyzes how the U.S. space program operates now and its near-future potential for fostering a commercial space industry. While working within the existing budget of the federal agencies that conduct and regulate space activities (NASA, DOD, NOAA, and DOT), we suggest cooperative ways for government agencies and the private sector to promote widespread commercialization of space transportation to accelerate the pace of exploration and economic development of space.

PART 2

SPACE'S POTENTIAL FOR SOLVING EARTH'S MOST PRESSING PROBLEMS

To a large extent, human quantity and quality of life, and the environmental quality of the planet, depend on abundant, clean and cheap energy. Currently the U.S. government spends $2.76 billion each year in pursuit of alternative energy sources.[1]

First World providers in the OECD nations have maintained supplies fairly well, with modern extraction and remediation techniques, employing new technologies such as fracking and horizontal drilling. However, the rapid growth of consumer demand in the newly emerging economies in East Asia and other areas has led to expansion of dirtier, more Earth-damaging, and less-safe extraction activities in other parts of the planet, such as the rapid expansion of coal production and coal power generation in China and the extraction of rare minerals in China and Africa under appalling conditions. As more and more parts of the Third World enter similar economic growth spurts, additional new sources of energy and minerals will be needed to prevent further degradation with all the associated externalities, many of which are shared globally.

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[1] Ars Technica. March 23, 2018.

Space has the potential to provide abundant clean energy and sources of certain minerals in airless, lifeless places that cause no environmental damage. Shifting our procurement off-Earth would raise human quality of life, lower the cost of living and help keep Earth's environment clean.

2.1 ABUNDANT CLEAN ENERGY

The principal energy source accessible in space with the highest potential for use on Earth is solar power. Solar Power satellites (SPS) can beam high-density solar power back to Earth. SPS has been studied extensively over the decades, starting with a large NASA/Department of Energy study in 1977–1978, up through the present day.[2] The Chinese space program has recently announced that the construction of such satellites will be among its long-term goals.[3] SPS requires construction of large (kilometer-long and larger) satellites in Earth orbit that collect solar power and convert it to electricity, and then transmit it by microwave or laser beams to sites on Earth (to receiving antennas called "rectennas") where it can be fed into the existing power grids. Technologically, every component of an SPS system has been proven—this is engineering that we already know how to do, testable in five years and operational in 10-15 years.[4]

SPS's two main advantages over conventional, Earth-collected solar power are:
Solar power's energy density is over twice as high in space as in Earth locations (and many times higher than in cloudy or northern locations) because the rays are undiluted by water vapor and other atmospheric substances.

By virtue of their location in geosynchronous orbit (a high-Earth orbit that tracks with Earth's rotation) SPSs can receive solar rays nearly 24/7.

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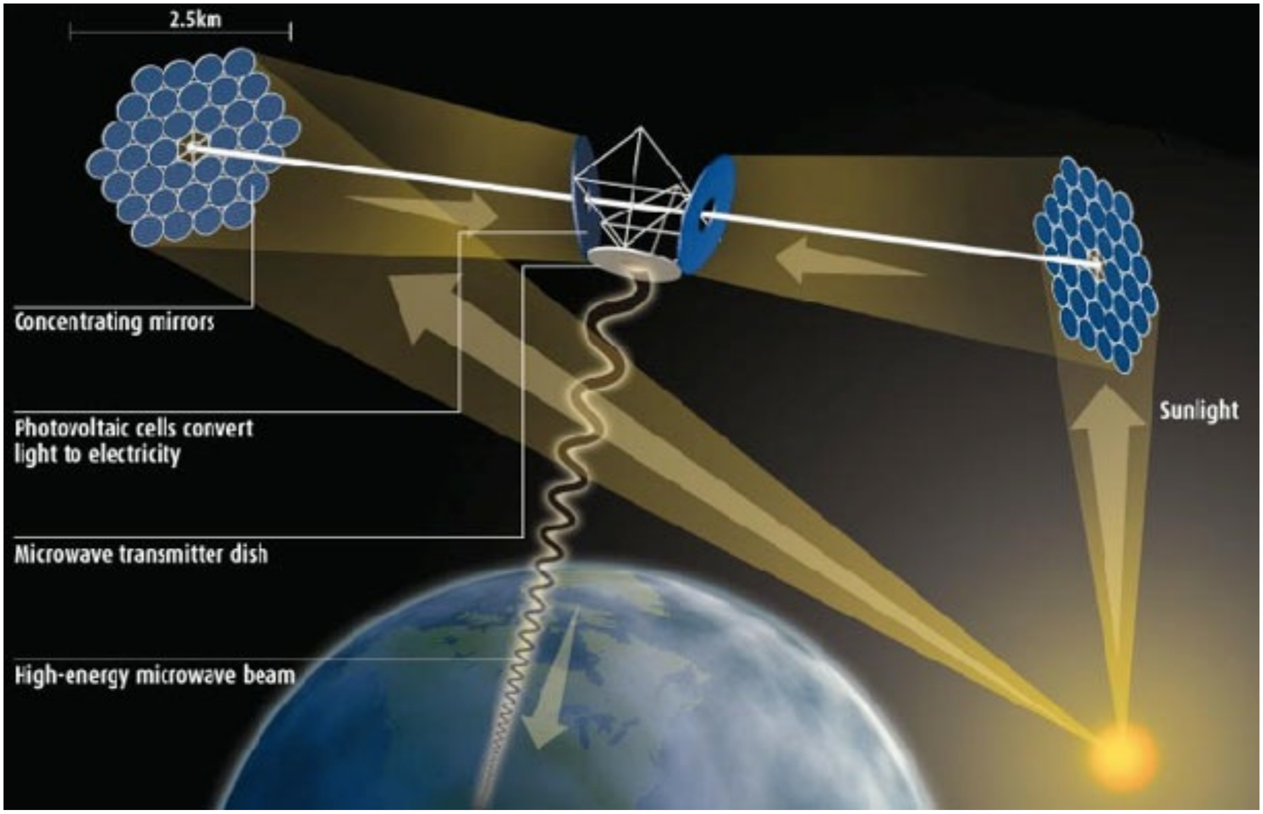
[2] U.S. Department of Energy. "Space-Based Solar Power." March 6, 2014. https://www.energy.gov/articles/space-based-solar-power

[3] Exploiting Earth-Moon Space: China's Ambition After Space Station. Chinadaily.com.an. Retrieved May 21, 2016.

[4] Foust, Jeff. A Renaissance for Space Solar Power? *Space Review*. Aug 13, 2007.

FIGURE 1: ONE CONCEPT FOR A SOLAR POWER SATELLITE



Source: Belvin, Keith W., John T. Dorsey and Judith J. Watson. "Solar Power Satellite Development: Advances in Modularity and Mechanical Systems." ***Online Journal of Space Communication*****. Issue 16. Space Segment. Fig. 2. https://spacejournal.ohio.edu/issue16/belvin.html**

2.1.1 USING SPS TO RESPOND TO GRID FAILURE

Emerging SPS technology could be targeted to certain areas using a portable rectenna that could be transported in a C-5 aircraft and set up on the ground to collect solar power and deliver it to the local grid. For example, Puerto Rico's catastrophic grid failure after Hurricane Maria would have made a great test case for SPS, which would have been able to provide substantial electricity to the island within a few days after the hurricane. But any grid failure anywhere could be temporarily overcome through the same means.

2.2 MINING ASTEROID RESOURCES

Although asteroids are farther from Earth than the lunar surface,[5] they require less energy to access, and a simpler transportation system, since they need no specialized surface-to-orbit transportation capability. Because they operate in microgravity, the mining machinery needs no structure to support itself—a distinct advantage. Both locations have essentially equal vacuum and extreme cold environments to contend with. Likely the first to be mined, near-Earth asteroids have similar solar-energy influxes to Earth, and the power for mining can be collected with the same kind of apparatus used in Earth orbit.

Potential asteroid resources can be divided into three categories in economic terms. These categories follow closely the scientific classification of asteroids but are not identical. All categories are somewhere between valuable and highly valuable in space because the potential for space manufacturing and infrastructure depends on getting resources to space, many of which are heavy or volatile to transport. Thus, for the vast majority of asteroid resources, it's their location in space to begin with, as well as their composition, that makes them valuable in space.

Valuable in space, valuable on Earth: Platinum-group metals (gold, silver, platinum, palladium) are the principal example of this. This is the only category that competes economically with Earth-derived counterparts. Their value depends on the cost of activity in space to mine and transport them and the distance to retrieve them, compared to the fluctuating supply of them on Earth.

Another example is rare Earth elements (REEs). REEs are exotic elements—the lanthanides, plus yttrium and scandium, 17 elements in all—that have become important in the manufacture of electronics, particularly lasers, chips and the new generations of high performance batteries needed for electric vehicles. Such use makes their secure sourcing strategic to both national defense and national economic competitiveness.

As their name indicates, the high-grade ores from them are rare, at least in sufficiently dense quantities to mine. Because they are atomically similar and formed by the same geological process, the process that produces them typically creates a range of several different REEs mixed together. Thus they seldom occur in concentrations of a single

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[5] Because of the consequent costs of travel time and schedule inflexibility due to constraints of orbital window.

element. Typically, they occur as a mixture of REEs bound up in varying concentrations in other ores, and found in exploitable quantities in only one or two spots on Earth. Unlike platinum-group and industrial metals, they are not exchange traded, but rather sold in private sales of discrete amounts of ores, with varying concentrations of different REEs. Thus, it is difficult to price either current REE amounts, or speculate about future values.

The U.S. has shut down its REE mines due to environmental concerns, exemplifying the role of environmental impact externalities in the continuing search for mineral resources. Currently, the People's Republic of China controls the sale of 95% of REEs, limiting exports to foreign users to favor Chinese manufacturers.[6] The deliberate Chinese manipulation of the global REEs markets is leading U.S. industries and defense planners to encourage the development of alternative sources of REEs, such as a California mine that Chinese price competition had shut down in the 1980s.[7] Also, reliable U.S. allies, such as Canada and Australia, are developing their own sources. Additionally, Japan has recently discovered very large deposits of REEs in shallow offshore seabed areas, which appear to be equivalent to China's reserves in quantity. The cost of seabed recovery in offshore waters may well be more than asteroid mining, however, and seabed mining would most likely have greater environmental impacts.[8]

The strategic importance of a secure REE supply demands more scouting of asteroid and lunar resources of these elements to determine location, concentration and accessibility of REEs-bearing ores. Once found, they need only compete with Earth sources to gain market support. Additionally, extraterrestrial sources preclude the environmental costs of mining activities, such as Chinese REE mining activities, which have raised international concern and may begin to affect pricing even of PRC-sourced REEs, if they are forced to price the externalities created by terrestrial REE mining.[9]

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[6] U.S. Geological Survey. "China's Rare Earth Industry." journalistsresource.org.

[7] "Rare Earth Elements in National Defense: Background, Oversight Issues, and Options for Congress." Congressional Research Service. March 31, 2011.

[8] University of Tokyo. "Discovery of Rare Earths Around Minami-Torishima." https://www.u-tokyo.ac.jp/focus/en/articles/a_00145.html

[9] Ali, Saleem H. "Social and Environmental Impact of the Rare Earth Industries.". Resources. 3 (1). Feb. 13, 2014. 123–134. doi:10.3390/resources3010123.

Valuable in space, possibly valuable on Earth: Aluminum and titanium from lunar sources, as well as ferrous metals such as nickel-iron, would fall into this category. Their competitiveness with terrestrial supplies will depend heavily on the costs of obtaining, refining and delivering them to Earth users, relative to terrestrial sources. However, their value as a structural material in space is unquestioned, even at a very early stage.[10]

Not valuable on Earth, highly valuable in space: The most immediate and proven resource is water, and its constituent elements of hydrogen and oxygen. This provides not only water necessary for human sustenance and radiation shielding mass[11] in space, but also hydrogen and oxygen, both valuable as spaceship propellants and in manufacture, without the need to transport them there, which is both costly and difficult. Frozen water, which can be thawed via solar power, is available on asteroids and the Moon, allowing for several points of availability, without having to overcome Earth's gravity to haul water—a relatively heavy substance—into space. Close behind water will be carbon and other chemicals obtained from the carbonaceous chondrite asteroids. Table 1 anticipates timelines for such endeavors, taking into account the time necessary for the required infrastructure to be in place.

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[10] Guerrieri, Mary L., John S. Lewis and Mildred Shapley Matthews (editors). 1993, *Resources of Near-Earth Space*, University of Arizona Press, 1993. ISBN 978-0-8165-1404-5

[11] The high levels of cosmic radiation in space beyond low Earth orbit will likely require any human-inhabited artifact, including ships and habitats, to have massive shielding to protect against exposure. The good news is that anything that is heavy, and not itself radioactive, can be used for such shielding. Water and planetary surface material—"regolith"—are two such materials, and even in space they are cheap as dirt, so to speak—that is, provided they are obtained from asteroids or low-gravity bodies such as the Moon.

TABLE 1: ACCESSING ASTEROID AND LUNAR RESOURCES

ECONOMIC CLASSES	EXAMPLES	USES	VALUE	NEED TO ACCESS	TIME HORIZON
1 Valuable in Space, Valuable on Earth	Platinum group metals, REEs	Precious metals, catalysts, electronic parts	Platinum = \$800/oz. Palladium = \$1,398.50/oz.	Low cost to LEO/fuel depot Asteroid mining techniques Low cost return to Earth	10 to 20 years
2 Valuable in Space, Possibly Valuable on Earth	Ferrous metals	Structural material	Cost of launch/ return and Cost of return	Low cost to LEO/fuel depot Asteroid mining / refining / costing On orbit structural assembly	15 to 20 years
3 Not Valuable on Earth, Valuable in Space	H_2O H_2 <—> O_2 Carbon Organic materials	Shielding (as H_2O) Propellant as H_2, O_2 Consumable chemicals, agriculture	Cost of launch—currently \$5,000/lb. LEO	Low cost to LEO/fuel depot Asteroid capture / water extraction	5 to 10 years (H_2O)

NOTE: Cost fluctuates daily. These costs are for 2-8-2019.

2.3

KEEPING THE BLUE PLANET GREEN

Not only would asteroid and lunar mining increase our access to resources, it would also reduce Earth-based mining, which is often environmentally disruptive and hazardous. From soil erosion to destruction of habitat to compromised well water, mining imposes many environmental costs. Transferring the activity to airless, lifeless places would remove that much disruption from environmentally sensitive Earth locations. The more environmental costs are accurately captured in the price of resources, the sooner space resources will be cost-competitive with them.

Some types of manufacturing have high environmental impact, releasing toxic heavy metals and/or problematic chemicals into the surface environment and contaminating water supplies. If these activities can be done in space, their hazards need never even enter

Earth's atmosphere. Plus, raw materials needed for manufacturing in space need not be hauled there when they can be collected in space. With the greatest difficulty about space travel being the overcoming of Earth's gravity when hauling heavy payloads, this can make for smaller, lighter space transport using less Earth-derived fuel.

Moreover, potential environmental hazards have limited some kinds of scientific inquiry (e.g., biological experiments, work with viruses, etc.) or have required extreme and expensive measures (e.g., Hadron collider) to ensure global safety. Space-isolated research provides an opportunity for scientific inquiry that cannot be considered on Earth.

2.3.1 SPACE-ISOLATED RESEARCH

The next likely prospect for space experimentation is energy-related and/or physical science experiments, particularly those that either require very large energy inputs, and/or have the potential for very large releases of energy. Advanced fusion experiments with the potential for large unplanned energy releases might also be done in deep space or on the Moon.

An "air gap" between computers and the internet is considered good security for certain purposes; similarly, a "vacuum gap" between such experiments and the bulk of humanity might be a reasonable precaution, or at a minimum a means of quelling public concerns, justified or otherwise, that might arise in such events. Such sequestration is provided by deep space or the Moon.

The lunar surface is the optimal location for such experimentation in the near term, assuming a basic space infrastructure and an initial lunar transport and base facility is built. With no atmosphere and already-existing radiation, it's ideally suited to experimentation and is perfect for isolating biological research specimens. The marginal cost of establishing an isolated experimental facility, which would not have to be fully self-sufficient, at some distance from the main base would be much cheaper than paying for an entire facility in some other location. The lunar surface offers the advantages of either an exposed location open to the vacuum and cold of space, and/or an underground facility, which might be preferable for some energy or physics experiments, and which would allow the lunar mass to help contain any unplanned releases of energy. Also, unlike a satellite in orbit or an asteroid on a near-Earth trajectory, there is zero chance of the facility being accidentally or deliberately de-orbited or diverted to strike or land on the Earth. To coin a phrase, what happens on the Moon stays on the Moon.

Some may argue that taking Earth's hazardous industries to space merely transplants our problems rather than fixing them. However, global solutions to Earth's challenges, especially environmental ones, are highly constrained when limited to the planet's surface, and must be continually weighed against human welfare—especially in developing nations. Using the entire solar system seems in general more apt to result in a cleaner and safer Earth environment.

2.4 REMOVING/REPURPOSING SPACE DEBRIS

Our increasing use of satellites and spaceships has left more than 170 million pieces of dangerous debris hurtling through near-Earth space at velocities that create hazards for our current use of satellites and further use of and travel in space. At the typical high collision closing speeds experienced in orbital debris collisions, a dime-sized piece of metal can destroy a space vessel's hull or satellites that we depend on for navigation, communications and defense. Developing the infrastructure to enable debris capture or removal disposes of these hazardous missiles, keeping our current use of space safe and increasing the chances that global participants will take care of their extra-terrestrial housekeeping duties as well. This capability would also allow us to distinguish between trash in need of removal and items useful for their location in space.

For example, an unfortunate side-effect of space launch is discarded upper stages of rockets and other large debris. A technology under development currently is robotic in-space recycling/repurposing of such discarded material. Several private companies' efforts are underway to address this most massive source of "space junk." For example, Nanoracks is partnering with the private United Launch Alliance (ULA) to incorporate the stages into space habitation plans, as the same tanks that once held propellant can also store atmosphere. Made In Space and Tethers Unlimited both have plans to upcycle parts from the stages as construction material for large, low-density space structures such as large aperture antennas or as supports for large solar arrays. This is likely to be the first source of "raw material" in space that is cheaper than launching payloads from Earth, and will pave the way for larger-scale material supply from lunar or asteroid sources by establishing a price-point and an identifiable demand for material, and the first services for making useful parts out of raw material in space.

In the long run, this is the kind of activity that will address a significant part of the orbital debris problem. By putting some sort of price, even if a low one, on the value of a spent stage, it becomes possible to consider the business plan of collecting older spent stages (the biggest source of "space junk" mass) for the scrap value. Disassembling these jettisoned parts and using their material to construct larger antennas or support structures, as current companies propose to do, effects a long-term solution to space debris through its "junk value."

The more we become comfortable remaining and working in Earth orbit and beyond, the more we will stop viewing obsolete or used-up assets in space as mere liabilities to be thrown out or burnt up, and start using them as assets in space that can be re-purposed or recycled, even to the point of finding a use for the International Space Station when its current function is superseded by new facilities. Such capability is likely to precede lunar or asteroid mining.

2.5 THE RIPPLE EFFECTS OF TECHNOLOGY

So far we've discussed direct, foreseeable potential, but developing a new frontier can be assumed to have greater benefits than we can anticipate. This is the nature of technology, whereby a rather mundane discovery can be world-shattering in its ramifications.

In electronics, for instance, integrated circuits made of germanium leapt technology forward; the simple replacement of the germanium chip with a silicon chip, and the cascade of innovation it spurred, ushered in a whole new and unanticipated age at least as momentous as the Industrial Revolution. Likewise, discovering raw material in space, as well as harnessing space's unique physical properties, can be expected to propel technology and quality of life forward in ways we cannot now predict. It's possible that microgravity alone could enable the formulation of valuable medicines or other substances we simply cannot make on Earth. For example, even with the limitations of our current space program, entrepreneurs are currently partnering with the International Space Station (ISS) and zero-G aircraft to make special optical fibers,[12] 3D printing projects and zero-gravity annealed silicon carbide wafers[13]—taking advantage of space's physical properties to create new products. Also, a scarce Earth mineral suddenly provided in abundance from

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[12] "Optical Fiber Production in Microgravity (Made In Space Fiber Optics)." May 9, 2018. https://www.nasa.gov/mission_pages/station/research/experiments/2421.html;

[13] "ACME Advanced Materials Produces Commercial SiC Wafers in Microgravity." http://www.a2-m.com/acme-advanced-materials-produces-commercial-sic-wafers-in-microgravity/

space would spur its use in ways we would never consider now due to the high price of scarce terrestrial resources.

Large-scale technological innovation, such as silicon chips, electricity, industrialization, navigational aids, etc. have revolutionized the ordinary person’s life way beyond what could be anticipated beforehand. Throughout history this has proven to be such a consistent characteristic of technology that unanticipated gains—or at least a tip-of-the-iceberg assumption—should be applied to the calculus of anticipated gains. This is especially true for transportation, as advancement means access to new places that bring their own panoply of benefits. Space transportation means access to not only space itself but planets and other bodies, each with its own cache of resources and properties.

The resources (energy, raw materials, physical properties and environmental potential) in space that we can currently quantify argue for a move from mere exploration to harnessing identified assets in space. Historically, this has involved a shift in governmental role, from (in early stages) the provider or subsidizer of goods and services to provider of infrastructure and governance, allowing for the private sector to identify and extract or harness the resources/capabilities that allow the free market to sustain the industry. In the space arena, government has retained its role of initial provider far longer than in most other fields, so this transition is particularly overdue.

PART 3

FROM EXPLORATION TO COMMERCIALIZATION

We have honed best practices for the evolution from exploration to commerce in our treatment of other frontiers. Historical experience demonstrates two distinct paradigms and the technologies that evolved to bridge them.

3.1 FRONTIER: THE AMERICAN WEST

Exploration: At the behest of President Thomas Jefferson and with funding by Congress, Meriwether Lewis and William Clark began the exploration of the Louisiana Purchase and the West, documenting their travels and findings. This ushered in a series of government-financed expeditions, mostly military, finding practical routes west, and mapping and documenting them. Based on the potential their observations conveyed, pioneers made treacherous journeys in self-sustaining covered wagons in what effectively experimented with useful purpose of the new territory. From gold discovery to agricultural potential to sea-trade opportunities, early pioneers confirmed that the West held great promise for the nation and its economy. Even if only covered wagons headed west initially, tapping the potential of the new land demanded the transportation infrastructure necessary to integrate it into the national economy.

Commercialization: It was only after transportation infrastructure was applied—when the network of railroads (and later, with the invention of the automobile, highways) allowed for frequent, safe, affordable transportation of people and goods—that commerce spurred the economic boom provided by the new frontier. The commercialization of the West expanded the U.S. economy exponentially, amassing new wealth and commerce for the entire nation. Using the newly available transportation infrastructure, the U.S. Geological Survey mapped the new territory and identified locations for the harvest of natural resources. While early settlers brought their necessities with them, eventual development of the West, from mining to manufacturing, provided local goods for later generations without having to send back to eastern sources for essential goods. The ease of transportation allowed for military use as well, making the new land defensible and its location strategically valuable.

3.2

FRONTIER: THE SEAS

Exploration: In the 15th and 16th centuries, growing trade led to technological breakthroughs in ship-building and navigation.[14] Funded by rich monarchs, the first ships set sail on their treacherous journeys to explore other continents and peoples. As demand for the new resources rose, trade began, but only as luxuries, initially for the very wealthy.[15] Journeys were expensive, extremely perilous and difficult, and thus the gains returned reflected that high cost.[16]

Commercialization: As more ships arrived off of undeveloped coastlines such as the Americas, or Australia, newly established port settlements rapidly developed capabilities for resupply of consumables, like food, rope and tar from local resources, so that ships need not carry all their necessities for the return trip, making more room for commercial cargo. This allowed ship design to advance to favor smaller, nimbler craft, where more room could be used to carry profitable goods, which developed into a thriving trade economy that

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[14] Hugill, Peter J. *World Trade Since 1431*. Johns Hopkins University Press, 1995.

[15] Ibid.

[16] Ibid.

pressed for even more technological advancement.[17] Trade became more frequent and therefore cheaper, and cheaper and therefore more frequent, ushering in a virtuous cycle. Private shipping flourished, providing not only a basis for trade but also a mastery of the seas that translated to a more robust naval defense, an unanticipated boon for nations due to the advancements produced by private commerce.[18]

But in terms of direct participation in commerce by ordinary people, it took the transformative technological advancement of the shipping container to drastically reduce costs, enabling an intermodal transport system that allowed for a better quality of life for everyone. The shipping container, which could be loaded from ship to railcar to truck, single-handedly commercialized international trade. Although its antecedents date as far back as the late 18th century, it came into widespread use after WWII when the shipping, railroad and trucking industries redesigned their vehicles to accommodate these standardized containers. This allowed for secure, safe and cheap transport of goods, leading to the post-war international trade boom and the globalized world economy of today.

3.3 HISTORY AS TEMPLATE

These historical examples demonstrate that the exploration paradigm has the following characteristics:

- Customized, self-sufficient individual expeditions into a wilderness, typically funded by wealthy governments and characterized by wide-ranging informational goals.
- Infrequent journeys made complex and unwieldy by the need for self-sustainment and the wide range of goals.
- Dangerous, difficult and enormously expensive journeys due to many factors, including the need for customization and self-sufficiency.

Once exploration identifies assets worth capitalizing, and governments adopt a focus on providing infrastructure to stimulate private sector use, the paradigm changes to foster rapid technological advancement and development of frontiers. Unlike the previous

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[17] Ibid.

[18] Rodger, N.A.M. *Command of the Ocean: A Naval History of Britain 1649-1815*. Norton, 2005; Levinson, Marc. *The Box: How the Shipping Container Made the World Smaller and the World Economy Bigger*. Princeton University Press, 2006.

historical examples, currently the private sector has already recognized that commercial space transport is a “when” rather than “if” scenario, and has anticipated commercialization. Multiple private companies are working on different approaches with different degrees of reusability. Some are established entrants in the market,[19] with dozens of successful flights for reusable vehicles and a long heritage of successful space vehicle design. This signals that we are due, indeed overdue, for commercialization. In space, we are past the purely exploration stage and thus it is time for institutional change.

3.4

CASE IN POINT: SATELLITE TECHNOLOGY IN LOW-EARTH ORBIT (LEO)—COMMERCIALIZING NEAR-EARTH SPACE

Having identified the vast potential for LEO operations through space exploration, the Soviet Union put the first satellite into orbit (Sputnik 1) in 1957, soon followed by the U.S.’ Explorer 1, ushering in a government-funded “race for space.” With government encouragement, AT&T launched a successful experimental communications satellite, Telstar, in 1963. Soon afterwards, the U.S. funded the monopoly corporation Comsat, followed by the international Intelsat monopoly. This merely moved the activity from one monopoly to another.

When the Nixon administration opened the field to competitive enterprise, private space architecture began with entrepreneur-founded PanAmSat. In the private sector, time is money, ensuring that applications of technology advance rapidly. Eventually, private satellite operators sought out private launch providers who could provide cheaper, more-flexible launches. In this way, we’ve already succeeded, to a limited degree, in commercializing space, primarily through introducing market discipline into a field previously run by monopoly technocrats who were insensitive to market considerations.

Monopoly vs Market: One Engineer’s Experience

A chief engineer of a competitive communications satellite company recounted a presentation made by a satellite construction company that previously had only worked for government and monopoly customers. The company proudly presented its new station-keeping device for satellites, which was indeed a technical improvement, potentially extending the on-orbit life of

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[19] SpaceX and ULA, for two examples. Although it has only launched suborbital reusable rockets to date, Blue Origin’s highly credible team and solid funding are likely to make it competitive in reusable orbital transportation in the future.

the satellite considerably, but also significantly more complex and obviously requiring more expensive construction techniques. The chief engineer asked the company for the cost-benefit analysis showing why it was a better choice than using the simpler, slightly less effective, but considerably cheaper prior technology, particularly given that the life of the satellite on orbit was also limited by other independent factors, and operators liked to replace satellites frequently with larger-capacity models. Not only had the company never performed such a study for its government and monopoly customers, but it had never been asked for such a thing; apparently no government or monopoly customer had ever expected such.[20]

The ending of NASA-operated, Shuttle-provided launch for private customers and the transition to private satellite launch by the U.S. in 1986 brought immediate benefits. Although the first private launches were of the same contractor-developed launchers produced with NASA and the Air Force, prices started to fall because the government procurement paperwork, a significant cost item, could be dropped. A European state-subsidized launcher[21] also brought competitive pressure, as did the entry of Russian and Chinese launchers into commercial service after the Cold War.

By the mid-1990s, the global launch field began to look something like a market. The advent of remote sensing (the imagining of the Earth by satellite, whether by photography, radar, or other spectra) via private operation through the launch of the SPOT 1 satellite[22] led to the spinning out to the private sector of the Spot Image Corporation.[23] Satellite imaging and telecommunications have both flourished under competitive private operation, allowing us to view and map our planet from afar and navigate more precisely, and triggering a proliferation of communications technology that now connects the world. Although the French opened the field up to the private sector first, the U.S. caught up and surpassed them by eventually going to a more competitive model.

Satellite telecommunications, initially used merely to improve existing modes of communication, gradually began to exploit the unique capabilities of space to offer new modes of communication. The revolutionary Iridium system, which connected phones via satellite relay without ever switching the call through an Earth station, allowed for calls to

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[20] Discussion with author Bennett. Approx. 1994.

[21] The national champion Ariane.

[22] Originally by the French space agency, CNES.

[23] Which is now part of EADS-Astrium, the European space conglomerate.

any spot on Earth, from pole to pole.[24] While some governments refused to abide communications that circumvented government eavesdropping, leading the company to bankruptcy, the Iridium system did serve to demonstrate the power of universal connectivity.[25] For example, commercially available satellite technology ensured that, for the first time, the Soviet government was unable to hide an embarrassing truth—the Chernobyl nuclear accident—from public knowledge, since Western media could buy SPOT imagery showing clearly that the Chernobyl containment vessel had been breached.[26]

Almost all satellite communication from the beginning of the Comsat and Intelsat systems have used geosynchronous orbit (GEO) satellites as fixed relays high in the sky, 22,300 miles above the equator. GEO satellites require more power and bigger antennas, but occupy a fixed location in the sky, allowing a simple fixed dish to send and receive the signal. This is why satellite TV dishes, which use GEO satellites, point toward the equator; the higher the latitude, the smaller the angle will be between the beam and the ground. Near the equator, the dishes point straight up; in Alaska, the dishes are aimed almost at the southern horizon.

LEO satellites, on the other hand, require low power and small antennas. Today's very small satellites can use primarily ordinary electronic components, allowing for a profitable enterprise such as SiriusXM satellite radio to flourish. Low cost means large numbers are feasible—SpaceX's constellation now under development looks to nearly 5,000 satellites in its first configuration, rising to 7,500 and ultimately 10,000. Such numbers allow genuine assembly-line production with all its attendant cost saving, creating a virtuous cycle.

As a result, using low-Earth orbit's unique physical properties for satellites has only just begun. Sparked by these technology and production advances, as well as our increasingly affordable launch capability, transparency and connectivity are poised for rapid and revolutionary transformation. Swarms of cheap, low-altitude[27] communications relays will permit small, cheap mobile phones to connect seamlessly with voice, data and vision from any spot on the Earth's surface, and similarly allow broadband connections for larger devices.

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[24] Bloom, John. *The Eccentric Orbits: The Iridium Story*. Atlantic Monthly Press, 2016.

[25] Ibid.

[26] "Astrium GEO Info Looks Back on the Chernobyl Disaster 25 Years Later with EO Technologies." *Space Daily*. April 18, 2011. http://www.spacedaily.com/reports/Astrium_GEO_Info_Services_Looks_Back_On_The_Chernobyl_Disaster_25_Years_Later_With_EO_Technologies_999.html.

[27] Under 200 miles of altitude.

This will accelerate the live-anywhere, work-from-anywhere trend already in process, making smaller and more remote areas—currently cheap real estate—more competitive as living areas.[28] Similarly, it will accelerate the global information economy for large parts of the developing world, especially as English-language proficiency is passing from an elite marker to an economic enabler for the general populations in areas such as India and Africa.

Similarly, swarms of cheap satellites in LEO (some of which might be dual-purpose satellites serving communications and imaging functions alike) can deliver high-resolution imagery, comparable to aircraft photography, in many different spectra—visible, infrared and radar—of any spot on Earth on a continuous 24/7 manner.[29] This generates a vast stream of economically valuable information to economic actors globally, and will likely be combined seamlessly with drone imagery to provide affordable data in detail not previously available. For instance:

- Farmers can monitor the effectiveness of irrigation through imagery of soil and leaf color, allowing small adjustments of water delivery tailored to very small areas, perhaps to individual plants.
- Fishing boats can take delivery of ocean surface color data, changes in which can guide them to fish stocks more efficiently.
- Wildlife preserves can be monitored in a finely grained way for habitat destruction and poaching.
- Security monitoring of remote areas can be delivered cost-effectively, combatting vandalism and misuse. [30]

Furthermore, the value of these and similar services must be understood in the context of contemporary software and its ability to use “Big Data” in ways well beyond past uses. The proliferation and saturation of data collection in and around Earth (and ultimately, the solar system) is an integral part of a seamless universe of high-value data about the world and everything in it that can be analyzed in a new and far more intense manner.

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[28] Bennett, James C. and Michael J. Lotus. *America 3.0*. Encounter Books, 2013.

[29] Duffy, Linda. “Small Satellites a Big Deal for Remote Sensing GeoDataPoint.” Geodatapoint Online. October 18, 2017. https://www.pobonline.com/articles/101139-small-satellites-a-big-deal-for-remote-sensing

[30] “100 Earth-Shattering Remote Sensing Applications and Uses.” *GIS Geography*. November 25, 2018. https://gisgeography.com/100-earth-remote-sensing-applications-uses/

While the new low-cost satellite companies are currently focusing on LEO, a revolution in the economic use of GEO is not far behind. Currently, the U.S. government is funding a public-private partnership to demonstrate robotic servicing and fueling of satellite platforms in GEO. Once that capability is established, GEO satellites become long-lasting platforms (essentially 26,000-mile-tall cell towers) to which companies can add antennas, power and transponders to serve a variety of markets.

Triggered by the private sector's ability to lower the cost to manufacture, launch and operate satellites, space imagery and connectivity will be an essential and omnipresent part of a seamless web of sensing and communication. Such an outcome will transform the conduct of everyday life, particularly in developing nations and isolated areas, accelerating current trends in widespread mobile telephony and commercial space imagery. This is a "when" rather than "if" situation, and the question remains which nation will position itself as the global leader. Table 2 shows our current satellite and remote-sensing capability, potential new uses, and what we need to achieve to attain that new capability. The near-term economic goal is reducing the price of launch to low-earth orbit to around $1000 per pound—a price that will generate significant private economic interest.

TABLE 2: SATELLITE AND MANUFACTURING POTENTIAL FOR COMMERCIAL SPACE-BASED INDUSTRY

	CURRENT USES	POTENTIAL NEW USES	REQUIREMENTS FOR NEW USES	AT MARKET PRICE OF $1K/LB/LEO WE CAN HAVE THESE
1) Telecommunications	High-priced GEO-based relay and broadcast	Mobile telephone constellation Global web for cheap data to rural areas	Cheap launch to LEO Cheap satellites	Constellation of LEO relays Cheap data
2) Remote Sensing	0.5 meter resolution Limited number of satellites Expansive data sets	Worldwide hi-res sensing of Earth Replacing air- and ground-gathered data for many apps	Cheap launch to LEO Cheap satellites	Swarm of sensors in LEO generating very cheap data stream
3) Space Manufacturing	Experiments on ISS	All uses are new	Cheap LEO launch Orbital free flyers*	Earth-sourced materials manufacturing possible for specialized uses

*** "Orbital free flyers" are other orbital facilities that are nearby and in the same orbits, and thus can quickly and easily be reached by cheap transfer craft**

3.5

ECONOMICS AND THE MARKET PRICE OF LAUNCH

The benchmark of commerce is when the cost of an activity or good decreases to the price the market will pay. Market price cannot be foretold or calculated reliably by experts, but can be discovered empirically through markets. Thus, reducing the costs of space travel so as to continue sending Americans into space means designing pilot programs that get new ideas into business hands to arrive at a market price. Due to its historical anomaly of growing out of a Cold War demonstration project for national security purposes, the "default" has been for space travel to be "priceless"—so expensive that no one but government can do it, keeping launch rare and exorbitant. Launches were so expensive as to be "priceless" for most of our history.

When the money spent on space does not pay for itself in commerce, it remains interesting but not terribly useful. Without a system, launches become infrequent because they are expensive, and expensive because they are infrequent, trapping space development in a vicious cycle. It was not until LEO launch transportation acquired a price, however high, that commercial service costs could be considered in a market context. Let's examine the numbers to understand how we got to where we are now and how we can, for the same amount we spend on NASA now, change our approach to develop and benefit from the assets of space.

3.6

WHAT WOULD SPACE INFRASTRUCTURE LOOK LIKE?

Making productive use of identified resources in space requires enough infrastructure to allow for mining, construction and manufacturing, as well as other activities. Any anticipated costs must assume that such infrastructure is there already. Realizing the efficiencies analogous to that of the railroads and shipping industries will require the following support for space vessels:

- Fuel depots (essentially gas stations) in appropriate orbits
- Fuel (from water) and water itself[31]

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[31] There's considerable debate on the best location and business model for space-harvested propellant. For example, LOX/LH2 (liquid oxygen/liquid hydrogen) might not be practical in LEO because of the difficulty of refrigerating LH2 while being heated by infrared light reflected from the Earth; also, there are many LEO orbits to be serviced. Various companies have offered diverse proposals, but it is possible that this will be an early economic use for a "cislunar" (lying between the Moon and the Earth) depot, because from there a tug can pick up a satellite in LEO, ferry it to GEO, and return to base without ever having to store propellant in LEO or deal with the many LEO orbits. To explore the many

- Shuttle for travel to lunar surface
- Lunar facilities, for resupply and for water and aluminum mining for construction in space
- Orbital facility complex

The most essential infrastructure on which to found an alternative paradigm consists of a multipurpose facility (or swarm of co-orbital facilities) in LEO.[32] In addition to this, a fueling depot, and eventually multiple locations, would accept water from any economically feasible source. A location at one of the Earth-Moon's five "Lagrange points"[33]—called L1 through L5— such as L1 (balanced between Earth's gravity and the Moon's, providing for stationary storage facilities), would permit easy access to and from many desirable locations. At first, water could be supplied from Earth. Later, as capabilities come on line, it could come from lunar polar ice deposits and/or asteroid sources. Solar power would disassociate the water into its components, hydrogen and oxygen, for fuel for transport from LEO to GEO for communications satellite purposes, and for missions to lunar and deep space, such as for asteroid mining, and Mars and other destinations. The water would also form a convenient material for radiation shielding mass.

While research on the effect of radiation on the human body is likely to remain a NASA responsibility, conclusions reached will inform the commercial sector on which approaches can be used for human-based space industry. In this way, commercialization creates the need for research, and research findings stimulate the commercial sector to innovate the most productive and cost-effective approaches.

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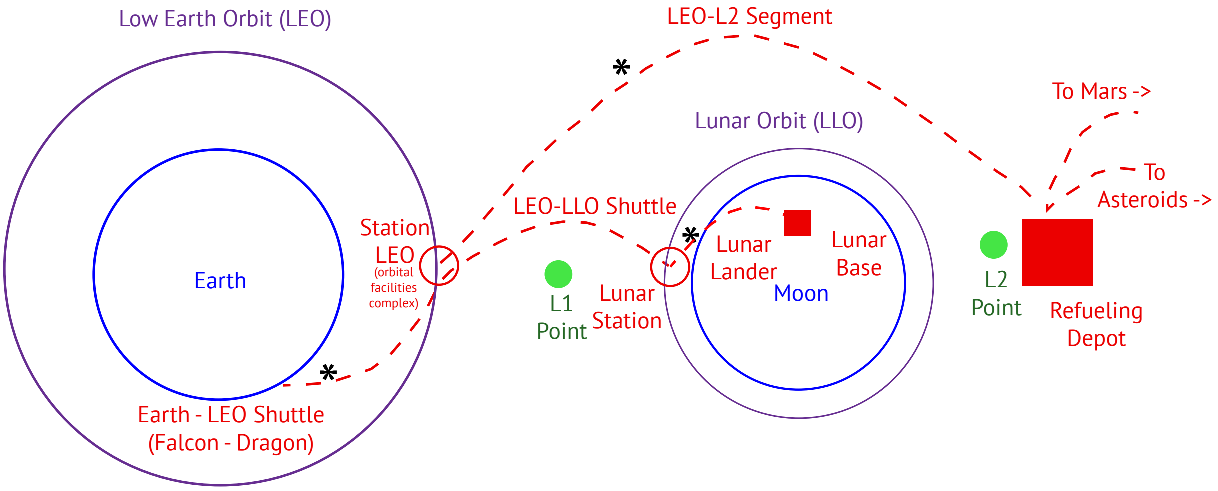
diverse and innovative possibilities in this emerging technology, it's best to allow for the most design freedom through private enterprise rather than centralized government endeavor.

[32] An equatorial LEO would avoid the higher radiation environment of the South Atlantic Anomaly, an important consideration if the facility is to be human-managed.

[33] In any system of substantial celestial bodies close enough for their gravities to interact to a significant degree, there are five points, known as "Lagrange points" (after the astronomer Joseph-Louis Lagrange, who discovered them). The first point in the Earth-Moon system, "L1" is where the Earth's gravity and the Moon's gravity are in balance, so that an object placed there would remain there. It would be a good place for certain infrastructure serving Earth-Moon transportation. L2, beyond the Moon, would be a good place for a propellant depot serving inner solar system transport. The Earth-Moon L4 and L5 points, which lie in front of and behind Earth in its orbit, have been discussed as locations for permanent space habitats.

For example, establishing further orbital stations in LEO (replacing or complementing the already-existing International Space Station) would lay the infrastructure for the private sector to develop regular transport to the Moon and back, consisting of a LEO-to-lunar-orbit shuttle craft, and a lunar-orbit-to-Moon surface lander and return vehicle. This would permit the construction and utilization of lunar surface facilities, including lunar-polar ice mining at the lunar south pole, lunar scientific research facilities, and, at later stages, mining of lunar soil for aluminum and oxygen.

FIGURE 2: SCHEMATIC OF BASIC SPACE INFRASTRUCTURE



Note: Schematic not to scale. *Not actual trajectories

In parallel, the orbital facility complex would serve as a base for asteroid mining operations and processing of the resources returned by those missions (see Figure 2). As extraterrestrial resources become available, the orbital facilities could begin to serve as construction facilities for large space structures, such as solar power satellites (SPS) for space and/or terrestrial uses, rotating space habitats (to provide artificial gravity) to expand the available human living space in orbit. These ships will likely be space habitats themselves, capable of accommodating people comfortably for eight-month missions. Without lunar aluminum or asteroid nickel-steel for structure, and lunar or asteroid water for shielding, fuel, and human consumption, such vessels will likely never be built.

Ambitious as these goals may sound, the technology to realize them requires no fundamental breakthroughs—just applied engineering. The first useful versions of these facilities are achievable as a 10-to-20-year goal within the current NASA budget, if it is used to leverage private investment. Like all infrastructure, it requires not only original construction, but also operation and maintenance, and legal oversight. But managing these overarching responsibilities—steering, rather than rowing—is a more suitable role for government than being direct participants in a market-driven industry.

Practical use of space will be driven by private sector technology for the purpose of commerce, as demonstrated by the global satellite market. This is because the private sector operates on potential, and then actual, financial reward. The need for endeavors to pay for themselves drives system-wide efficiencies that reduce costs as much as possible. Just as laying the railroads to the West eventually led to standardized railcars with standardized interoperable couplers and brake hoses that were interchangeable on any railroad throughout the continent, and later the shipping industry drove global transport to accommodate standardized shipping containers, so we can expect space infrastructure to drive increasingly efficient, cheap and frequent launch in standardized, reusable vessels.

PART 4

U.S. SPACE TRAVEL ON THE CURRENT AND NEW PARADIGMS

4.1

THE CURRENT STRUCTURE AND HOW WE GOT HERE

Many writers addressing the commercial space question consider the task of transportation from Earth to orbit fundamentally easy, and that governmental space agencies are filled with obtuse people who simply ignore the logical way to approach the task. All one needs to do, according to their narrative, is to turn it over to the private sector, who would hire smarter people to do it by the smarter way, which is obvious.

This narrative is highly misleading. To begin with, although the task is conceptually simple, its implementation has required enormous work by several armies of highly intelligent, well-educated and well-trained people in Germany, the U.S., Russia, and elsewhere. Many rockets were blown up in the process, and all of the basic techniques now forming the handbook of launch vehicle engineering were developed by painstaking trial and error. Almost all of these people, for the first half-century of organized effort, were government employees or contractors. The taxpayers of these and other nations have foregone many alternative uses of their funds in order that their governments could afford this work.

The knowledge from this enormous effort is now contained in engineering textbooks and curricula, and in the brains of engineering faculties and in the workforces of space agencies and aerospace companies. Starting with a few pioneering efforts in the 1980s and 1990s, private companies are now proliferating into an entire industry. They have harvested this expertise and applied it to a new set of projects, freed from the constraints of the political-industrial system that dominated its uses for its first half-century or more. The staffs of these private companies are not smarter than the agency and contractor workforces—in fact, they are for the most part the same people. Nor have their employers been geniuses who suddenly came up with approaches the government agencies were too stupid to develop themselves. For the most part, the innovations the entrepreneurial companies are deploying were first developed in government agencies, and then set aside or never completed as politics led to their abandonment. Many of the innovations now being deployed, like the hybrid engines of Virgin Galactic (first developed by the U.S. Navy in the 1960s), the thrust-braked descent of SpaceX's reusable boosters (heirs of the Lunar Descent Module and the DC-X in the 1990s), or the winged vehicle of Sierra Nevada's Dream Chaser (heir of the Air Force Dyna-Soar), all had their heritage in government agencies' far-sighted projects that were canceled due to politics.

Almost all the approaches used by cutting-edge companies like SpaceX and Blue Origin were well known to aerospace engineers and had been thoroughly discussed in aerospace engineering forums for decades. Furthermore, the decision-makers at the top of the relevant government agencies were for the most part intelligent and experienced engineering managers. It would also be a mistake to make NASA, the Air Force, or the other government agencies in charge of American space launch into villains. The fault lies primarily in the system itself, especially the interplay between Congress, the contractor companies, and the agencies charged with maintaining America's space capabilities.

If there is human fault, it lies in the cumulative consequences of thousands of small decisions made by managers, administrators, and politicians, pressured into decisions they knew at some level were sub-optimal, but in most cases seemed the least bad of available choices within the constraints of the system they had to accept as the condition of working in the space industry. Occasionally the consequences were immediate and drastic, as with the decision to launch the Shuttle Challenger despite the possibility that the booster seals might be weakened by the cold early-morning temperature.

More often it is just a matter of seeing a good program canceled, or seeing a program produce a less good product because politics laid on too many conflicting requirements and/or failed to fund the project adequately. For example, the Shuttle program combined all of these flaws. The loss of Challenger was ultimately the result of managers pressured by politicians to commit to an unrealistic flight rate (the number of Shuttle flights per year) to justify promises that had been made in order to have the program funded at all. The flight rate was, in turn, too ambitious because the vehicle was too complex. That was a consequence of the fact that the Shuttle had stretched the limits of its design and performance to accommodate too many conflicting requirements, undertaken to acquire as many potential users as possible, which it needed to justify its existence.

Even many of the space program measures that ended up having unforeseen and undesirable consequences were introduced with the best of intentions, and seemed at the time to be the best, and often the only, means of solving urgent problems facing the defense aviation and space industries. Cost-plus contracting was the only way to get contractors to attack wildly ambitious development and production efforts, which otherwise would likely have bankrupted them in the midst of wartime or near-war emergencies. However, just as in the case of the trans-continental railroad subsidies, profiteers took advantage of loose wartime administrative systems to pad their pockets, creating embarrassing scandals. So reporting requirements were tightened, and tightened again, until administrative costs skyrocketed, resulting in the famous absurd prices for coffee cups or hammers. Aircraft progress, and then novel space launch requirements, created demands for exotic alloys and degrees of purity never before encountered, requiring documentation of materials sources back in some cases to the ore from which the metal was refined. Some were necessary, others were not, but it was hard to tell which would be which. And all of these measures ran up the cost of hardware.

What is the consequence of the peculiar circumstances under which the system for developing and operating spaceflight evolved? Although, as we have seen, the energy requirements to get people to orbit are substantially greater than sending them on a long (7488 statute miles, in our example) air journey, neither the energy disparity per se, nor the other various operational factors (greater harshness of the environment through which they must operate, the necessity of the spacecraft carrying its oxidizer, etc.) justify the current enormous disparity in price between a ticket from any one point on Earth, however, distant, to any other, and a ticket from Earth to Earth orbit.

Rather, the great bulk of the disparity lies in the structure of the space transport industry as it exists today, and that of the air transport industry. Yet forces are now at work to reduce the disparity, and if these forces are expanded and encouraged by good policy, the disparity can be reduced by very substantial margins, although it will probably never be eliminated. Later sections will discuss what such measures should be, and why, but since our current structure owes much to the unique history of the U.S. space program, it’s first important to understand how and why we got where we are, and what the main players and products are that comprise the past and present U.S. space program.

4.2

EVOLUTION OF THE U.S. SPACE PROGRAM UNDER THE CURRENT PARADIGM

The United States government took no notice of rocketry or space launch technology until the Second World War. An American, Robert Goddard, undertook experimental development supported by a small amount of private foundation funding with liquid-fuel rockets in the prewar period, roughly in parallel with similar Russian and German experimenters. During the war, the German government paid their experimenters large amounts of state funding to develop the Vergeltungswaffe-2 (V-2) short-range ballistic missile, which became the first human object to undertake controlled flight to space, although not to orbit. At the end of the war, the U.S. Army seized numerous V-2 rockets, manufacturing facilities, and research personnel, particularly Chief Researcher Wernher Von Braun, and brought them to the U.S., where they were eventually installed as part of what is now the Army Ballistic Missile Agency (ABMA) at the Redstone Arsenal in Huntsville, Alabama. Although officially charged with developing longer-range ballistic missiles, Von Braun continued to argue for their use as space launchers as well.

In parallel, the U.S. military continued to examine the uses of space launch and satellite technologies. In 1946 Project RAND, a branch of the Douglas Corporation (later to become the RAND Corporation) wrote, under Army contract, a study of satellite technologies entitled “Preliminary Design of an Experimental World-Circling Spaceship” (Report No. SM-11827). This study built on V-2 design approaches to describe a satellite launcher that could deploy a reconnaissance satellite.

For a long time, chronologies of U.S. space activities noted the unclassified 1946 report, but then assumed that the U.S. government lost interest in the topic until Sputnik. Due to the declassification of Cold War-era records, it is now known that the publication of the report was followed by more detailed and highly classified design efforts to create an implementable program to build and place into service a functional satellite reconnaissance capability at the first opportunity.[34]

These design efforts bore fruit, and U.S. launch vehicle development began with President Eisenhower's 1954 decision to approve the RAND Corporation's Project Feedback recommendations to the Air Force, which had become a service independent of the Army in 1948.[35] This project, the successor to the 1946 study, laid out the basic architecture of the original U.S. satellite reconnaissance system, calling for the Air Force to develop a space launch variant of the Atlas intercontinental ballistic missile, then under development, and launch a reconnaissance satellite with it, using a return beam vidicon (RBV) system, (essentially, a television system) for imaging targets on the Earth and returning the signal via television frequencies.[36] The space launch vehicle variant of the Atlas missile first placed a satellite into orbit in November 1958, only months after the first test flight of the ICBM version.[37]

The classified nature of the ambitious U.S. space program of the 1950s created a dilemma for the Eisenhower administration. From the discussions in the declassified Project Feedback report, we now know that the U.S. was deeply concerned that, if the U.S. launched a satellite before the Soviets, the USSR would create a political campaign to oppose satellite overflights of national territories without permission from the overflown nations, as is the case in aviation. The chosen solution was to let the Soviets fly first.

However, when this was accomplished by the USSR in 1957 with the launch of the Sputnik-1 satellite, the Administration was unprepared for the panicked reaction of the U.S. public, who saw it as evidence of Soviet primacy in science and technology. In response, in 1958 the Administration built upon a small research agency known as the National Advisory Committee on Aeronautics (NACA), forming the National Aeronautics and Space Administration (NASA) to create a separate, civilian space program, using selected bits of formerly classified military technologies to achieve quick progress.

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[34] "Project Feedback Summary Report." Lipp, J. E., and Robert M. Salter, Eds. The RAND Corporation. 1954 (Classified until 1992.) https://www.rand.org/pubs/reports/R262z1.html

[35] Ibid.

[36] Ibid.

[37] "Atlas Missile History." Strategic Air Command. http://www.strategic-air-command.com/missiles/Atlas/Atlas-Missile_History.htm

Upon taking office in 1961, President John F. Kennedy sought to identify a highly ambitious, highly visible space project with which the U.S. could visibly demonstrate its technological superiority over the USSR in space. Satellites were spectacular, but the first human in space—the USSR's next planned milestone—was even more spectacular. By that point, only a Moon landing was sufficiently spectacular, yet sufficiently distant in time, to allow the U.S. a good chance of winning.

To achieve this, a step-by-step program began with the Redstone ballistic missile (basically an enhanced V-2) launching the Mercury capsule on a suborbital flight, then launching the Mercury into orbit on a more powerful Atlas, followed by a two-person crew using the Atlas for the Gemini crewed launch vehicle program.[38] Both of these launch vehicles were developed by the military, not NASA—the Army in the case of the Redstone, and the Air Force in the case of Atlas. NASA first entered the launch vehicle development business with the start of the Apollo Moon landing program in 1961, and with the transfer of Wernher Von Braun's engineering team at Redstone Arsenal in Alabama from Army to NASA control.[39] All the major orbital launch vehicle families used by NASA—the Thor (later the Delta), the Atlas, and the Titan—had originally been developed by the Air Force as military missiles.[40] The fledgling NASA shortly thereafter had the bulk of the Army's missile group in Huntsville transferred to its control, now forming the Marshall Space Flight Center (MSFC) where it continues today.

After the successful conclusion of the Apollo program, NASA was left with the powerful, successful, but very expensive Saturn V launch vehicle, oversized for most of the missions NASA was likely to undertake. It therefore abandoned the gradual evolution of its launch vehicle families to build the winged, horizontal-landing, partly reusable Space Transportation System (STS) more commonly known as the Space Shuttle. This vehicle was designed to be quickly refurbished and turned around, avoiding discarding its expensive engines and airframe; through achieving a high utilization ratio, NASA sought to greatly lower the marginal cost of spaceflight.[41]

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[38] "A Brief History of NASA." National Aeronautics and Space Administration. https://history.nasa.gov/factsheet.htm

[39] Ibid.

[40] Ibid.

[41] Lethbridge, Cliff. "History of the Space Shuttle Program." spaceline.org http://www.spaceline.org/rocketsum/shuttle-program.html

It was a bold and mesmerizing vision. However, because it was America's only means of space access, Congress redirected the program to serve all possible customers.[42] The Air Force and the intelligence agencies were loath to risk the exposure of their highly classified technologies by an emergency forced landing at a risky foreign airfield and demanded an expensive "cross-range" capability.[43] This drove up the complexity and cost of the system. The Shuttle in the end failed to achieve its operational design goals, and therefore could not meet its programmatic cost goals. Worse, it did not meet its reliability goals, losing two out of a fleet of five spaceships with all aboard in the course of 135 flights.[44]

From its beginning in the 1960s, space launch for non-governmental users began as an entirely non-market, politically rationed good. Market-like features were introduced painfully slowly and haltingly. At first, NASA (the only free world provider) launched non-governmental payloads grudgingly and only informed users after the fact what their "reimbursement" (price) would be. In the early 1970s, it turned down the request of a European satellite consortium, Eutelsat, to launch a satellite because it would steal market share from the international monopoly Intelsat. Europe responded with its own alternative launch program—the Ariane launch vehicle project—and requested partnership in the upcoming Space Shuttle project. In the late 1970s, when the U.S. rejected that request, its developer—the European Space Agency (ESA)—offered Ariane to the world launch market via a spinoff "European champion" entity, Arianespace, creating minimal competition for the first time.

Since the loss of the Shuttle Challenger in 1986, NASA has gradually transitioned more and more of its launches back to legacy launch vehicles and withdrew the Shuttle from commercial payloads. That year, the Reagan administration allowed the historical contractors who had developed these legacy launch vehicles for the government to offer the launchers to customers other than the U.S. government (including private satellite operators and foreign governments) starting with McDonnell Douglas' (now Boeing's) Delta and General Dynamics' (now Lockheed Martin's) Atlas vehicles, whose owners created a joint venture private company called United Launch Alliance (ULA). This withdrawal of the Shuttle from commercial payloads, and the privatization of the legacy launchers Delta and Atlas, led to something like a genuinely competitive field for the first time, soon after to be

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[42] Ibid.

[43] Ibid.

[44] Ibid.

joined by Russian and Chinese state launchers after the end of the Cold War. Yet even this market was distorted by state subsidies and holdover oligopoly attitudes. Every launcher had been developed by governments and then handed off to quasi-commercial providers; none were optimized as commercial launchers.

Only recently, in the second half of this decade, has space transportation moved toward real market pricing, when competitive pressures finally led ULA to follow SpaceX in posting up-front prices for its vehicles. For the first time, businesses can now estimate costs for their ventures with some confidence in launch price, leading to long-range business planning. In this way, private companies have taken the first steps toward developing a space-based sector of the economy that can improve life on Earth.

For example, SpaceX began flying its 60-ton-to-LEO Falcon Heavy in 2018, and has a proven flying track record with the reusable Falcon 9 rocket. Its well-funded competitor, Blue Origin, is also expected to begin suborbital tourism service in 2019. Both have announced plans to build launchers in that category. But many obstacles to space-based commerce persist, as NASA has been slow to mesh with private sector space designs, with structures that prioritize economy, reusability and standardization, rather than the legacy launch paradigm.

For example, today, for its deep-space probes, NASA relies on contracted launches with manufacturers of the traditional missile-derived vehicles—Boeing and Lockheed-Martin, now in the ULA. To launch its astronauts to the International Space Station (ISS), NASA currently pays the Russian space agency Roscosmos.

Despite this handoff of what was once a core role of NASA, the agency is at the same time building the very large Space Launch System (SLS) booster and Orion capsule, intended for crewed deep space missions beyond Earth orbit, and scheduled for a first flight in June 2020.[45] The earliest version of the SLS will launch 70 metric tons to LEO; later versions would lift up to 150 tons. NASA has justified this move by the fact that there is no currently existing private capacity for payloads in the 70-to-150-metric-ton-to-LEO category. However, SpaceX founder Elon Musk announced in 2017 the intent to develop the Big Falcon Rocket (BFR), which would provide 150 metric ton payloads to LEO, matching the ultimate maximum payload of the SLS family. By pursuing a reusable vehicle of this size, Musk has essentially staked his colors to the mast in the cause of large-scale use of space,

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[45] NASA, Orion Spacecraft. https://www.nasa.gov/exploration/systems/orion/index.html

since only a few flights of BFR would easily deliver the equivalent of the launch output of the entire global launch industry in 2017. Blue Origin is developing a launch vehicle of similar payload.

Given these achievements, in 2019, NASA plans to launch astronauts on American commercial launch vehicles on a contract basis with the private sector. NASA and the private sector together worked out the Commercial Orbital Transport Systems (COTS) program to stimulate development, the Commercial Resupply Service (CRS) for the current ongoing operational missions, and the current Commercial Crew Development (CCDev) programs for Space Station resupply and crew change.[46] These programs encourage development and competition by pre-paying companies working on launch vehicles and capsules for returnable cargo and crew.[47] Under these programs, NASA plans to use SpaceX's Dragon capsule on its Falcon 9 launcher and Boeing's Starliner capsule on ULA's Atlas V launcher.[48] NASA intends eventually to upgrade to ULA's new, partially reusable vehicle, the Vulcan, when it becomes available.[49]

4.2.1 THE LUNAR GATEWAY

While contracting with the innovative private sector is a positive step, it does not change the current paradigm, which constrains options to only the narrow field it has created. The Lunar Gateway provides an illustrative example.

In response to the Administration's Space Policy Directive 1 (SPD-1) directing NASA to return humans to the Moon, NASA has designated the Lunar Gateway project[50] as its primary means to achieve that goal. As currently planned, the Lunar Gateway is a crewed orbiting space station, using a modular architecture similar to the current ISS, in an elliptical orbit[51] around the Moon.

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[46] NASA C3PO Commercial Crew and Cargo Program Office NASA. https://www.nasa.gov/offices/c3po/home/

[47] Ibid.

[48] Ibid.

[49] United Launch Alliance. www.ulalaunch.com

[50] Formerly known as the Lunar Orbiting Platform–Gateway, or LOP-G.

[51] An elliptical orbit is one that varies in altitude around the object it orbits, being at one point high and at the opposite point low, so that a two-dimensional plot of the orbit is in an elliptical shape.

The purpose of Gateway is to act as a platform for humans controlling machines carrying out exploration and development tasks on the Moon's surface, with the advantage that controllers in orbit around the Moon can command the machines remotely without the 30-second time lag that makes the task much more difficult when done from Earth. It would also serve as a base for crews descending to the Moon for direct human activities. Since a spacecraft optimized for the trip from the Earth, or Earth orbit, to the Moon is not optimal for descending to the Moon's surface or returning to orbit, NASA is currently proposing to send a craft or series of crafts optimized for those tasks to the Gateway.[52] There they would be assembled into a multi-stage spacecraft and sent down to the Moon's surface and back. The current designs for lunar surface craft are too heavy to be sent fully fueled from Earth to the Gateway in one piece. NASA's solution is to send one large component to Gateway on SLS, when that becomes available, and the other, smaller components either by commercial vehicle or SLS to Gateway, where they would be assembled into the mission vehicle.

This plan has drawn criticisms from both advocates of traditional space approaches, and from New Space advocates.[53] The authors of this paper broadly agree with the critics. To begin with, NASA's decision that the vehicle components must be sent fully fueled (or "wet") from Earth to Gateway greatly reduces the number of options for getting it to the Moon, in fact to only one, the SLS. This narrowing of options to one pre-planned solution is precisely the problem with the status quo. NASA's defense is that establishing a fuel depot at the Gateway and conducting in-space fueling as one of its initial tasks would add complications and the potential for unanticipated problems to the plan. But the cost and flexibility benefits of using cheaper vehicles than the SLS, and learning how to conduct fueling operations, are things that would have to be done in any event in order to become a spacefaring nation.

The pathway advocated in this paper would call into question the advisability of building a Gateway at this point in space development at all. The critical tasks we identify include steps such as building and learning to use fuel depots and in-space refueling as an early priority, followed by switching to lunar and/or asteroid fuel sources as early as possible. Other priority tasks include understanding the health issues of long-term (one year plus)

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[52] These would consist of a "transfer vehicle", which would go from the Gateway's elliptical orbit to a low circular lunar orbit ("Low Lunar Orbit" or LLO), a "descent vehicle," which would go from LLO to the lunar surface, and an "ascent vehicle," which would go from the lunar surface back to LLO.

[53] "New Space" advocates refers to those who support a globally emerging private spaceflight industry.

exposure to microgravity and space radiation beyond LEO, and, assuming they are negative, to begin serious efforts to create long-term in-space facilities using rotational pseudogravity and heavy shielding. Gateway advances few if any of these objectives, and by its long time line (envisioning lunar surface missions no sooner than 2028) pushes all of these critical tasks into the mid-term future. There is really no justification for such a delay.

Using the capabilities now under development by SpaceX, Blue Origin and others, obtaining maximum flexibility by commercial service purchases and focusing carefully on these key priorities is the path to space utilization. The Lunar Gateway is an expensive distraction and should not be pursued.

4.2.2 BLUE ORIGIN'S NEW GLENN AND NEW ARMSTRONG

Although SpaceX has gained the most publicity of any new entrant into the private orbital launch field, another privately financed launch company, Blue Origin, is considered by many industry observers to be an equally if not more serious entrant into the field. Founded by amazon.com founder Jeff Bezos in 2000, Blue Origin has been funded almost entirely by Bezos' direct private investment, allowing the company to develop with no need for publicity and no need to promote its shares or seek other private investors. In the past few years Blue Origin has begun to participate in the more market-like government launch service procurement activities, such as the Air Force's EELV II program, but has declined to act as a traditional government contractor.

To date, Blue Origin has conducted a series of uncrewed test flights of its suborbital space tourism vehicle, the New Shepard.[54] It anticipates beginning crewed suborbital flights with paying flight participants in 2019.

In parallel, it has begun development of its large orbital launcher, the New Glenn, which it anticipates beginning revenue service in 2021. It already has six paying customers signed up for flights beginning in that year.[55]

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[54] All its vehicles are named after Space Race-era U.S. astronauts, such as Alan Shepard, John Glenn, and Neil Armstrong.

[55] The New Glenn is a two-stage fully reusable launcher using lox-methane engines for the first stage and lox-liquid hydrogen engines for the second stage. It has a target payload of 45 metric tons to LEO, approximately 99,000 pounds. Blue Origin is developing a crew capsule for it that will permit the launch of flight participants.

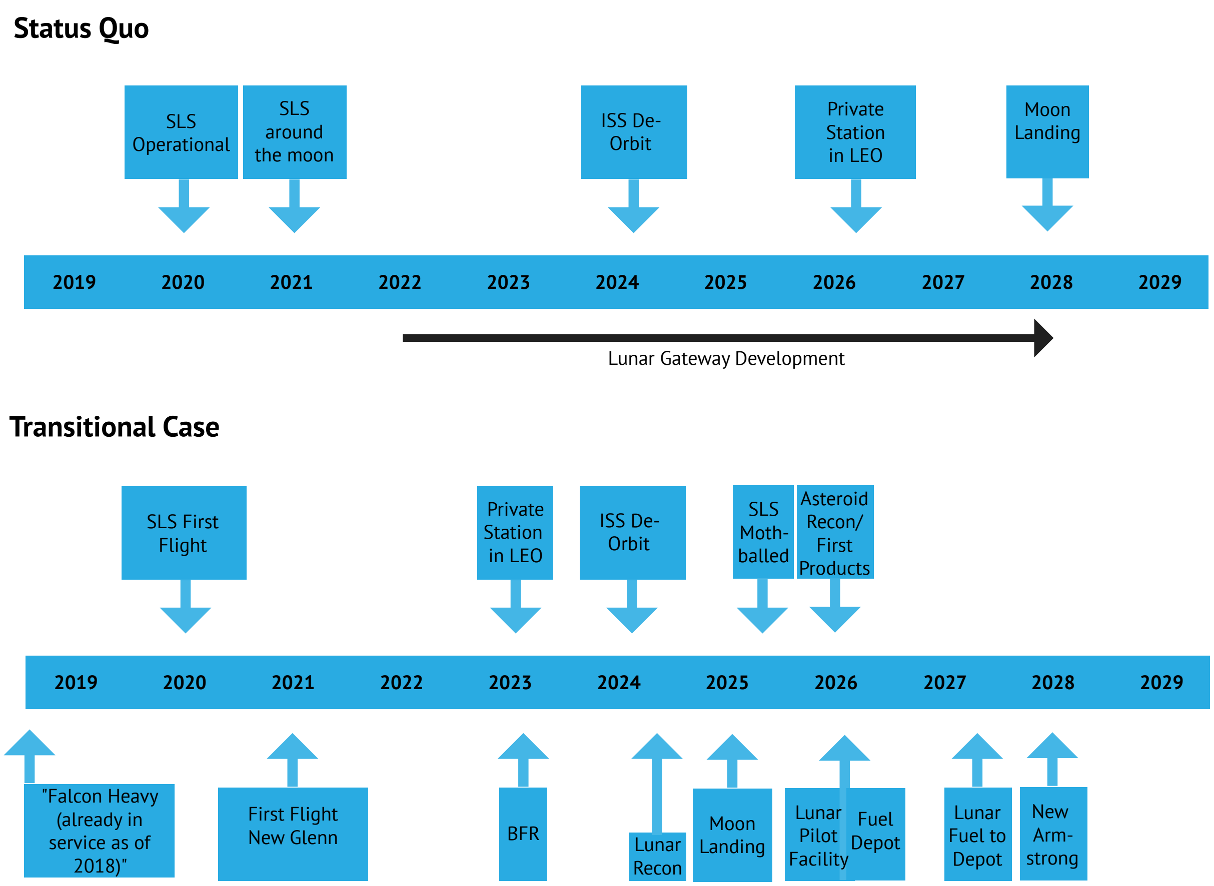
For annual funding of Blue Origin, Bezos liquidates a billion dollars of Amazon stock each year—a level he has pledged to maintain indefinitely. This provides the company with a more stable funding base than other private firms, or government agencies dependent on annual appropriations. Blue Origin has used this funding to establish design, test production and launch facilities, and to hire a staff of highly experienced professionals. Its engine test and suborbital launch activities have demonstrated their ability to deliver results. Therefore, the company's announced launch target date of 2021 for New Glenn is entirely credible.

Additionally, Blue Origin has discussed its intent to follow New Glenn with a larger launch vehicle—the New Armstrong. Unlike the case of New Glenn, the company has not published detailed specifications for this vehicle, but its general descriptions indicate that it would be in the same category as SpaceX's BFR or NASA's SLS, and capable of launching a crewed Mars mission. Although there is no indication that the New Armstrong design has been finalized or that hardware development has begun, it has been noted by some knowledgeable observers that many of the systems and components being developed for New Glenn could be used for a New Armstrong-class vehicle, and that the production facilities now being established in Florida would be adequate for New Armstrong as well. Therefore, development of New Armstrong could conceivably support a launch as early as 2025, although based on various company announcements, an initial operational capability in the late 2020s is more likely.

Although both SpaceX and Blue Origin have had optimistic development timelines in the past (as has NASA regarding SLS and its predecessors), both companies have consistently delivered the technological capabilities and prices they have promised. With both SpaceX and Blue Origin now pursuing credible large vehicle programs in parallel, it is reasonable to base space development plans on private capability, rather than pegging timelines to SLS and the fortunes of its appropriations processes.

The commercial launch world is now enjoying a flowering of many new actors and innovative technologies, but not all the ideas are new. Many of the innovations now being deployed by private-sector space developers, as listed earlier, were first developed by government institutions, but abandoned later as a result of inter-departmental rivalries or side-tracked because they threatened politically favored alternatives. The fruition of these ideas is a testimony to the ability of market incentives to bring forward innovations that in many cases were originally developed in government agencies. Structural change to the new commercial paradigm would bring about development of space long before it would be reached through the current exploration paradigm, as illustrated in Figure 3, and would add commercial priorities that would make for a financially sustainable industry.

FIGURE 3: TIMELINE 2020–2030



Envisioning space development as a privately funded enterprise is difficult, given our long-standing government-based structure, but comparison with another form of commercial transportation helps illustrate how space travel might change under a commercial paradigm.

4.3

SPACE TRAVEL VS COMMERCIAL AIRLINE TRAVEL

Space travel is, of course, more complicated and more expensive than airline travel, yet comparisons between them illustrate the exploration versus the commerce approach. The main driver of the commercial approach comes down to frequency of launch, which is only likely to be attained via private sector provision in the commercial paradigm. Frequency of launch, through sheer economics, improves structural efficiency and safety and reduces cost. But how does this occur?

One way to think about the cost of space flight is to start with the fact that the energy required to lift a given human being to low Earth orbit (LEO) is roughly 40 times that needed to transport a person from Los Angeles to Sydney, Australia.[56] Yet a quick Internet search discloses that a round-trip nonstop coach ticket between LAX and SYD costs $1,068; 40 times that is $42,720—a far cry from the commercial price for a ride on a Russian capsule to the International Space Station—currently the only commercial service available—at $70,000,000–$80,000,000, round-trip.[57] So, why is space travel so expensive relative to air travel?

One clue involves looking back to the early days of aviation. Back then, long-range air service was pushing the boundaries of the technologies and logistics of the day, and had many of the characteristics of today's space travel—use of converted military systems, very small numbers of purpose-built aircraft, and large standing armies of ground staff relative to miles or passengers flown. When Imperial Airways inaugurated its London-Sydney service in 1935, then the longest air route in the world, the trip took six days (flying only in daylight) and a one-way ticket cost £13,000, even though the service was heavily subsidized by the British government. In today's currencies that is equivalent to £885,300, or US$1,150,890. That is well below the Russian $70 million to orbit, but still a sum that only a government or large corporation might pay to transport a high-ranking employee. What differences in the circumstances of these two trips produce that disparity, and how might they be remedied?

4.3.1 STANDARDIZED VEHICLES

The vehicles produced for the LAX-SYD flight are also produced for many other journeys, have a standardized, efficiency-based structure, and, because the flights are numerous, their costs have been amortized over many millions of tickets sold.

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[56] That is based on a rough energy-only calculation, ignoring the fact that the aircraft does not have to carry its own oxidizer, the harsher environment of space compared to the atmosphere, and other challenges. Even taking all those into account, the disparity is still enormous.

[57] Mosher, Dave and Skye Gould. "NASA is paying Russia more than $70 million to bring an astronaut home in their space ship tonight." *Business Insider*. Sept. 6, 2016 http://www.businessinsider.com/space-travel-per-seat-cost-soyuz-2016-9

Vehicles for transport to and from Earth orbit are produced solely for that purpose. Only several thousand such vehicles have ever been constructed, and are often customized for each mission.

4.3.2 FULL-TIME LAUNCH “FACTORY”

The Russian Space Agency’s launch facilities at Baikonur (Kazakhstan) were for a long time the busiest launch facilities in the world. Today, thanks primarily to SpaceX’s low-cost entry into the marketplace, Cape Canaveral in Florida has that distinction. Yet no more than a few dozen launches per year (20 in 2017 at the Cape, with another 12 from other U.S. launch sites, compared to 13 at Baikonur, as SpaceX takes market share from the Russian Proton) are flown from them, which means that each individual launch customer is paying a substantial cost of supporting the small army of specialists needed to run the sites. Given the higher cost of operations in the U.S., the cost vs. user ratio for America’s busiest launch site, Cape Canaveral Air Force Station, is even worse.[58]

In contrast, the operational and support facilities for the airlines are used for thousands of other journeys by millions of other travelers, and the costs of building and maintaining those facilities have also been amortized over millions of trips. Furthermore, the specialized equipment and services the airlines use there are supported by a far larger global industry.

4.3.3 REUSABLE VEHICLES

With the exception of SpaceX’s Falcon 9 first stage, all orbital launch vehicles currently used are thrown away on their first and only flight.[59] (The Space Shuttle system reused one element, the Orbiter, and initially recovered its Solid Rocket Boosters (SRBs) from the ocean and reused them. However, the Orbiter required long and expensive refurbishment between uses, and the SRB recovery and refurbishment proved not worthwhile.) In contrast, airliners typically make many daily flights with a minimum life of 20 years, and many much longer.

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[58] Launch Log. Spaceflight Now. https://spaceflightnow.com/launch-log/

[59] Kuczera, Heribert et al. *Reusable Space Transportation Systems*. Springer Verlag. Berlin, 2011.

Possibly as many as 2,000 DC-3 aircraft, a type first built in 1933, are still in revenue service worldwide today, including foreign versions built under license.[60]

Of course, reuse is not a panacea, as the Shuttle experience demonstrated. Earth-to-orbit launches and return trips travel through a rough environment, and design of vehicles for reuse, and the refurbishment process itself, carry costs. SpaceX is gradually reducing the refurbishment times and costs for its boosters, and recently reused a booster a second time. In order to achieve significant cost reductions, SpaceX and other launch companies will have to demonstrate the ability to reuse launchers rapidly and with low refurbishment costs. United Launch Alliance's Vulcan rocket, now under development, will demonstrate an intermediate strategy, by recovering the engine package from its first stage and reusing it, while letting the relatively cheap tankage fall into the sea. The next few years will be interesting as we learn much more about the potential, and limits, of reusability as a practical launch cost reduction strategy.

Because successful commerce is based in cost per unit (in this case, launches), efficiency is mandatory, which makes the private sector the optimal source for money-saving features like reusability. This is why companies like SpaceX are now producing proven reusable rockets.

4.3.4 LIGHTER LOAD THROUGH INFRASTRUCTURE

Today the aircraft and airline industry serves transportation between various populated and advanced areas where all infrastructure, other than that specifically needed for flight, already existed. Every developed country, and most developing countries, have now had airports and support facilities for decades. Only upgrades are needed from time to time.

Space transport takes off from a developed facility, but its destinations are for the most part devoid of every single thing needed to sustain life, starting with air. A single space station exists, built at the cost of $100 billion, in which basic needs can be met on a very small scale for a short time. All other launchers must bring along with them everything needed for support, and even uncrewed vehicles must bring power supplies and fuel to sustain their operations in space, or their return if they intend to return. So the cost of launch includes the cost of launching a wide variety of consumables and capabilities,

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[60] Glancey, Jonathan. "The Douglas DC-3: Still Revolutionary in its 70s." BBC. http://www.bbc.com/culture/story/20131009-dc3-still-flying-at-70

including (for crewed missions) human life support. A depot in orbit where supplies could be accumulated would permit individual vessels to be sleeker and nimbler, cheaper and safer.

4.3.5 PRICED LAUNCH FOR BETTER PLANNING AND LESS WASTE

Being commercial, airlines' flights are carefully and competitively priced, which supports airline budgets for skilled staff, supply lines, ancillary contracting (food service, airport service, et al.), purchase of new planes, etc. This enables companies to plan for their needs so as to keep service continuous and quality high with little waste. Such efficiency is passed on to the customer through lower prices.

To date, the number of launch events per year are many orders of magnitude below that of airline operations, and many of these efficiencies are simply not possible at the historical scale of launch activity. The transitions already made to commercial launch, by SpaceX and increasingly the evolving United Launch Alliance, have begun the movement to more airline-like practice. The right policy choices will accelerate this process.

As a government endeavor, space travel's customized and infrequent flights make planning all but impossible. Complex and disparate mission goals reflecting political trade-offs, non-standardized vessels, and unknown and fluctuating amounts of federal funding often make for difficulty in planning, and therefore waste. Indeed, missions are so infrequent that they often rely on several years of federal funding, whose variability wreaks catastrophic consequences on NASA.

The Centrifuge Experiment, or the Consequences of Fluctuating Funding

In early human spaceflight (the Mercury and Gemini missions), the key medical questions were "can human beings even live in zero gravity" (a Mercury mission goal), and "can they stay healthy long enough to get to the Moon and back" (a Gemini mission goal). Not long afterward, however, attention turned to longer duration spaceflight, for space stations and possible trips to Mars—and the picture got more complicated. Clearly there were health effects from long durations in zero gravity.

There are engineering solutions for creating gravitational pull. For example, pseudo-gravity created through applying centrifugal force via a rotating facility was demonstrated at a very low level during the Gemini mission. One justification for a U.S. space station was to answer how much gravity it takes to stay healthy in space. Space Station Freedom, and later the International Space Station, planned a small human centrifuge to perform tests that addressed that question.[61] *If it had been found that, for example, lunar gravity of 0.16g was enough for health, and the Apollo astronauts fared better on the lunar surface than they did in space, that would be relatively easy to provide with a rotating facility.*

Despite the importance of this question—arguably the greatest biomedical unknown in all of human spaceflight—once the ISS was begun, the centrifuge module was canceled after it had been largely completed, due to temporary budget pressures. (It is currently on display in Japan.) Meanwhile, we continue to spend more than the cost of a centrifuge on studying the effects of long-duration zero gravity flight on astronauts. To this day we do not even have long-duration data on rats in this regard, let alone humans.

And yet, Congress' budgetary actions are understandable. In the exploration paradigm, the gain is information, not goods or services, making NASA's budget subservient to other, more immediately pressing expenditures. But without a firm idea of budget, and with every launch a multi-year monolithic project, historically NASA has had trouble planning missions efficiently or effectively. Only recently, with the COTS and Commercial Crew programs to support the ISS by commercial flights, NASA has now demonstrated a regular series of flights. This points the way to future improvement.

4.3.6 SAFETY IN NUMBERS

The Wright brothers' first tenuous flights were perilous indeed, but increased numbers of flights led to a learning curve that made flights safe. The industry is now the safest of all modes of transportation (see Figure 4).[62]

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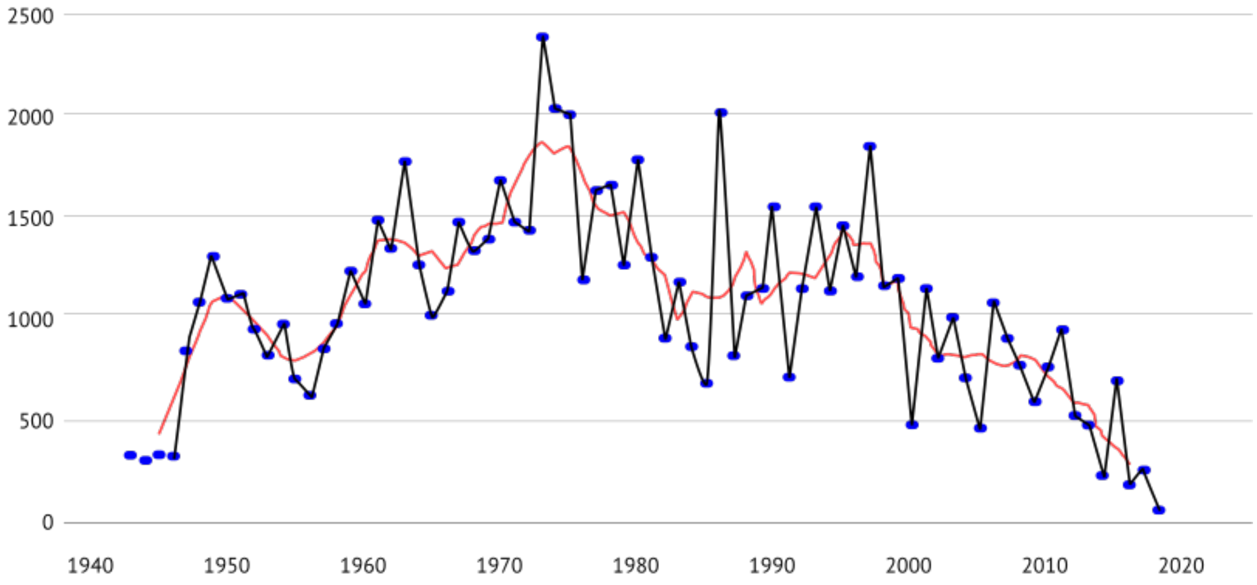
[61] Centrifuge Accommodations Module. Wikipedia. https://en.wikipedia.org/wiki/Centrifuge_Accommodations_Module

[62] Derived from "fatal airliner (14+ passengers) hull-loss accidents." Aviation Safety Network. Flight Safety Foundation. https://en.wikipedia.org/wiki/Aviation_safety#/media/File:Number_of_fatalities_from_airliners_hull-loss_accidents_per_year.svg

FIGURE 4: AIRLINER HULL-LOSS ACCIDENT FATALITIES, 1942-2017: NUMBER OF FATALITIES FROM AIRLINERS HULL-LOSS ACCIDENTS PER YEAR



NOTE: Fatalities since 1942, five-year average in red: fatalities peaked in 1972.

Source: Derived from "fatal airliner (14+ passengers) hull-loss accidents." Aviation Safety Network. Flight Safety Foundation. https://en.wikipedia.org/wiki/Aviation_safety#/media/File:Number_of_fatalities_from_airliners_hull-loss_accidents_per_year.svg

By contrast, space is not a burgeoning commercial industry. Too few launches make for a shallow learning curve, as launch is kept too infrequent and too individually unique to apply the kinds of statistical analysis that have led to modern aviation safety.

Repeated launch of the same type does not necessarily reduce risk—although it gives opportunity to—but increases predictability of risk, which allows for accurate calculation of risk assessment. Gradual improvement through statistical analysis of failure (the Deming method), which has worked wonderfully well in aviation, cannot yet work in space travel because the total number of like events (the “n” in statistics) has not yet risen to a statistically significant number; this is why aviation-type certification cannot yet be meaningfully applied to space regulation. But just as with all forms of transportation that began as perilous journeys into frontiers, the more we do it, the safer we can make it.

4.4 PRIVATE INDUSTRY PRACTICES

Since government and private industry have different paradigms for space transport, it is difficult to compare actual nuts and bolts type costs. But employing a more bottom-line-focused approach, a NASA study compared SpaceX's actual Falcon 9 development vs. what it would have cost under traditional NASA practices, finding significant cost saving from the very substantial reduction in overhead imposed by government contracting practices (see Table 3).[63] This resulted in a two-thirds cost reduction applied across the board in every element of the private sector program, even without the benefit of infrastructure. New design and production practices that save even more money will likely emerge in future generations, especially if infrastructure is applied. This is the continuation and fruit of the gradual introduction of more and more market incentives and market-like practices in space launch over the past 30 years.

The private sector is not only building rockets better and cheaper than NASA can, but also transitioning small satellites into mass production. For Earth observation and satellite internet, private companies are currently making dozens or even hundreds of similar satellites in the first mass production efforts. Compared to Earth-based industries, this is modest, but in space, it's significant. Likewise, in the small satellite market there are now "catalog" parts available from manufacturers for the specialized components needed to make a satellite—instruments, thrusters, communications radios, solar arrays—so that most small satellites are no longer constructed completely from custom parts. The transformative effect of this mass production is attracting significant (>$1 billion in 2017[64]) private investment as the business paradigm evolves into an industry. Such activities demonstrate that the private sector is already creating a space industry economic sector, hampered only by the lack of infrastructure and the current space travel paradigm.

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[63] NASA study on Falcon 9 costs vs. equivalent vehicle under government contracting rules. https://www.nasa.gov/pdf/586023main_8-3-11_NAFCOM.pdf

[64] *Space Investment Quarterly*. Q1 2018. https://www.spaceangels.com/post/space-investment-quarterly-q1-2018; Foust, Jeff. "Space Ventures Raise Nearly $1 Billion in Equity Investment in First Quarter of 2018 Led by SpaceX." *Space News*. April 12, 2018. http://spacenews.com/space-ventures-raise-nearly-1-billion-in-first-quarter-of-2018-led-by-spacex/

TABLE 3: COMPARISON COST OF FALCON 9 AND EQUIVALENT GOVERNMENT VEHICLE, UPDATED

		Firm Fixed Price Acquisition (FALCON 9)			Cost Plus Fee Acquisition (EQUIVALENT GOVERNMENT VEHICLE)		
Elements	Weight (lbs)	Develop-ment* (FY2010 $M)	2 Test Flight Units (FY2010 $M)	Total (FY2010 $M)	Develop-ment* (FY2010 $M)	2 Test Flight Units (FY2010 $M)	Total (FY2010 $M)
Stage One (Including Engines)	39,080	$188.7	$109.3	$298.0	$370.6	$218.3	$588.9
Stage Two (Including Engine)	6,506	$89.0	$23.6	$112.6	$184.7	$59.6	$244.4
Fee (12.5%)		$0.0	$0.0	$0.0	$69.4	$34.7	$104.2
Program Support (10%)		$0.0	$0.0	$0.0	$62.5	$31.3	$93.7
Contingency (30% Vehicle, 10% Engine)		$0.0	$0.0	$0.0	$193.2	$91.7	$284.9
Vehicle Level Integration (8%)		$22.2	$10.6	$32.8	$44.4	$22.2	$66.7
Total	45,586	$299.9	$143.5	$443.4	$924.8	$457.8	$1,382.8

NOTE: "Development" encompasses "DDT&E", or Design, Development, Testing and Evaluation.
Source: NASA study on Falcon 9 costs vs. equivalent vehicle under government contracting rules.
https://www.nasa.gov/pdf/586023main_8-3-11_NAFCOM.pdf

4.5

VICIOUS CYCLES

Our current approach to space travel has spawned several vicious cycles that entrench the current system, making the exploration paradigm increasingly harder to evolve past. This is because:

- Our customized, complicated and difficult launches are expensive; they are expensive, in part, because they are customized, complicated and difficult.

- The more complicated and difficult a journey is, the more perilous it is, because there are more things that can go wrong, and a failure of any one part can doom the whole mission. Conversely, the more perilous a journey is, the more that political authorities are under pressure to make it safer. Typically, the way they try to do this is by adding precautions that make the whole mission even more complicated and difficult to achieve, thus, ironically, making the mission less safe.
- Infrequent launch makes us have to "rebuild the launch factory" of skilled personnel and unique supplies for each launch; having to re-establish that support system each time makes launches more costly, and thus we launch less frequently.
- Every pound of useful payload[65] on a rocket costs more money and makes the rocket have to be larger and more powerful; the heavier the useful payload, the more fuel it takes to launch it, adding to the weight a given engine must lift.
- Expensive launches make for little demand by private parties; little demand makes for high costs per user, which lead to expensive launches.
- Congress varies its funding because each launch is so expensive amid an array of competing concerns, and this fluctuating funding is partly what makes each launch so expensive. When any blip in the budget can cancel or postpone a launch, it makes for unreliability. The more unreliable the launch is, the less Congress is motivated to fund it, and the less reliable it becomes.

After the termination of the Space Shuttle program, NASA proposed a large, expendable launch vehicle project called the Evolved Expendable Launch Vehicle (EELV) program, using Shuttle-derived components, particularly solid rocket boosters and Space Shuttle main engines. In tandem, NASA is developing a new space capsule intended for crewed deep space missions beyond Earth orbit—the Space Launch System (SLS) and Orion capsule—and scheduled for a June 2020 first flight.[66] Market-like reforms such as the Air Force's EELV program have brought improvements. But programs such as the SLS continue many of the old problems.

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[65] Space launch discussion can be confusing because different members of the team have different working definitions of "payload." To a propulsion engineer, everything an engine must lift, aside from the engine itself, is "payload." To a launch service marketer, only the weight a customer pays to lift is "payload." Other specialists have definitions in between. It is useful to clarify which definition is being used.

[66] NASA, Orion Spacecraft. https://www.nasa.gov/exploration/systems/orion/index.html

Driving all these vicious cycles is our structural rut: We have accepted that this covered-wagon approach is a given for space travel. Experienced aerospace engineers, of course, have come up with many innovative approaches that might have improved costs substantially had a whole system been built around cost reduction. Every one of the innovations that private companies like SpaceX have applied were thought of by engineers from the old system, who never had the chance to put them into practice.

The system's assumptions about how space activities are conducted do not imagine or provide for changes that would be wrought by having facilities in space. Because we have never done anything else, we can't imagine doing anything else, and we plan our future space activities with this status quo approach, further entrenching it. Let's take the simplest example of infrastructure and consider the changes it would allow in one current use of space.

4.6

HOW PARADIGM CHANGE DRIVES SYSTEMIC EFFICIENCY, EFFECTIVENESS AND INDUSTRY

Facilities in space would be more than just fuel depots and storage areas, and their capabilities would improve our current use of space. For example, a communications satellite is essentially a load-bearing structure (the "bus") that holds racks of electronic communications gear (transponders), antennas to receive/send information to and from Earth, and solar arrays to power it. Transponders are compact, rugged and modular, but the solar arrays and antennas have to be as large as possible. The bigger their reach, the more capability they have.

Their basic function does not require them to be heavy, but currently they must be manufactured that way. This is because these structures have to survive launch itself—a very high-vibration environment. The rocket engine thrust reflecting back from the launch pad creates astoundingly high noise levels, which, combined with the solid rocket strap-on boosters and the buffeting of passage through Earth's thick lower atmosphere, demand that materials be rugged and strong enough to survive, even though that is not required in space. Volume, weight and width restrictions on payloads also dictate the configuration of these structures, requiring them to fold up into a small space and demanding that the mechanisms, actuators, hinges and so forth necessary for deployment of them in space be designed to withstand the stressors of launch.

By contrast, imagine there was the simplest possible facility available in space to do one simple step—to turn a "launched" satellite into a "ready to operate" satellite. All the facility does is unfold antennas and solar arrays, precluding the need for them to auto-deploy using much delicate and sophisticated equipment. A significant part of the satellite's cost has now been eliminated and replaced by the facility, which can be used over and over again. Suppose that we then launch transponders, a "bolt together" truss for the "bus" framework, panels for solar arrays, and panels for antennas. A robotic or human facility could attach these components, and now not only are the components launched much simpler and at lower cost, but they are also significantly lower weight. Without the easily broken machinery to self-deploy, there's room for lightweight packaging material to cushion the structural components against launch loads. This is indeed one of the possible futures of geostationary satellites—modular "rack" satellites to which components are robotically attached.

Another example is solar power satellites (SPSs)—the abundant clean energy discussed earlier. SPSs are built with relatively inexpensive, simple construction materials (for support frames and mirrors) rather than electronics; it's delivering the components to space with their self-assembly/self-deployment machinery having to survive the vibration of launch and deploy them when in space that make the current costs higher than using Earth-collected fuels.

Lower space transportation costs would at some level make this abundant clean energy source competitive with or even cheaper than terrestrial power generation—the "breakeven" point. Low-cost material from the Moon or asteroid sources or from "bulk" launch would further reduce SPS costs and achieve breakeven sooner.[67] But with upcycled space debris (such as upper rocket stages) or mined lunar or asteroid materials, and a manmade outpost (an orbital facility) on which to work, the whole way we approach satellites changes. Without the need to survive launch, function alone can dictate design, achieving breakeven more easily.

This is one powerful example of how a future where there is "something" already in space can change how we do economically valuable activity in space. And of course, once there is

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[67] Some think breakeven has already been reached, and some think it won't be reached without space materials. Likely we've got a ways to go for breakeven for bulk power, but it's close, especially in high northern areas where power is expensive. Experts cannot reliably determine how low a cost can go, but markets can. Pilot market-based programs that put these goals in the hands of business are likely to help drive costs down.

such a capability, it would enable new things not currently possible. For example, once we can fabricate large antennas or large solar arrays from smaller pieces, there is no limit to how large we can make them! This is the same capability needed for scaling up from communications satellites to power satellites, or allowing for larger antennas that can communicate from a satellite to handheld devices rather than needing a “dish” on the ground.

It’s this focus on infrastructure, this “highways, not covered wagons” approach, that will change the cumbersome way we do things now to much lighter, faster, sleeker and infinitely more functional options. By providing the environment needed for current and future private sector technology to flourish, such a repurposing of current funding lays the foundation for a thriving tech-based industry rather than continuing our lonely space “backpacking trips through the wilderness” caused by the vicious cycles of the status quo.

We can’t simply change one of these factors to raise ourselves out of these vicious cycles—it has to be a whole systemic shift. This is not merely an expansion of the status quo by increasing NASA’s use of contracting; it is structural change the redefines the roles of government and the private sector to do what they do best. The fact that the private sector is already pursuing the efficiencies that will allow a private space industry beyond mere LEO satellites to flourish signals that the exploration paradigm’s utility is in steep decline. With this paradigm shift in mind, we will consider Congress’ options for NASA funding in Part 5.

PART 5

A NEW APPROACH TO NASA FUNDING

5.1

BACKGROUND

To understand the current situation, it is important to understand where space fits into the nation’s activities, the government’s activities, and NASA as an agency. The U.S. government as a whole spent approximately $34 billion on unclassified space activities in 2018—a relatively representative year.[68] Roughly, $20.7 billion was spent by NASA, about $2.3 billion by other civilian agencies, primarily for weather and Earth observation satellites, and the rest for administration, overhead, ground infrastructure, security, etc. The Department of Defense’s spending on space, thought to be its largest category, can be estimated at about $8 billion or $9 billion per year on publicly known activities, including the Global Positioning System satellites, and military communications and weather satellites, all of which provide critical services to U.S. forces worldwide, and in the case of GPS, are now critical to the functioning of the U.S. economy as well. NASA spending, therefore, is a significant part of U.S. spending on space. Outside of a few years in the 1960s, it has been so throughout its existence.

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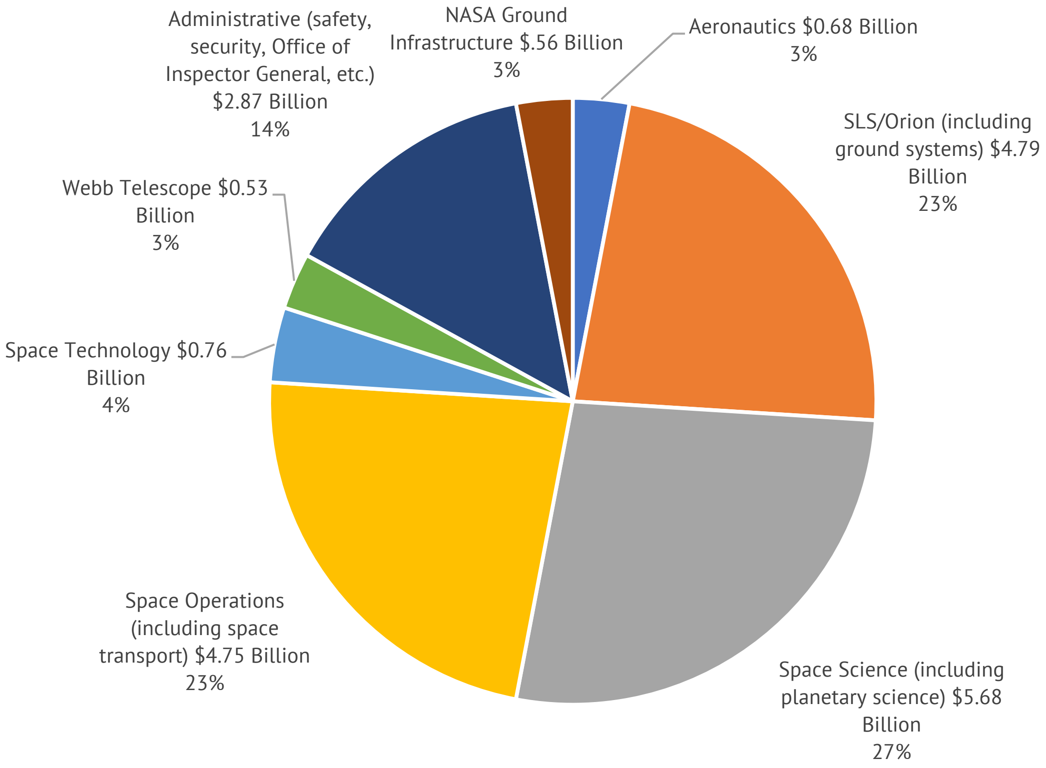
[68] OECD Reports. The Space Economy at a Glance, 2014. Oct. 23, 2014. Table 1.1

FIGURE 5: NASA ANNUAL SPENDING ON SPACE ACTIVITIES ($20.7 B IN 2018)



Source: Dreier, Casey. "NASA wins big in 2018 budget deal." The Planetary Society. March 22, 2018. http://www.planetary.org/blogs/casey-dreier/2018/20180322-fy18-omnibus.html

5.2 PUBLIC APPROACH VS. PRIVATE APPROACH

5.2.1 THE PUBLIC APPROACH

Of the $20.7 billion in NASA’s 2018 budget, $4.79 billion was spent on two programs: SLS/Orion and ISS. While NASA is working with private contractors, this practice can only save so much in costs. The SLS and ISS are designed by NASA and Congress, with all the inefficiencies that generates. For example, as many old Shuttle components are used as possible, both to save money in the short run—a penny-wise/pound foolish approach—and support the Shuttle program, but that also traps new missions into using old technology that doesn’t mesh well with the best and most forward-looking practices, leading to long-term inefficiencies and higher costs. In addition, everything from parts to launch matters is politicized, since these government entities are politically driven rather than efficiency-driven. This makes for specifications that are much more complex than an industry's use would require, making our current space program complicated, difficult and unnecessarily expensive. Moreover, NASA's focus has always been exploration and research, rather than contributing to a space industry. As a result, these missions don't contribute permanent, useful infrastructure in space that would develop space's potential uses. Such a 1960s-era approach—especially in an age when space has demonstrated value and commercial entities are delivering equivalent capability at far less cost—obstructs the economic potential for the private sector to develop a space industry funded by private means and for-profit endeavors.

5.2.2 THE PRIVATE APPROACH

By contrast, ULA and SpaceX both have highly automated production facilities, each capable of supporting dozens of launches a year. With the emergence of SpaceX, we have two highly capable companies able to address the full range of government and commercial payloads. This has led to competitive behaviors, for example, prices are now published—and are falling. SpaceX has demonstrated the ability to soft-land and reuse the first stage of Falcon 9, while ULA is pursuing refueling and reusability of its upper stage. SpaceX has demonstrated a larger Falcon Heavy rocket, and ULA and Blue Origin are developing comparably large rockets, all in the >50 ton to LEO class. As a result, we have one, and are likely to have three U.S. companies capable of delivering payloads large enough to perform lunar missions—at far lower costs than SLS.

SpaceX's Starship (also termed BFR, for Big Falcon Rocket) is still under development, but intended to carry >150 metric tons of payload, matching the fully built-out capacity of later SLS variants. Once proven as a flying system, BFR will almost certainly undercut SLS on price and undercut any justification for a publicly built and operated launch system. More recently, SpaceX founder Elon Musk has announced that the BFR could also be used as a point-to-point transport for inter-continental travel on Earth, which would give it a much larger immediate market base than purely Earth-to-orbit systems. SpaceX is currently scheduling a precursor BFR test article for flight in the first half of 2019.[69]

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[69] Wang, Brian. *The Next Big Future*. "Flight Tests of the World Changing 100% Reusable SpaceX Starship Will Start 6 Months Early." December 23, 2018. https://www.nextbigfuture.com/2018/12/elon-musk-tweets-first-flight-tests-of-spacex-starship-will-be-in-march-or-april.html?fbclid=IwAR0sIe2X0JNlWcUYydx9mUbTKaFknpvOT6KlTYgEuqqMZ9FPevSqj1HcqkY

Suborbital Human Flight

This report has not discussed suborbital human flight or terrestrial point-to-point human flight through space in any detail. This is partly because its focus is primarily about what can be done in space once market incentives and market-like practices have revolutionized the economics of transportation to Earth orbit and beyond. However, the prospects for suborbital and point-to-point commercial activity are important to the spaceflight business as a whole. As discussed previously, size of production runs and numbers of passenger-miles flown are important for both cost reduction and technological improvement, a virtuous cycle. Producing and operating systems for suborbital and point-to-point flight increases the market for components which have commonality with orbital systems, and increases our experience base with exo-atmospheric flight. There are cautions about projections of point-to-point passenger numbers, as there are issues of safety, location of takeoff and landing sites sufficiently near large cities, tolerability of the acceleration, deceleration, microgravity conditions in flight, and ticket price. Some people might be willing to pay four times first class fare (to take an arbitrary example) to get from Los Angeles to Tokyo in 90 minutes, but others might find being pinned back in their seat by multiple Gs, and vomiting during turnover, less attractive than 10 gentle hours in first class at a quarter the price. Additionally, current progress in atmospheric supersonic flight may well provide an intermediate option of, say, a four or five hour flight to Tokyo for less than twice the price of subsonic.

—James C. Bennett

5.3

EVOLUTION TO A PUBLIC-PRIVATE PARTNERSHIP THAT USES THE BEST CAPABILITIES OF EACH

NASA has already taken steps in this direction. For example, the Commercial Cargo program for ISS used a much more commercial approach to buying private launch resupply for the ISS. Given that NASA's SLS and Orion have already been superseded in price, design and operational readiness by SpaceX's Falcon Heavy, with other private companies competing as well, it is clear that the private sector can offer a complete rocket product for far less than NASA's current SLS/Orion budget. If SpaceX or Blue Origin can produce reusable large launchers in the 60-metric-ton-to-LEO class, as both have planned, then either company, or both, will be able to offer comparable services to SLS at an ever-decreasing cost as further economies in production and re-use are worked out.

NASA experts currently see the value the private sector brings to planned NASA space endeavors, contracting for and purchasing many components for its missions. While this is a step in the right direction from the 1960s race to the Moon, when government hand-crafted every aspect of every space mission, what's needed now is a recognition of what NASA does best and what the private sector can provide, now and in the future, and reallocating NASA's budget to maximize the best of each. This would evolve the current NASA/private sector partnership to get more bang for the buck and would foster an industry that is increasingly self-sustaining financially. Instead of government providing eternal financial support for space activities, NASA in this paradigm operates more as a venture capitalist, making an investment in the infrastructure for a NASA/private sector partnership that serves both government and commercial transportation needs.

Redirecting NASA's SLS/Orion budget to purchasing tickets to fly on an "off the rack" rocket from the private sector is just good business sense. When NASA becomes a customer of private companies, it does more than save money and time: it stimulates a fledgling industry that is increasingly self-sustaining. When NASA purchases from companies competing to deliver the most useful and safest space products at the lowest prices, government becomes the anchor for space activity. Plus, NASA then has funds left to invest in the most basic infrastructure—"space railroads and depots." This greatly improves and increases exploration, military and commercial space activities, since NASA astronauts, DOD and private participants can all use the infrastructure. Such an approach is the best and fastest means of getting American astronauts back to the Moon, continuing necessary deep space exploration and research, and working toward missions to Mars.

For every task NASA tries to undertake but does not do well, another task in the category of things NASA does do well remains undone. To understand what NASA should not be doing, it is necessary to understand what it does well.

NASA is easily the planet's most experienced and successful organization for the exploration of interplanetary space beyond Earth orbit. NASA has brought together and melded into teams the best collection of aeronautical and astronautical talents, skills and capabilities on the planet. Over the decades since humanity first ventured into space, NASA has by far the best record of probes that have flown by or landed on all of the solar system's major planets, and a number of minor bodies at extreme distance as well. Its research centers are remarkable focal points of expertise in studying and exploring our solar system.

Although other agencies—including the Russian, European, Japanese, Indian and Chinese space establishments—have accomplished remarkable things themselves (often in collaboration with NASA), NASA is still the most ambitious and most complete actor. NASA's capabilities in aeronautical research and various fields of science have been unparalleled in the past and remain excellent today. These functions will continue as well, although there is some debate as to whether they should be spun out into smaller, more-focused agencies. These capabilities, which include such endeavors as research on the human body in space, can generally be categorized as the exploration function, since they are valuable to the overall space effort of the nation, and should be well funded.

5.4

MAKING FUNDING FOLLOW FUNCTION TO PUT AMERICANS BACK IN SPACE

In short, NASA going forward with its current paradigm and mix of projects, even with substantially increased funding, will not reduce the costs of spaceflight, nor will it unlock the door to a wide range of innovative products and services that are currently being planned by the private sector. With taxpayer funding, NASA's endeavors currently compete with private companies, ensuring we continue exploring rather than harnessing resources in space.

For example, NASA's 2018 budget allocated $4.79 billion to SLS/Orion and ISS, whose functions could reasonably be performed by the U.S. private sector within a few years. More to the point, their functions would not only be effectively matched, but within that budget a whole new space infrastructure could be brought into being, using an anchor investment of taxpayer funds to leverage a large additional investment from private sources. The basic strategy would be to rededicate NASA to its best and highest uses: the exploration of the solar system and the universe beyond. The functions of space launch to low Earth orbit and maintenance of facilities in Earth orbit were once exotic capabilities at the very edge of our technological reach. Today, they are tasks that private enterprise can and does perform at much lower costs.

Clearly NASA's planned vehicles are in competition with the private sector, and not keeping up. This goes against general U.S. policies (particularly as outlined in the Office of Management and Budget (OMB) Circular A-76), although successive administrations, both Republican and Democrat, have tended not to see space launch as a field that the private sector could take over, and that the government should refrain from competing in.[70] This has not been done from ideology so much as a failure of imagination, from a feeling that space was so “special” that ordinary assumptions just didn’t apply to it. This is unfortunate, wasting NASA funds with duplicative endeavors. NASA could do so much more with that extra $4.79 billion currently spent on SLS and ISS, preferably activities that private parties cannot do.

As we have seen, initial reorientation of NASA might result in budget savings of up to $4.79 billion per year by the mid-2020s. This seems like a lot, but even the first stages of the three elements discussed—construction of co-orbital facilities including water procurement, low-cost launch, and an orbital fuel depot—would cost something on the order of $100 billion each over perhaps 10 years, if built by NASA using the paradigms existing today. This $300 billion would cost $30 billion per year over 10 years, which is equal to the entire NASA budget even in the most optimistic scenario, ignoring the worthwhile and even critical planetary science and exploration missions that today absorb the majority of NASA’s budget. Thus even the building of infrastructure can realize the economic benefits of the private sector approach.

5.5 NASA AND CONGRESS: FROM VICIOUS CYCLES TO VIRTUOUS CYCLES

One problem of applying the NASA paradigm to routine operational functions is that it sets off a vicious cycle. As discussed earlier, launches are expensive because they are so infrequent. Because they are infrequent, the payloads must be ultra-reliable, and must pack in as many functions as possible. As a result, they are handcrafted and expensive. But since the best way to lower costs and to make equipment more reliable is by gaining experience, and experience requires many repetitions, neither payloads nor launchers ever get much cheaper or more reliable. Furthermore, since the congressional districts that benefit from the jobs created require that the jobs be continuously maintained, they have every incentive to stretch the performance periods of the jobs out as long as possible, running the costs up even more. Typically, when cost-cutters in Congress try to control these runaway costs, they settle for buying fewer items, since that is a simple measure, whereas actually making them less expensive is complex and requires specialized knowledge.

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[70] “Will Trump and Mulvaney Bring Back A-76?” FCW. December 22, 2016. https://fcw.com/articles/2016/12/22/a76-trump-update-rockwell.aspx

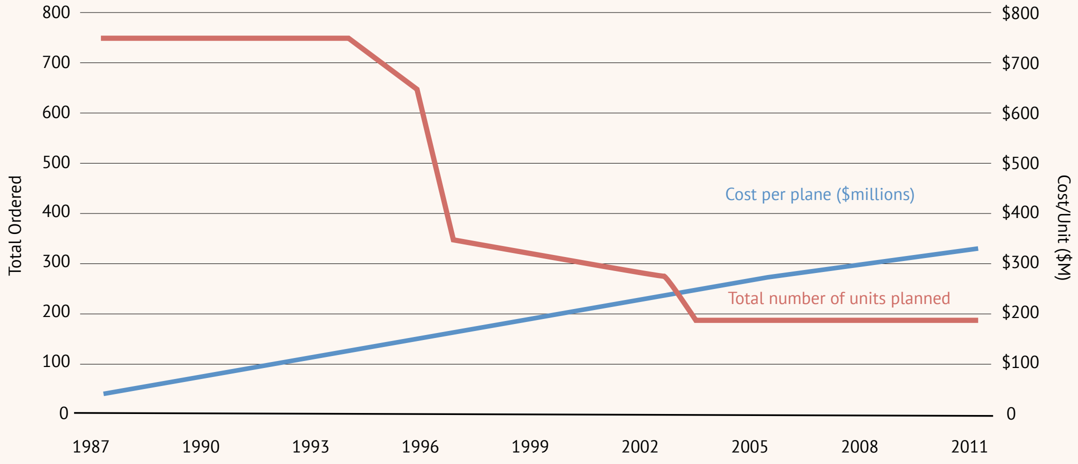
Buying fewer items makes them even more expensive on a per-item basis, and prevents ever making them inherently cheaper.[71]

The F-22 Fighter: Low Numbers = High Cost per Unit

Low numbers equals high cost per unit is exemplified in the F-22 fighter program. The F-22 has been an excellent fighter, combining for the first time low observability ("stealth") and supersonic performance. But between the cumbersome U.S. military/aerospace procurement system (which, as shown in the case study of Falcon 9, would have cost three times as much if developed by NASA's legacy procurement process) and the cutting-edge nature of its technology, its costs grew alarmingly. Congress did not help by forbidding foreign sales, even to highly reliable allied militaries like the UK, Canada and Japan. Then, driven by sticker shock, Congress cut back the U.S. Air Force's buy from the original 750 aircraft to 183, which raised the cost further from the original estimate of just under $35 million per aircraft to $339 million apiece. This is doubly wasteful because the lessons learned as the aircraft is produced lead to a per-unit cost of the last aircraft that is substantially lower than the first. The F-22 has performed so well that the Air Force recently completed a study of how much it would cost to put it back into production, and Japan recently began studying the idea of producing a hybrid of the F-22 combined with the advanced software of the F-35, provided that the U.S. dropped its counterproductive ban on export.*

**Globalsecurity.org. "F-22 Raptor History."*
https://www.globalsecurity.org/military/systems/aircraft/f-22-history.htm

F-22 COST PER UNIT vs Total Order Number (1990–2012)



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[71] Although this frustrates NASA technologists as much as—or even more than—anybody else, the paradigm that has evolved between NASA and Congress (it would be unfair to blame it solely on NASA) is very difficult to escape for those inside that system.

Fortunately, the alternate path we propose creates, in contrast, a virtuous cycle, in which each step makes the next more cost-effective. This can already be seen occurring with the advent of well-funded private launch providers like SpaceX and Blue Origin. SpaceX was designing a launch vehicle from scratch, and could assume that it would be producing vehicles in larger numbers and reusing them. It was also creating its production facilities simultaneously, and specifically for the launch vehicle design. Together these advantages allowed it to develop a vehicle that was cheaper to develop, cheaper to build, and cheaper to launch—a third of the cost compared to what it could have achieved using the NASA-congressional paradigm, as shown earlier.

In a system where the cost of launch is critical, such efficiency immediately gave SpaceX a powerful advantage in the launch market as its reliability was gradually accepted by launch customers, gaining a large share of the world's non-governmental launches in its class. This in turn fulfilled the expectations of its original plan and validated its launch number assumptions. What most tellingly points to the future, however, is when SpaceX used its base in the commercial marketplace to capture what was previously a governmental purview—transport of cargo, and soon human crews to the ISS. Even with the exploration paradigm (rather than the commercial one), the private sector is proving its ability to be more effective and efficient than government.

Because it must fund itself, the private sector's focus on efficiency provides the following main categories of cost savings:

- #1 Greatly reduced reporting costs and record-keeping costs
- #2 Consistent multi-year funding
- #3 Greater workforce flexibility and better retention of high-value workers
- #4 Faster design-build-test-modify cycles
- #5 Wider sources of supply
- #6 Ability to experiment with cost-saving approaches and quickly change to take advantage of those that work (rather than being locked into an approved contract, as NASA is).

In the context of a space industry, when the private sector can design its own vessels based on commercial functions, without the complexities NASA mandates, spacecraft should become simpler, nimbler, standardized—and vastly less expensive. In this way, the private sector points the way out of NASA's vicious cycle trap. NASA and the private sector (including not just SpaceX, but also Orbital ATK and Boeing, as old-paradigm companies begin adapting to the new paradigm) together worked out the Commercial Orbital Transport Systems (COTS) program to stimulate development, the Commercial Resupply Service (CRS) for the current ongoing operational missions, and the current Commercial Crew Development (CCDev) programs for Space Station resupply and crew change.[72] These programs encourage development and competition by pre-paying companies working on launch vehicles and capsules for returnable cargo and crew.[73]

While some criticize this as subsidy, it is actually a sensible investment for government resulting in lower transportation costs than NASA otherwise would have, providing multiple technology paths as each company tries out different solutions, and, most importantly, leveraging federal funds with new funding from the private sector. Federal funds spent purchasing what the government needs in space from private vendors multiplies the amount of money spent on developing space capabilities, because the private vendors expect to also sell the capabilities thus created to new private users.

Nothing on the critical path to space—low-cost launch, orbital facilities, fuel depots, Earth-Moon transport systems, and lunar and asteroid mining capabilities—is likely to be affordable using only the current NASA paradigm. And no matter how much money Congress sinks into a declining system, the opportunity cost of NASA competing with the private sector holds the industry back. However, by using federal funding intelligently along the lines of NASA's new direction, exemplified by COTS, CRS and CCDev, the sequence of capabilities could well be affordable within NASA's current funding.

Low-cost launch is already well under way. New orbital facilities can be offered, which could be created by private firms like Bigelow Aerospace with federal laboratories as "anchor tenants," and other orbital facilities which are nearby and in the same orbits, and thus can quickly and easily be reached by cheap transfer craft.[74] Such a complex of facilities could host a wide range of activities, and would be the next step. While we cannot predict precisely how far and how fast this path can be unrolled, because the amount of private funding that could be leveraged cannot be precisely predicted, it certainly is faster than the current system, which does not maximize leveraging of funding. Use of COTS-like contracts that provide predictable payments at progress milestones provide even greater leverage for

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[72] Commercial Crew and Cargo Program Office, NASA. https://www.nasa.gov/offices/c3po/home/

[73] Ibid.

[74] Such nearby facilities are called "co-orbiting free flyers."

a small, low-risk alteration in the shape of federal cash flows—note this is not an increase in total federal expenditure.

Finally, in the first stage we have looked only at the $4.79 billion per year that might be saved by ending the ISS and SLS/Orion programs. The rest of the NASA budget, particularly the ongoing planetary exploration programs, is not considered. However, as the new paradigm unfolds, its capabilities also make it possible to conduct more exploration for less funding, taking advantage of lower launch costs, orbital assembly, and commercially available deep space capabilities that have the potential to transform the way deep-space exploration missions are done.

For example, asteroid-mining craft must be capable of traveling long distances into deep space, performing complex tasks, and returning data and samples (and ultimately substantial amounts of products). It may be possible to produce variants of these craft for outer-planetary exploration, launching them to LEO facilities cheaply, and using adapted deep-space transfer craft to propel them to their destinations. Asteroid mining would also pay for much of the infrastructure needed to communicate and control spacecraft in deep space. For that matter, NASA might be able to share space on commercial asteroid missions, merely paying to place some of their own instruments on board and use the commercial data system to return their output. Even further, NASA might merely solicit proposals to provide the actual planetary data desired, allowing private resource companies to plan deep-space missions for their own purposes using data sales to government as one of several sources of funding.

By using common systems and components with commercial spacecraft built in larger numbers, and taking advantage of lower launch costs, scientists might be able to get more science out of substantially lower budgets, in turn freeing up further percentages of the NASA budget for more anchor tenancies and Commercial Cargo-style progress payments to take the U.S. space sector further along its development path—and more rapidly. This is how a virtuous cycle can be implemented within NASA's current budget.

5.6 PARADIGM CHANGE BEGINS WITH POLICY CHANGE

The military and aerospace procurement system, in tandem with the appropriations and authorization functions of Congress, needs to change its ways in two particular areas. First, in the case of heavy NASA launchers like the SLS, the government must make a realistic assessment of existing (e.g., Falcon Heavy) and forthcoming (e.g., BFR and New Glenn) heavy launchers to determine whether the high costs (both of acquiring SLS, and operating it) are now justified in continuing it, when equivalent capability is available, domestically from private sources.

Second, federal agencies must review the way they procure space transportation for what are legitimately their own missions—goals like the ongoing planetary exploration and the space science program, weather satellites, and the GPS satellites (whose constellation must regularly be replaced over time). These are still mostly procured in the “exploration” mode, where a government agency, (NASA, NOAA, or the Department of Defense) contracts with an aerospace company to build a rocket, specifies the hardware in great detail, requires cost documentation on everything in great detail, and then pays the contractor to run the launch operations. The Commercial Crew and Commercial Cargo programs for ISS have attempted to move to a more commercial paradigm—the equivalent of buying a scientist an airline ticket instead of buying an airplane so that the government can fly him. However, under the guise of guaranteeing crew safety, the old paradigm is creeping back in. A more systemic reform may be needed to aid the transition to commercial-style operation.

Pulling U.S. space policy out of its structural rut begins with such policy changes. Our lone commercial space industry of satellite launch again exemplifies how this plays out.

The Roots of Commercial Private Satellite Launch

Satellite launch remained a government service until after 1986. Then in a sharp policy change, the Reagan administration forbade NASA from offering commercial services on the Space Shuttle and told the DoD to end its reliance on NASA as well. The private launch industry of today has its roots in that decision, and even so, it has taken a generation for two viable competing companies to develop from scratch the means to effect private launch. In their wake, more companies are rising to the challenge.

Human spaceflight requires a more sophisticated approach, and is therefore behind in commercialization, in part because NASA, as the largest actual user of human orbital spaceflight at present in the U.S., has used its position as buyer to become a de-facto regulator of human launch, despite having no legal mandate to do so.[75] *In spite of many opportunities to simply make crewed variants of the same commercial spacecraft carrying cargo to the ISS, NASA has demanded extensive changes and dictated even the subtlest changes in design features of the spacecraft and launch vehicles used, cleaving to the hand-crafted approach rather than the commercial, standardized "boxcar" favored by private industry. As a result, when U.S. citizen Dennis Tito purchased a ride to space in 2001, he had to do so on a Russian spacecraft. And even as private companies are developing human rocket transport, NASA has chosen instead to continue to rely on Russian spacecraft for U.S. astronaut flights to the ISS at ever-escalating prices. As of this writing, the first commercial U.S. human spacecraft to orbit has not yet flown, in spite of the reasonable likelihood that an astronaut wearing a space suit could be carried to the ISS on the next cargo flight of SpaceX's Dragon capsule with essentially no modification.*

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[75] That power is lodged by statute with the secretary of transportation.

PART 6

TRIGGERING THE VIRTUOUS CYCLE FOR SUSTAINABLE PROGRESS WITHOUT ADDITIONAL NASA FUNDING

6.1 OVERVIEW

In order for the private sector to invest in space technology, it must have a reliable asset to leverage. The first of these would be provided by improvements to regulatory policies that would create clear and legal property rights in space. That begins the flow of investment to the private sector. Requiring NASA to procure as much as possible through private means creates another reliable funding source for the private sector to leverage. The money NASA saves through private procurement should be invested in the sort of space infrastructure (for example, fuel depots, Lagrange-point storage centers, in-space water procurement, etc.) that can help develop the industry. Once the private sector has infrastructure on which to allow industry to flourish, it can be a self-sustaining cycle, just as with air, land and sea transportation and commerce.

An illustrative example of such a virtuous cycle might have the following steps:

#1 Regulatory and policy procurement improvements (see Part 7 for details) remove regulatory uncertainty, create unambiguous and legally enforceable property rights (or effective analogues thereof) in space. This allows private investment to begin flowing and turns federal needs for space capability into one segment of a reliable market for space transportation on commercial terms, giving private providers an attractive and legally solid market in which to operate.

#2 Private space launch providers, encouraged by a more positive regulatory regime and the emergence of more reliable markets, create more efficient launch vehicle production capabilities and accelerate the reusability of launch vehicles. As a result, launch costs drop to or below the $1000/lb price target from multiple providers.

#3 As launch costs drop, companies are able to fund plans to develop private facilities in low Earth orbit. NASA lets anchor-tenant contracts for space on private facilities to replace the International Space Station, which is currently planned for de-orbit in 2024. NASA funding supports (preferably by means of an anchor tenancy, purchase guarantee, or other market-oriented mechanism) the development of a base for a variety of co-orbital facilities, a fueling depot (with sufficient solar power to dissociate water to oxygen and hydrogen) initially supplied from Earth but gradually transitioning to lunar and asteroid sources, a variable-gravity biological research facility to determine how higher animal and human life copes under various gravity levels, including lunar and Martian gravities, and a pilot space solar power system. These facilities are placed in low equatorial orbit, and launch is relocated to equatorial locations.[76]

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[76] Initially from the big European equatorial launch site in Kourou (French Guiana) and barge launch in the Pacific, while an equatorial spaceport is built on American territory (such a Palmyra Atoll south of Hawaii). Equatorial launch and equatorial orbit have two large benefits: First, the position further enhances the payload capabilities of launchers, since the Earth rotates faster at the equator and the additional velocity adds to the payload capacity of the launch vehicle when launched to the east; Second, by avoiding the higher radiation exposures of the South Atlantic Anomaly, equatorial orbit increases the allowable exposure of humans to extra-vehicular activity, making on-orbit assembly more readily feasible, and allows habitats intended for long-term human occupancy to be built with much less radiation shielding, lowering their cost.

Additionally, NASA creates a Strategic Orbital Water Reserve (on the model of the government's Strategic Petroleum Reserve) and issues an open purchase order for as much water as can be delivered to the orbital fuel depot at a cost target of $1000/lb., the price decreasing by 5% every year to a floor of $500/lb. in 10 years. Such future stability will suffice to generate private interest.

#4 As LEO orbital refueling facilities become available, launch companies begin to change the way payloads are launched to GEO. They now deliver the satellites to an LEO terminal, where an orbital transfer vehicle (OTV) fueled from the depot takes it to GEO, releases it, and the OTV returns to its LEO home port (in the scenario in which a fueling depot is placed in LEO). This reduces the cost of placing a payload in GEO substantially. (The typical rule of thumb is that a launch vehicle can deliver a given payload to GEO for approximately three times the cost of its delivery to LEO.[77]) By using an OTV fueled from a LEO refueling depot, therefore, a payload can be placed in GEO for a third of the price per pound of a conventional launcher, plus the price of the OTV ride. The latter will depend on the cost of the OTV, amortized over the number of trips its service life might provide, plus the direct costs of the trip, including refurbishment costs from the previous mission, fuel, and personnel time allocated to the trip.

The lower price and availability of fuel and services in LEO permit the beginning of space manufacturing with intermittently human-tended additional facilities, not attached to the main infrastructure, but in the same orbit, and nearby, allowing simple, cheap in-space shuttles to quickly and cheaply transfer people and cargo among such facilities. (The technical term for such close but independent units is "co-orbital free flyers".) Additionally, asteroid mining companies begin fueling prospecting voyages from the LEO fueling station. NASA begins funding of an Earth-Moon transportation system, using anchor contracts to buy rides on a private transport service from LEO to lunar orbit, and from there descending to the lunar surface via a specialized lander/ascent vehicle. Pilot mining projects begin to bring lunar ice-derived water from the lunar south pole to LEO where it is sold to the fuel depot. Another pilot mining project begins separating aluminum ore from the lunar regolith and smelting it, returning it to LEO for fabrication.

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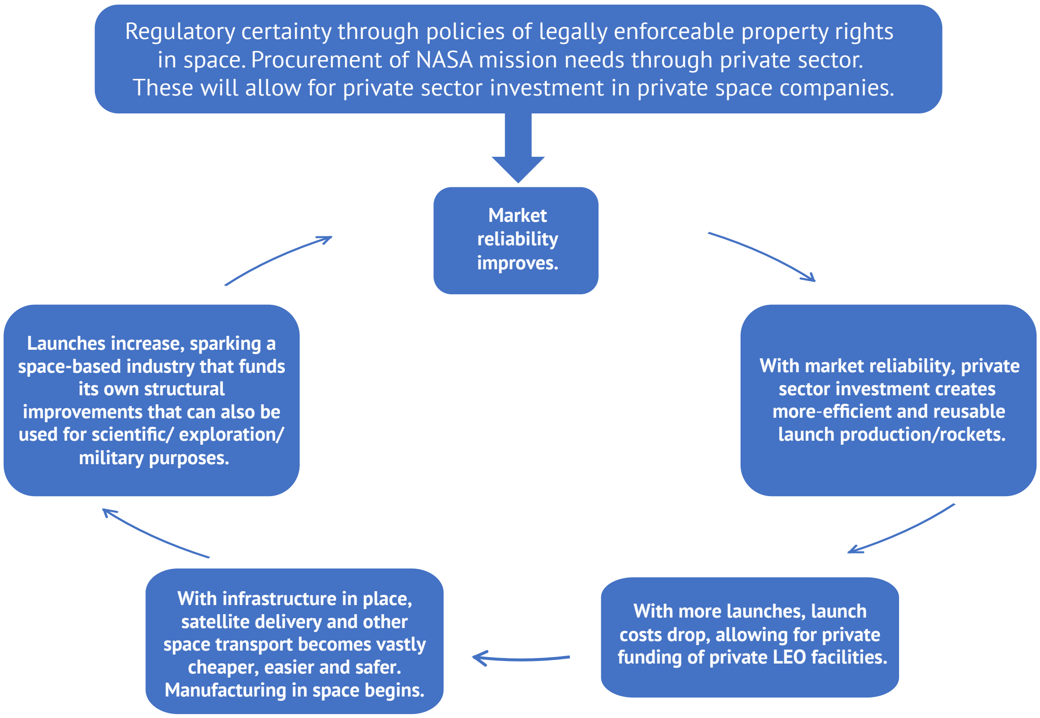
[77] Chatters, Edward P, Bryan Eberhardt and Michael Warner. *Orbital Mechanics*. Chapter 6, Launch Costs section. Air University, U.S. Air Force http://www.au.af.mil/au/awc/space/au-18-2009/au-18_chap06.pdf

#5 The greatly increased launch rate due to the growth of activity in LEO and beyond reduces launch costs to $500/lb. Planning begins for a mass accelerator system on Earth for acceleration-tolerant payloads, while a smaller mass accelerator system is installed on the Moon for cheap transport of water, lunar ores, and shielding mass to a stable spot in the Earth-Moon system (one of the Lagrange points), where a habitat is placed to serve as a transit node. Research results from the variable-gravity facility establish that Martian gravity is adequate for long-term habitation, and that a large-scale Mars transport using centrifugal force for pseudo-gravity is under construction in LEO, using lunar aluminum and asteroid nickel-iron for structure, and lunar water for consumables and shielding mass. The same techniques are being used to construct a large rotating habitat in low-Earth equatorial orbit. Space Solar Power Satellites begin delivering power to Earth locations. Several lunar bases are continuously inhabited, with outlying installations for astronomy and high-risk biological research.

Figure 6 shows how such a virtuous cycle is initially spurred by regulatory certainty, setting the cycle to sustain itself as it develops economic traction.

FIGURE 6: THE VIRTUOUS CYCLE FOR SUSTAINABLE PROGRESS



Regulatory certainty through policies of legally enforceable property rights in space. Procurement of NASA mission needs through private sector. These will allow for private sector investment in private space companies.

Market reliability improves.

With market reliability, private sector investment creates more-efficient and reusable launch production/rockets.

With more launches, launch costs drop, allowing for private funding of private LEO facilities.

With infrastructure in place, satellite delivery and other space transport becomes vastly cheaper, easier and safer. Manufacturing in space begins.

Launches increase, sparking a space-based industry that funds its own structural improvements that can also be used for scientific/ exploration/ military purposes.

6.2

TRANSPORTATION INFRASTRUCTURE'S NETWORK EFFECT: MAINTAINING THE VIRTUOUS CYCLE

Major transportation infrastructure projects create industries through the "network effect": they bring together what were previously local or regional marketplaces into a wider market area, and the number of new users they attract is more—often far more—than the sum of the individual markets they connect. By making it possible for more users to go more places more rapidly, cheaply and easily, more parties make the decision to go than previously. The network effect means that the more points you connect, the more the use multiplies, rather than merely adding. This is easily seen in past transportation infrastructure projects such as the U.S. Interstate Highway System and the Transcontinental Railroad.

Even adjusted for inflation, the Interstate Highway Program has returned six dollars for every one invested.[78] The Transcontinental Railroad, despite the poor supervision of the private partners involved, was similarly a great benefit to the U.S. in the long run. In addition to the indirect value of revenues gained from new settlement areas, the U.S. government got half-price transport of its cargoes and personnel over the land-grant railroads. This benefit (i.e., the obligation to transport government goods and people at 50% off) was so useful to the government that heavy wartime rail traffic threatened to bankrupt the railroads, which were having trouble affording proper maintenance—which ultimately threatened war production and troop/weapons movement. As a result, the government voluntarily relinquished its half-price transit in 1944.[79]

Despite its frequent use in space literature (to the point of cliché), the Transcontinental Railroad analogy is somewhat more applicable than recent examples, for several reasons. Firstly, it involves creating a transport capability over very lightly inhabited space, unlike the Interstate System, which merely upgraded existing capabilities between settled points. The Transcontinental Railway made its own customers by making dense settlement feasible at all. Secondly, the railway was created by a public-private partnership, in which most of the cost was contributed by the private sector. Some was guaranteed by the

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[78] Cox, Wendell and Jean Love. "40 Years of the U.S. Interstate Highway System: The Best Investment a Nation Ever Made." American Highway Users Alliance. 1996. http://www.publicpurpose.com/freeway1.htm

[79] Railroad Land Grants. Association of American Railroads. https://www.aar.org/keyissues/Documents/Background-Papers/Railroad-Land-Grants.pdf

government, conditional on performance and with the assets of the railroad pledged as security. In actual fact the guarantees were never called on. The rest of the cost was met by subsidy, with (as previously noted) an obligation to provide discounted services in return, an obligation that ultimately returned far more value than was paid in subsidies. This general approach could be used in a public-private space infrastructure partnership, obviously using modern fiscal and reporting controls.

The creation of such a space transportation infrastructure will open a great storehouse of resources to U.S. and global industry. We can improve on historical approaches with much more-sophisticated public-private partnerships. Access to resources and abundant clean energy will drive the private involvement, while vast environmental and economic benefits will drive the public involvement. Bringing together the best capabilities and most incentive-compatible roles of each will enable the most efficient and effective approaches, even if NASA’s $20.7 billion budget does not grow.

6.3

REALLOCATING FUTURE NASA FUNDS

The ISS budget: $1.2 billion. Since the ISS is already scheduled for de-orbiting, it would be reasonable to propose de-orbiting it earlier, especially if an alternative private facility with greater capacity and less taxpayer support were to replace it in the near future. Such an alternative facility could be a first step toward in-space infrastructure. The ISS budget might be available for reprogramming somewhere in the early 2020s.

Orion and SLS: $4.79 billion in the 2018 NASA budget. As discussed earlier, this is directly competitive with a private alternative that is almost certainly cheaper and better. It is likely that even if SLS and/or Orion are defunded, there will be substantial termination costs, and there will be a strong incentive for NASA to find alternative internal employment for the SLS and Orion workforces. Funding from these programs will probably take several years to become fully available for alternative uses.

Science. This **$6.2 billion** includes $2.2 billion for the planetary program (NASA’s exploratory function), a half-billion for the Webb space telescope, and about $3 billion for all other science, including Earth science. This last category is worthwhile science, which no doubt might be performed more cheaply. There is some question as to whether it belongs in NASA or should be spun out and funded through the National Science Foundation. There is probably some synergy in having the research co-located with the planetary science. If done right, however, planetary (including asteroid) missions could be turned into a useful market segment for private providers. Experimenters should be required to explore cooperative funding arrangements with private parties, such as asteroid mining companies, as part of their mission design and transportation selection process.

Aeronautics and space technology, at roughly $1.4 billion. This was the historic core function of the N.A.C.A., NASA's predecessor. It is still valuable, has a constituency of companies that incorporate its output into their products, and in general is a worthwhile activity. As with space science, there is some question as to whether NASA is the home for it, especially the aeronautics portion.

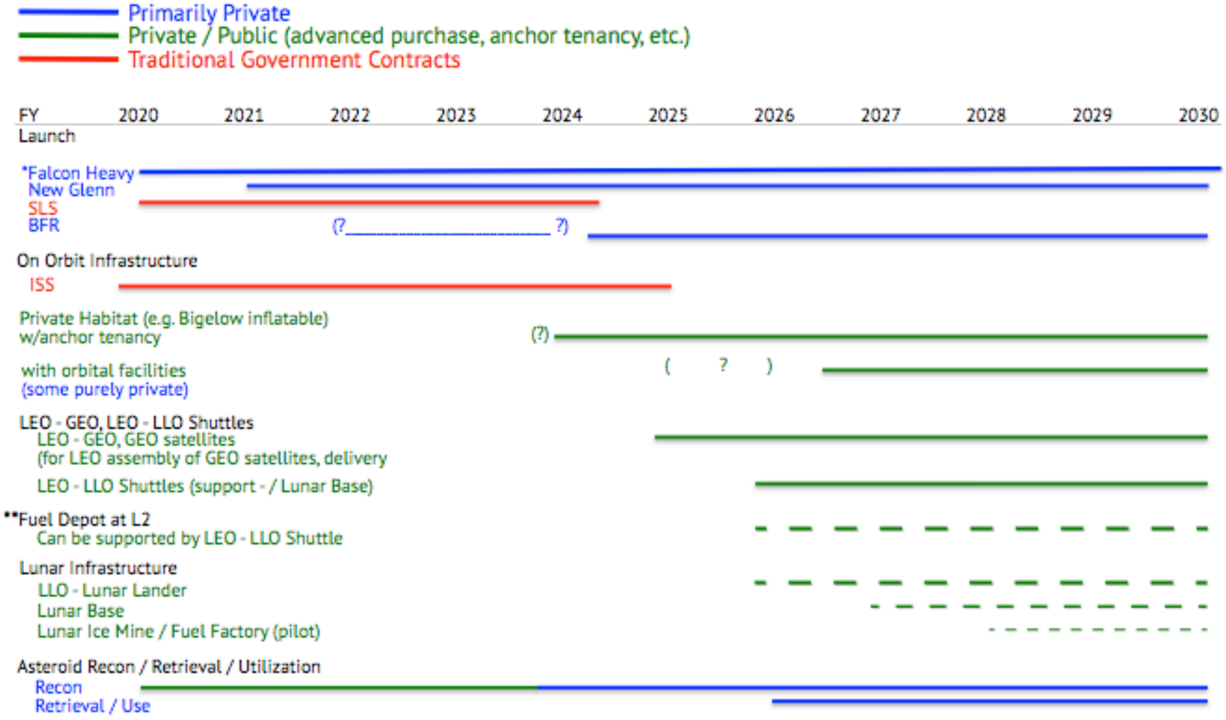
Safety, security, construction, environmental, etc.: About $2.5 billion.

Given these calculations, we see a picture of roughly $5.9 billion per year for infrastructure becoming available in the 2021–2025 time frame, coming primarily from the SLS, Orion, and ISS budgets. Altogether NASA should be able to leverage this public funding somewhere between 3:1 and 10:1 with private capital if the legal framework can give investors certainty as to title and operating environment. Given the greater efficiency of private operation, this should be adequate to launch the virtuous cycle described previously. In addition, pushing for policy to make all federal space activities shop private first when possible will add the NASA space science and exploration activities to the support base for space infrastructure and quite likely add the larger federal national security space budgets (civil, military, and intelligence) to the customer base as well.

6.3.1 QUANTIFYING EFFECTS OF THE PARADIGM SHIFT

The potential exponential cost reduction and technological advancement of such a paradigm shift cannot be precisely quantified. This is especially true in a frontier like space, where we have only begun to identify caches of resources and uses of physical and material properties of space. These rough order of magnitude cost and timeline estimates are based on our current technological capability, knowledge of space resources and current costs, with firm estimates in the near future—through about 2025, when infrastructure would be complete enough to support a fully commercial space industry. From that point, estimates are less firm, as depicted by dotted lines in Figure 7, as we cannot know which technologies will dominate and which additional resources and efficiencies will proliferate. New ideas will be tested and many will fail. Some companies will fold and others rise up with new perspectives. Such a pattern and outcome is consistent with past technology leaps and acquisition of frontiers. But we know from history that transportation infrastructure catalyzes economic advancement, and that industries are created and sustained through private investment and commerce.

FIGURE 7: TIMELINE FOR TRANSITION TO PRIVATE, COMMERCIAL SPACE PARADIGM



* Falcon Heavy has been in service since 2018

**Technologies for a fuel depot at L2 are proven feasible but development has not begun.

Currently, we are experiencing a radical transformation in space transport as private actors and market forces have slashed the costs of accessing space. These advancements have already greatly reduced costs for not only NASA, but also civilian (mostly satellite) and military space transport as well. These cost reductions, especially for classified military applications, cannot be quantified within the current available budget breakdowns, but are likely to follow similar cost reductions to NASA's. As with other transportation industries, increasing efficiencies continue to drive down costs, but order of magnitude efficiencies come with infrastructure that can sustain a space-faring industry, where NASA and military and civilian companies become customers on private space transport, as we have seen with shipping and rail industries and even with Antarctic exploration. We argue for shifting to an approach based on our current reality of new private launch capability at a fraction of the cost of government procurement, whereby government invests in infrastructure and allows the private sector to innovate to develop efficient transportation and financially sustainable use of space resources.

PART 7

GOVERNMENT'S NEW ROLE IN SPACE

7.1

GOVERNMENT'S LEGAL ROLE IN IMPLEMENTING A SPACE INFRASTRUCTURE

The U.S. government has a number of functions, several of which have a role in implementing a space infrastructure. Among these functions are:

- Defense
- Foreign Relations
- Police (Constabulary Function)

In order for the private sector to operate in space, it requires a number of functions that are taken for granted on Earth, but currently do not exist in space. Any government plan for encouraging a space infrastructure must include the establishment of a secure and dependable political and legal framework in which private activity can do its job.

Defense: Currently, critical defense functions—including communications, reconnaissance and geospatial location (i.e., GPS)—depend on America's ability to use space unmolested. All of these capabilities will be targets for enemy action in any major conflict against a space-capable power. (The list of such powers currently includes China, Iran, Russia and

North Korea, and will continue to grow.) Future commercial space infrastructure will also be a target in such cases.

Currently, the U.S. has little capability to protect either governmental or private assets in space from either Earth-based or space-based attack. This must be remedied within the foreseeable future. Currently, the U.S. Air Force is the designated organization for all space defense functions. NASA has no role other than to lend support where it can; in fact, NASA depends on the Air Force for many operational functions, such as overall management of the launch ranges. There has been a several decades' long active debate as to the desirability of creating a separate armed service under the secretary of defense to carry out the U.S.' space defense functions. Various options discussed have included a "Space Corps" within the Department of the Air Force (in the same way that the Marine Corps is within the Department of the Navy), or alternatively an entirely separate Space Force, in the same way that the Air Force was separated from the Army.[80] This issue has now come to a head with President Trump's stated desire to create a separate space armed service. As of this writing, the Department of Defense is drafting a plan to comply with the president's call for a "sixth Armed Service to join the five already existing." That language could be taken to endorse either an Air Force or Marine Corps model, or even a Coast Guard model in which a Space Guard would be under a civilian Cabinet department (e.g., Transportation) in peacetime but come under the Department of Defense in time of war or emergency. The "five existing services" language includes all of those models. Although examining the merits of the various models is beyond the scope of this paper, we endorse the general principle of raising the level of focus on space in the defense establishment.

Foreign Relations: Foreign relations, specifically the negotiation and implementation of international law regarding activities in space, is currently a critical-path item in the growth of private activity in space. Currently, the basis of international law that governs space consists of a treaty—the 1967 Treaty on the Peaceful Uses of Outer Space, generally known as the Outer Space Treaty[81] or "OST" and its appended Liability Convention[82]—which sets

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[80] "Debate Over Separate Space Force in Spotlight At Space Symposium." *Colorado Springs Gazette*. April 15, 2018. http://gazette.com/debate-over-separate-space-force-in-spotlight-at-space-symposium/article/1624404. The Trump administration has now chosen the Navy/Marine model with a separate space service within the Department of the Air Force.

[81] "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies." 1967.

[82] "Convention on International Liability for Damage Caused by Space Objects." 1972.

the rules for liability from outer space activities. The U.S. has signed and ratified these treaties, and domestic regulation serves to implement them for American-flag operations. There is also a Moon Agreement,[83] which seeks to establish the rules for use of the Moon's and other space bodies' resources, and since it was signed by more than five governments, it is technically part of international law.

But none of the signatories who have signed and ratified the Moon Agreement are actually spacefaring powers. The U.S. signed it at the end of the Carter administration, but never submitted it to the Senate for ratification. The Trump administration, like every administration since its signing, has no plans to submit the Agreement to the Senate during its current term of office. The Outer Space Treaty was negotiated and signed in 1967 at a time when no party expected significant private activity in space, or the establishment of mines and settlements on the Moon or other extraterrestrial bodies. It banned any claim of national sovereignty in extraterrestrial bodies, required any private activity to be subject to regulation and control by a sovereign government, affixed liability for damage done to the overseeing government, but provided no further details regarding private claims of ownership of extraterrestrial resources.

The Moon Agreement calls for the establishment of an international authority to license and tax the use of lunar and planetary resources, along the lines of the Seabed Authority established by the Law of the Sea Treaty, but it remains a dead letter in the face of refusal of any space-going power to sign and ratify it. Most interpretations of space law accept the in situ use of extraterrestrial resources—that is, lunar or Martian resources could certainly be used to build and supply a lunar or Martian base. They also accept that asteroid resources, at least asteroids of a certain size, could be captured, mined or otherwise converted into privately owned resources and returned to Earth or Earth orbit and used and/or sold. The analogy is a bit like fish in the open ocean—while they are swimming in the sea, they belong to no person and no nation. Anybody can fish for them, but once they are caught, they are property.

As a result, the space mining industry situation allows some private space development activity to begin, but with substantial handicaps for large sectors of it. Existing U.S. legislation clarifies the ownership of resources derived from asteroids—the "caught fish" of the above-mentioned metaphor. Luxembourg, seeking to be an international financial center for space business, has also followed suit. Until firm title can be laid to

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[83] "Agreement Governing the Activities of States on the Moon and Other Celestial Bodies." 1979.

extraterrestrial lands and resources, land title to extraterrestrial bodies cannot be used as collateral for debt financing, except at a substantial discount, if at all, because of the shadow on the legitimacy of the claim. Companies projecting profits from use and sale of space resources in fundraising documentation could be at risk of prosecution for securities violation, no matter how carefully disclaimers and risk disclosures are written. This forces companies seeking to raise funding for space development to rely on a fairly narrow range of incentives and will increase the pressure from venture capitalists to obtain government subsidies or guarantees.

In 2016, domestic legislation[84] was introduced in the House of Representatives (American Space Renaissance Act) by Rep. Jim Bridenstine, now the NASA administrator, to offer a legal safe harbor (at least within the U.S.) for companies seeking to claim and use extraterrestrial resources, but such guarantees are weak at present. Although it did not pass in that session, some of its provisions were incorporated into other legislation, and it is likely that Administrator Bridenstine will work with the Administration to pursue these ends further. Ultimately, the U.S. must substantially improve the international legal framework, either by replacing the current Outer Space Treaty, Liability Convention, and Moon Agreement with a more workable and commerce-friendly arrangement, or by obtaining a general consensus on a more realistic and workable interpretation of the existing agreements.

The space development community continues to debate whether the current treaty situation can be remedied by amendment, interpretation and domestic legislation, or whether the treaties should be rejected and the U.S. should seek to promote a new treaty. Arguing against the latter, some hold that, in the current international climate, a new treaty could easily be worse than the old one.[85] The current position of the Administration, as articulated by National Space Council Chief of Staff Scott Pace, is that the OST does not prevent private exploitation or use of resources, and notes that the OST does not use terms like “common heritage of mankind” or “res communis” to describe space, unlike, say, the Law of the Sea Treaty or the Moon Agreement, but merely declares space “the province of mankind,” a less restrictive term that does not imply any ban on property. “Province of mankind” merely affirms the right of ships of any nation in peaceful pursuits to navigate

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[84] In the 115th Congress the American Space Renaissance Act bill was numbered HR 4945.

[85] A representative sample of the argument can be found in John Hickman’s article “Still Crazy After Four Decades: The Case For Withdrawing From The Outer Space Treaty” in *The Space Review*, September 24, 2007. http://www.thespacereview.com/article/960/1

space freely. Therefore, the U.S. does not pursue a rejection of the OST, but merely a reasonable interpretation.

Recent discussions have floated one idea that has merit: negotiating with some number of market-oriented, space-faring or space-using nations and establishing a mutual recognition agreement to recognize each other's property claims in space and mutually resolve conflicting claims between parties from two or more signatory states. This would allow property claims recognized by the U.S. government to be sold or used as security in markets in, say, the United Kingdom or Japan without fear of fraud prosecution, thus greatly increasing the total amount of capital that could be tapped for investment. This could be done within the framework of the OST, or outside of it if all such states withdrew.

The Constabulary Function: This function consists of maintaining law and order in spacecraft and space habitats under the U.S. flag, protecting the property of Americans against threats below the level of war, conducting search and rescue in space, and mitigating or eliminating hazards to space navigation. Maritime constabularies such as the U.S. Coast Guard conduct all four such functions at sea for the U.S.; other nations divide the functions in different ways—the Canadian Coast Guard, for example, does not carry out the law and order function, leaving that to the Maritime Division of the Royal Canadian Mounted Police.

There has been substantial discussion over the past two decades over the idea of a U.S. Space Guard as a constabulary force in space carrying out those and other routine operational functions of government in space.[86] Today, NASA commanders in spacecraft and space stations have arrest powers, which have never been used, but as populations in space grow, it is certain that such a function will be needed. NASA is, by its nature, unsuited to routine operations, so the creation of a Space Guard might be a good opportunity to offload more functions from NASA, helping refocus it on its destiny at the far frontiers of exploration.

As noted preciously, the debate over a sixth U.S. armed service for space will impact the need for delivery of constabulary services in space. A Space Service may indeed follow the Coast Guard model, which would include constabulary functions as one of its basic roles. However, if an Air Force or Marine Corps model is chosen, it reduces the chance that a

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[86] Bennett, James C. "Proposing a 'Coast Guard' For Space." *The New Atlantis*. Winter 2011. https://www.thenewatlantis.com/publications/proposing-a-coast-guard-for-space

separate Space Guard would be established in the near future, as the political capital to establish two organizations may be lacking. In that case a space constabulary arm might be created as an autonomous part of a Space Service.

7.2 GOVERNMENT'S SCIENTIFIC ROLE IN SPACE

7.2.1 BASIC AND APPLIED RESEARCH

Beyond the resources already discovered in space that have commercial potential, more exploration is needed, as well as continuing research of the space environment. This will be greatly facilitated by infrastructure, but the lack of immediate return on investment makes it an unlikely candidate for private investment. As such, this must be a continuing mission for NASA.

NASA's predecessor—the N.A.C.A.—carried out basic and applied research in aeronautics, and provided this research to U.S. aircraft manufacturers to aid them in maintaining technological competitiveness. The N.A.C.A. airfoils, for instance, became the reference standard for wing cross-sections for all manufacturers, providing a useful toolkit for aircraft design.[87] This function has also been provided for space since NASA's founding, but since manufacturers were historically working on either NASA or military contracts, the research was typically folded into the manufacturing contracts.

This function should now be reoriented to support America's private space manufacturers and operators. The rest of NASA's planetary and space science research will also be invaluable to space resource prospectors and habitat builders, and NASA should continue to maintain its expertise, while gradually reconfiguring these capabilities to support space utilization, as the Department of Agriculture supports farmers.

7.2.2 SPACE LAUNCH AND LAUNCH VEHICLE DEVELOPMENT

Today NASA is still in the launch vehicle design and development business with the SLS, scheduled for a first flight in 2019. The U.S. faces a choice of two quite distinct paths: one, to continue to support SLS and Orion at current levels, and ultimately conduct a space program consisting of a small number of launches that will lift large facilities and deep-

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[87] Clarkson University Publications. "The NACA Airfoil Series." http://people.clarkson.edu/~pmarzocc/AE429/The%20NACA%20airfoil%20series.pdf

space missions on one piece, ready to operate when launched, or at most in a small number of components that can be easily mated in orbit. The other is one in which privately developed and operated medium-size launchers are sufficient to start initial operations, and space capabilities rely on assembling and fueling space hardware in space. The second path requires many more individual launches than the first, putting a premium on low-cost launch and reusability.

Advocates of the first path point out that the private sector has promised many capabilities that have been much slower to appear than initially promised, and many companies have disappeared, taking their promises with them. The promises of low launch cost, reusability and orbital assembly mostly remain promises, although SpaceX has been steadily demonstrating greater and greater capabilities over the past few years. Meanwhile, the SLS relies mostly on proven components—in fact, the first flights of Block 1 SLS will use actual Space Shuttle engines that were produced for that program as spares and have been sitting in storage.[88] The first flight is now near, and (as SLS advocates argue) conservatism suggests that spending the relatively few billions to acquire the capability is only prudent until the private sector has actually fully demonstrated equivalent capability.

In response, advocates of the alternative path point out that the SLS has had even more stops and starts in its development path—considering that it is only the latest of a long line of Shuttle-derived launchers going back to the “Shuttle-C” (for “Cargo”) proposals of the mid-1980s, and yet it is only just now about to fly. True, many of these stops and starts have been due to Congress, but that is part and parcel of the public path, and would remain so all the way along in the future. The real cost of the public, large-launcher path is the opportunity cost—the matter of what the same amount of money spent on SLS could accomplish if spent on buying commercial launch service on private flights and contracting for the building of infrastructure on orbit, and paying for a government role as an “anchor tenant” on private facilities in space such as a research facility or a fuel depot in space. Such actions could, as previously discussed, leverage much larger amounts of money from the private sector for space capabilities. The COTS, CRS, and CCDev programs are pathfinders for such a leveraging strategy.

Although SLS funding should optimally be diverted to a commercial purchase strategy, the Administration likely will not expend the political capital needed to terminate the current

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[88] Space Launch System Facts. NASA. https://www.nasa.gov/sites/default/files/atoms/files/sls_fact_sheet_final_10112017.pdf

program, given the large impact the program's spending has on Alabama and Florida. (In particular, Florida will probably be a key, closely contested state in the 2020 presidential elections, so no reductions to the SLS workforce at Cape Canaveral are likely to be announced until after that year.) A compromise solution might be to push for increased spending on commercial service purchase, while SLS proceeds to flight status. The SLS will run out of surplus Shuttle engines by the early 2020s, and a decision point will arrive in which substantially more funding would have to be spent to start production of a new engine for SLS. If, by this time, SpaceX's Falcon Heavy has flown with a 60-ton payload, or the recently-announced SpaceX BFR has flown with 150 tons, or another private option has proven itself, it will be easier to make the argument that there is less risk in taking the off-ramp from that path.

7.3

RETURNING TO NASA'S REAL VOCATION: EXPLORING AT THE EDGE OF THE NEW FRONTIER

Scarcely had the ink dried on the signatures on the Louisiana Purchase in 1803 than Thomas Jefferson began planning what became the Lewis and Clark Expedition. The following year, their Corps of Discovery began their journey to map and inventory the young country's purchase. From that time onward, the exploration function has been a role of the U.S. government. The Louisiana Purchase doubled the size and resources of our fledgling nation.

Today, the U.S. verges on accessing a far greater region of resources, including the prospect of scientific discoveries that might revolutionize our understanding of ourselves and our universe. The harvesting of this bounty will mostly be done by the American private sector, as has always been the case. But the U.S. government will have key roles in defending, policing, adjudicating and facilitating this harvest.

NASA's past accomplishments have been key in bringing us to this threshold. But as the private sector fills and now begins to eclipse public use of technology, we approach a fork in the road. Will NASA try to hold on to mature functions that can now be turned over to the private sector or other civil government agencies, or will it relinquish those roles and focus on its core mission—the exploration and study of further frontiers? We believe that, as we have demonstrated, the time is right for government to transfer all near-Earth launch and habitat functions to the private sector. Other support functions might best be given to a new entity such as the proposed Space Guard, organized for the performance of routine functions. This will permit NASA to become a pure exploration and research entity, preserving the truly unique teams and capabilities of its laboratories. Although it will be smaller, it will be more focused, targeting its budget dollars to its distinct core missions of research and exploration. As creating key infrastructure stimulates a private and commercial paradigm, space exploration missions will also reap the benefits of less expensive and more frequent launch in standardized spacecraft, allowing for a wider range of exploratory probes bringing back a much wider and deeper sample of data. As non-critical functions get pared away, it will also be possible to reduce the headquarters overhead, as the span of control becomes greatly reduced.

PART 8

RECOMMENDATIONS

To set NASA and the U.S. space sector on the right path, we make the following recommendations:

LEGAL/SECURITY RECOMMENDATIONS:

The U.S. government should continue active planning as begun by the current Administration for the defense and internal policing of U.S.-flagged spacecraft, space stations, and extraterrestrial facilities, including consideration of creating a Coast-Guard-like constabulary service for space. The U.S. government should also create a working group, including representatives of the space development community, to examine and make recommendations on the space treaties and international legal environment as they affect the U.S. space sector. Upon its reporting, the U.S. government should give due consideration to its recommendations regarding interpreting, modifying, and/or withdrawing from existing and pending space treaties and agreements. The U.S. should begin discussions with other market-oriented, space-using nations on a multilateral agreement within or without the framework of the Outer Space Treaty, recognizing each other's property claims on space assets.

Congress should create legislation establishing U.S. recognition of transferable resource rights, analogous to private property rights, based on first capability of reaching space resources, and transferable rights to keep-away zones around space objects, consistent with international law. It should, furthermore, create safe-harbor provisions for buying, selling, and hypothecating such rights on open markets or exchanges and in commercial and financial contracts under U.S. jurisdiction without risk of prosecution for fraud, provided that such rights are appropriately registered and verified by the U.S., consistent with international law.

PROCUREMENT POLICY RECOMMENDATIONS:

The U.S. government should declare a policy of reliance on the private sector for launch operations and in-space facilities on terms and conditions similar to those of private sector users, starting with commercial resupply and crew transportation to ISS. The baseline future scenario for an ISS should be the government's letting of anchor-tenant contracts for research space in an orbital facility or facilities.

NASA missions of any sort, including science and exploration missions, should be performed whenever possible by issuing purchase orders for results, such as data gathered from specific targets under specific conditions, rather than contracting for the development of means of obtaining such data. Evidence of market failure, judged by an agency external to NASA, should be required before permitting NASA contracting for construction or operation of spacecraft.

The U.S. government should establish a working group that includes representatives of the space development community to recommend procedures and mechanisms to ensure that NASA's spaceflight and space operations research supports private sector research and development in the same way NASA and its predecessor, the N.A.C.A., support the aviation industry.

POLICY IMPLEMENTATION RECOMMENDATIONS:

The U.S. government, in an agency external to NASA, should establish criteria to determine when the U.S. private sector capabilities in heavy-payload launch become sufficiently reliable that NASA should establish a timetable for exiting the development of large-payload launch vehicles and winding down existing large-payload vehicle launch operations.

The government should select NASA's future exploration missions (crewed and uncrewed) so they can take on propellant from an on-orbit facility, establish advance purchase contracts that are financially trustworthy for the purchase of that propellant and, with private industry, develop standard interfaces and interconnects for the delivery of that propellant. Industry should be allowed innovative freedom to find the best delivery mechanism. Such a pilot on-orbit refueling facility should be a 10-year objective, including a government open purchase order for delivery of water to an orbital fueling facility at a fixed price equal to the effective price of fuel launched from Earth, which should be unlimited for the first 10 years of operation.

NASA, in its periodic setting of solar system research and exploration priorities, should give preference to dual-purpose probes—i.e., those that serve both scientific research goals and also provide useful scouting data for space resource harvesting, and further possible economic uses of space and its properties.

ABOUT THE AUTHORS

Authors **Jeff Greason** and **James Bennett** have extensive experience in commercial space ventures.

Jeff Greason was a founder and initial CEO of commercial space company XCOR Aerospace, with prior experience at Rotary Rocket and Intel. In 2009 he was a member of the Augustine Committee on U.S. human space flight plans. He co-founded the Commercial Spaceflight Federation and served as one of its directors for many years. He was involved with the passage of the Commercial Space Launch Amendments Act of 2004 and served on the Commercial Space Transportation Advisory Committee (COMSTAC) for many years. Greason is currently chief technology officer of Electric Sky. He is an associate fellow of the American Institute of Aeronautics and Astronautics, a governor of the National Space Society, and holds 25 U.S. patents.

James Bennett was a co-founder of two space-launch start-ups, Starstruck, Inc. and American Rocket Company, which pioneered hybrid rocket propulsion. He served on the 1984 White House Task Force on Space Commercialization and was later a member of the Secretary of Transportation's Commercial Space Transportation Advisory Committee (COMSTAC). Currently a consultant on commercial space, he is space fellow of the Economic Policy Center, London, and a fellow of the Centennial Institute in Golden, CO. He is also a former board member of the National Space Society.