Leveraging the Emerging Space Economy to Meet Critical Government Needs

The shift is underway. Where should policy makers focus their efforts?
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EXECUTIVE SUMMARY

ROCKET SCIENCE RUT
Stubbornly high launch costs, largely unchanged for over 50 years, have been the primary barrier to the expansion of the space industry.

BREAKING BARRIERS
Over the past decade, launch costs have been lowered by an order of magnitude, thus laying the foundation for the emergence of a new, expansive space economy.

ROLE REVERSAL
With this transition, we expect commercial economic activity to overtake and, in the long-term, greatly exceed government spending on space activities.

EARTH FOCUSED
Today, the bulk of commercial space activities are oriented toward delivering services (primarily communications and Earth observation) to customers on the Earth.

SLIPPING THE SURLY BONDS
Enabled by lower launch costs, new and yet undetermined, industries will emerge in LEO and cislunar space.

BUILDING A NEW SPACE ECONOMY
These emerging industries will deliver new products and services to Earth (i.e., pharmaceuticals, space-based solar power, etc.) but will also support self-sustaining economic activities within cislunar space and the moon.

LAYING A NEW FOUNDATION
Today’s underlying space infrastructure is insufficient to support the development and growth of these new, emerging activities and industries. The U.S. government, working in conjunction with private industry, should focus its investment efforts on building the space infrastructure needed to support the future space economy.

RIDING THE WAVE
Recognizing the paradigm shift underway, the U.S. government must decouple from traditional procurement and regulatory practices and embrace new engagement models that leverage commercial sector innovation and investment to outmaneuver and outpace adversaries.
U.S. SPACEPORTS

SpaceX

OTVS

Moog

OSAM

Northrop Grumman

ORBITAL REFUELING

Orbit Fab

DEEP SPACE COMMS AND SDA

CommStar

COMMERCIAL LUNAR UTILIZATION

Astrobotic
INTRODUCTION

LAUNCHED IN 1906, HMS DREADNOUGHT BATTLESHIP WAS A TECHNICAL AND DESIGN MARVEL, BRISTLING WITH LARGE GUNS AND POWERED BY NEW STEAM TURBINE TECHNOLOGY THAT ENABLED IT TO OUTRUN ALL EXISTING WARSHIPS.

Overnight, HMS Dreadnought revolutionized naval warfare, rendering obsolete the world’s stock of capital ships, along with centuries of prevailing naval tactics. In a like manner, SpaceX’s Falcon 9 rocket, first launched in 2010, has dethroned the industry’s longstanding national oligopolies, shattered price barriers, and ushered in a new era of commercially driven investment, innovation, and optimism.

Was the Falcon 9 really a “Dreadnought moment” for the space industry? It would be hard to argue with the numbers. Since 2015, cumulative private investment in the space sector has totaled $16.8 billion, up from $940 million over the prior decade, while startup activity has exceeded 35 per year since 2015, up seven-fold from ~5 per year averaged in the 2000s. The pace of technological development, long dictated by government-funded Programs of Record, has sprinted forward as a spirit of risk-taking opportunism overtook a stagnant culture of risk mitigation.

Transformative technologies such as optical crosslinks, electronically steered antennas, and on-orbit satellite servicing – technologies that languished for decades as government-funded R&D projects – are on the cusp of entering mainstream adoption. Private companies are actively pursuing suborbital and orbital human spaceflight, more than two dozen are planning commercial moon ventures, and private industry is investing more than $30 billion to develop LEO broadband constellations.

The implications of this ‘new space era’ will be profound. While government spending still dominates the industry narrative today, private sector spending will inevitably become the industry’s driving force, similar to the transition in semiconductor R&D where the U.S. government invested twice that of private industry 40 years ago but is now outspent by 23:1 (according to the Semiconductor Industry Association).

This commercial paradigm shift represents both an opportunity and a risk for government decision-makers. The opportunity lies in the commercial sector’s ability to act as both an accelerator and a force multiplier to government investments. However, profit-seeking commercial efforts will not always align with government needs and priorities.

How can the government best harness the raw ambitions of the entrepreneurial space community? While it is important for the government not to pick winners and losers (thus creating a new, dependent, industrial base), we offer a number of practical steps the government can take to support and promote space-based activities that not only align with economic and national security priorities but help to achieve them.
SCOPE AND METHODOLOGY

THE SPACE INDUSTRY WAS BORN OF THE MILITARY BATTLEFIELD, BROUGHT TO MATURITY THROUGH THE COLD WAR SPACE RACE, AND REMAINS TIGHTLY COUPLED TO GOVERNMENT AND MILITARY AFFAIRS. IN 2019, U.S. UNCLASSIFIED DEFENSE AND INTELLIGENCE SPENDING ON SPACE ACTIVITIES TOTALED $23 BILLION, COMPLEMENTED BY AN ADDITIONAL ~$22 BILLION OF NASA SPENDING.

While cognizant of these facts, this report is principally focused on the trends and growth prospects of the commercial space industry, with an emphasis on the intermediate future (i.e., 5-10 years). These commercial actors are responsive to, but not principally focused on national security concerns. Given the increasingly rapid pace of commercial space development, many of the technologies and capabilities being applied in the commercial domain can nonetheless be leveraged for national security benefit, as outlined herein.

The report’s conclusions do not profess to offer a comprehensive or conclusive survey of all potential business outcomes but instead reflect the authors’ institutional knowledge of the commercial marketplace, supplemented by a limited scope survey of well-placed and experienced industry stakeholders.
IT STARTS WITH LAUNCH

Futurists, novelists, and the motion picture industry have long portrayed a confident vision of human activity beyond Earth's gravity. But 60+ years after Sputnik 1, this vision is largely unfulfilled.

In 2020, global launch activity reached its highest level since 1990 but still fell below the average annual launch rate from 1965-1985. Every year, more people climb Mt. Everest than have collectively reached space since the era of human spaceflight began. And, aside from space-to-Earth communications services (TV, broadband, imagery, etc.), the space industry has long been searching for a new and significant commercial success that can be delivered from space. The chief impediment to greater commercialization has historically boiled down to one key challenge – the tyranny of high launch costs.

With few exceptions, launch costs to Low Earth Orbit (LEO) have remained stubbornly fixed within a range of $10,000 to $20,000 per kilogram, whether measured across time, launch vehicle size, or country of origin. The arrival of SpaceX changed this dynamic.

On the precipice of bankruptcy following the third failed launch attempt of its single-engine Falcon 1 rocket, SpaceX was rescued by NASA in December 2008 with a $1.6 billion contract to develop a medium lift vehicle (the Falcon 9) and cargo system for resupply missions to the International Space Station (ISS).

With the shift to the Falcon 9, SpaceX has moved aggressively to drive down launch costs through vertical integration, automation, reusability, and a high flight rate. The result? The Falcon 9 debuted with a LEO launch cost of ~$5,700/kg, but by 2015, five years later, SpaceX lowered the cost by more than half (~$2,700/kg) with the introduction of its upgraded “full thrust” design. SpaceX's Falcon Heavy cut launch costs in half yet again (~$1,300 kg), and CEO Elon Musk has said that the company's forthcoming Starship could eventually lower costs to $10/kg.
In addition to dramatically lowering launch costs, SpaceX also rekindled a renewed interest in rocketry, spurring competitors to announce development plans for no less than 100 new launch vehicles. While only two of these new launch vehicles have reached orbit, the momentum established strongly suggests a sustainable trend of increasingly lower launch costs and improved access to space.
While lower launch costs will undoubtedly increase the range and competitiveness of existing satcom and EO services, the impact of lower launch costs will be most profound on space-based technologies and business models that have never moved beyond the PowerPoint phase due to unsupportable economics. For some of these projects, the future is now. But which ones?

With deference to Yogi Berra, it’s tough to make predictions, especially about the future, but there are ample historic precedents pointing to immense value creation through the opening of new industries. Sticking with an example close to home, few people would have predicted the economic and societal impact of GPS technology, which was originally developed by the U.S. Air Force for military navigation and missile targeting. Once opened for commercial use, GPS has become a pervasive element of consumer/business life, spawning numerous multi-billion companies.

**IMPLICATIONS OF LOWER LAUNCH COSTS**

Put simply, lower launch costs improve the affordability of current space services while also facilitating entirely new business models that were simply not possible at historical launch costs.

This thesis has already proven out in today’s satcom and EO (Earth observation) markets, where a flood of new companies has entered the market with constellations of lower-cost satellites, challenging incumbents. A prime example of this trend can be seen in the market for small LEO communications satellites, where NSR is forecasting annual satellite orders to expand nearly 30-fold by 2023 as compared to the pre-2020 historical average.

![Communication Satellite Orders (100 - 500 kg.)](chart)

Source: NSR.
LAYING THE RAILROAD TRACKS

HISTORICAL ECONOMIC PRECEDENTS ARE ANOTHER POINT OF REFERENCE FOR GUIDING THE GOVERNMENT’S ROLE IN THE 21ST-CENTURY SPACE ECONOMY.

From railroads to aviation and the internet, the government has often been at the center as a customer, regulator, investor, and sometimes impediment to the development of numerous industries. Historical precedents would suggest that government support is best optimized when focused on the infrastructure building blocks (i.e., “the railroad tracks”) that help to de-risk private investments that must inevitably follow.

What are some of the key building blocks of the 21st-century space industry? Or, more appropriately, what are key building blocks where government support could lead to major advances in space commercialization? It’s a critical question because, inevitably, government funding decisions are a zero-sum game (i.e., funding Technology A implicitly leaves fewer dollars for Technology B). And, as noted, well-directed government funding can lead to companies like SpaceX undertaking dramatic innovations that turbocharge the U.S. industrial base.

Below is a table of space-based technologies that we believe currently have sufficient investment and competition to ensure a reasonable probability of commercial success. Some of these could still benefit from government support but do not merit the highest investment priority.

| Commercial Startup and Funding Activity of Select Space Industry Technologies |
|-----------------------------|-----------------------------|-----------------------------|
|                             | PRE-2010 Legacy Players | NEW ENTRANTS POST-2010 |
|                             | Startups | Equity Raised ($,M) | Startups | Equity Raised ($,M) |
| OISLs                       | 4       | 25               | $111   |
| Spacecraft propulsion       | 15      | 37               | $198   |
| Launch Reusability          | 8       | 24               | $1,570(1)(2) |
| Flat Panel Antennas         | 1       | 19               | $612   |
| Small/responsive launch     | 16      | 74               | $2,718(2) |
| SAR satellites              | 5       | 7                | $629   |

(1) Excludes SpaceX, which has individually raised $6.4 billion. (2) Relativity Space counted in both sections. Source: Company reports and Quilty Analytics.

At the opposite end of the spectrum, technologies such as nuclear propulsion and Active Debris Removal (ADR) are often identified as important to the space age of the 21st century but do not have a viable commercial path without specific government regulatory changes and/or investments.

As indicated by the graphic below, today’s commercial space economy (A) delivers two services from space – satcom and EO – which collectively total ~$26 billion in annual revenues worldwide. These industries are well-supported by an industrial base (B) comprised of satellite manufacturing, launch, and ground equipment. Looking to the future, lower space entry costs will enable new commercial activities and industries (C) to emerge, extending throughout cislunar space. Today’s space industrial base, while necessary, cannot sufficiently support these future growth activities. Instead, these activities will require an entirely new industrial base (D) specifically oriented to the unique challenges of operating in cislunar/lunar environs and potentially beyond.
While certain elements of this infrastructure, such as a cislunar Position, Navigation and Timing (PNT) system might best default to a neutral government function, we believe the preponderance of these activities can and should be developed, owned, and operated by commercial entities.

Unfortunately, many of these markets/activities exhibit the classic challenge of chicken or the egg paradox. And, absent clear market demand or anchor customers, investors are typically wary of “build it, and they will come” investment strategies. Consequently, there exists a clear and compelling role for government to make targeted investments, as further enumerated in the recommendation section of this report.
In 2015, Amazon founder Jeff Bezos declared his vision of enabling “millions of people to live and work in space,” while moving heavy industry off planet Earth. The first step in carrying out that vision – lowering launch costs – has already made strong gains, albeit not (yet) at the hands of Bezos’s launch company, Blue Origin.

While one can argue with the premise of millions of people in space, there can be little disagreement that the traditional nature of the space industry has forever changed, and the age of the cislunar economy is within reach.

What role should the government play in bringing about this vision, and where specifically should government invest? As previously stated, we believe government efforts should primarily be focused on the critical infrastructure elements that will be necessary to grow the cislunar economy.

OUR ASSESSMENT OF THE INDUSTRY IDENTIFIED SIX PRIMARY AREAS OF INVESTMENT THAT SPAN FROM DOMESTIC U.S. SPACEPORTS TO THE MOON. SOME OF THESE FUNCTIONS, SUCH AS SPACEPORTS, ARE INARGUABLY A GOVERNMENT FUNCTION, WHILE OTHERS WOULD LIKELY REQUIRE A MIXED GOVERNMENT AND COMMERCIAL APPROACH.

Our rationale for selecting these six areas is subjective and not without reproach. That said, we believe all six represent necessary areas of focus that hold the potential to benefit government and commercial stakeholders alike.
**U.S. SPACEPORTS**

**OVERVIEW**

Similar to an airport or seaport, a spaceport is a physical site encompassing a launchpad and/or runway with support facilities for launching space vehicles. There are currently 22 active spaceports globally, including five locations in the U.S., that carried out at least one (non-experimental) orbital launch attempt in 2020. Some of these spaceports support reentries for reusable launch vehicles.

In the U.S., the Federal Aviation Administration (FAA) is responsible for licensing spaceports and individual launch attempts, which must be coordinated with adjacent air traffic. There are currently 12 FAA-licensed commercial spaceports in the U.S., six of which have never successfully completed an orbital launch. Three of these sites (see table below) are joint-use locations with co-located commercial and federal launch sites, while eight sites are exclusively commercial. Vandenberg Space Force Base is classified as a federal launch site (i.e., not FAA licensed) but has supported an average of three FAA-licensed commercial launches per year over the past 20 years.

In addition to these FAA/federal launch sites, there are currently three private spaceports located in the U.S. that are not licensed by the FAA but are nonetheless subject to FAA launch licensing requirements. Of the three sites, only SpaceX’s Boca Chica site has been approved to conduct orbital launches (currently capped at 12 per year).
## U.S. Spaceports, License Type, and 2020 Orbital Launch Attempts

<table>
<thead>
<tr>
<th>SITE</th>
<th>LOCATION</th>
<th>OPERATOR</th>
<th>LICENSE TYPE</th>
<th>2020 ORBITAL LAUNCHES</th>
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<td><strong>MIXED USE (COMMERCIAL / FEDERAL)</strong></td>
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<td>Space Florida</td>
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<td>Virginia Commercial Space Flight Authority</td>
<td>Vertical</td>
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<td>Mojave Air &amp; Space Port</td>
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<tr>
<td><strong>FEDERAL</strong></td>
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<td></td>
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<td></td>
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<tr>
<td>Vandenberg Space Force Base</td>
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<td>U.S. Space Force</td>
<td>Vertical</td>
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<tr>
<td><strong>COMMERCIAL</strong></td>
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<td>Adams County Colorado</td>
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<td>SpaceX Launch Site Boca Chica</td>
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<td>SpaceX</td>
<td>Vertical</td>
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</tbody>
</table>

While most FAA-certified launch sites can support horizontal launch, there were only two horizontal launch attempts in 2020 – a test flight of Virgin Galactic’s StarShipTwo, and the unsuccessful maiden launch of Virgin Orbit’s LauncherOne.

Horizontal launch presents several benefits, including responsiveness and flexible inclination angles, but there are currently only two operational air-launched systems, Northrop’s Pegasus and Virgin Orbit’s LauncherOne, both of which are capable of carrying relatively small payloads (433 kg and 300 kg, respectively) into orbit.

In contrast to the plethora of horizontal launch sites, there are only five FAA-licensed vertical launch sites located in the U.S. that carry out the preponderance of U.S. launch activity, including all launches above ~400 kg.
OPPORTUNITIES

Access to space has long been a cornerstone of U.S. policy, and trends are aligning to make space access increasingly important to our nation’s security, industrial base, and continued technology leadership. These trends include:

- **ADVANCES IN ROCKET DESIGN AND REUSABILITY THAT MAKE ACCESS TO SPACE MORE RELIABLE, COST-EFFECTIVE, AND AVAILABLE.**

- **RECOGNITION THAT SPACE HOLDS TREMENDOUS PROMISE FOR IMPROVING THE UNDERSTANDING OF OUR PLANET AND TRANSFORMING THE WAY WE COMMUNICATE AND ENGAGE IN COMMERCE, BOTH IN THE U.S. AND GLOBALLY.**

- **GROWING INTEREST IN SPACE TOURISM IS EXPECTED TO LEAD TO AN INCREASED NUMBER OF LAUNCHES ALONG WITH ADVANCES IN SAFETY AND RELIABILITY FOR HUMAN SPACEFLIGHT.**

- **MAJOR COMMITMENTS TO SPACE MISSIONS BY OTHER NATIONS, BOTH ALLIES AND ADVERSARIES, THAT WANT TO EXPLOIT SPACE-BASED OPPORTUNITIES TO SERVE THE INTERESTS OF THEIR COMMERCIAL AND GOVERNMENT SECTORS.**

U.S. launch activity, which had fallen off to an average of 17 launches annually from 2001 to 2010, has seen a strong resurgence in recent years, culminating in 36 vertical orbital launch attempts in 2020, including 24 launches by SpaceX alone.

In addition to its industry-leading flight rate, SpaceX has also been instrumental in inspiring a renewed interest in the launch sector, including nearly three dozen U.S. launch startups and dozens more internationally. Underpinning this flurry of startup activity, market forecasters are projecting unprecedented growth in launch activity, driven by LEO broadband megaconstellations (30,000+ satellites), more than 60 “little LEO” constellations, and an upsurge in cislunar, lunar, and planetary missions.

1https://www.faa.gov/space/licenses/
Current U.S. spaceport infrastructure, regulations, and air traffic control procedures are likely insufficient to meet forecasted launch demand. In fact, the U.S. could face significant launch constraints even if a fraction of new launch vehicles currently in development make it to market.

As of June 30, 2021, the FAA was forecasting 40-56 licensed and permitted launch and reentry events in FY21 – horizontal, experimental, and vertical launches – including those from Rocket Lab’s Mahia, New Zealand launch site (but excluding government launches, which are not licensed).

The FAA’s forecast stands in stark contrast to the actual historical launch rate over the past 40 years, which has averaged 26 launches per year, with a peak launch rate of 43 launches in 1997. Notably, 97% of these launches have taken place from only two launch sites, Cape Canaveral spaceport and Vandenberg Space Force Base.
Based on the number of new and anticipated launch vehicles expected to enter the market in the next four years, this capability gap could grow more severe over time, even recognizing the fact that launch providers are overoptimistic both in timing and launch rate. For example, SpaceX initially projected a Falcon 9 launch tempo of 30-40 launches per year in 2018 but is only now hitting this rate in 2021. Likewise in 2014 Rocket Lab projected 52 launches per year by 2016 but only achieved one-fourth of this launch rate in 2020.

But even if we discount some of the more ambitious projections, anticipated launch activity could exceed the 40-year historical peak (43/year) by a factor of three to five times by 2025. And this forecast explicitly excludes the ambitions of Astra Space (~300/year), Phantom Space (~125/year), and SpaceX with Starship (multiple launches per day).

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**Estimated 2025 Annual Launch Rate for Select Vertical Launch Vehicles**

[Graph showing payload capacity to LEO for different launch vehicles]
OUR NATION’S CONTINUED LEADERSHIP IN SPACE MAY WELL BE DETERMINED BY WHETHER U.S. LAUNCH CAPACITY CAN BE EXPANDED RAPIDLY ENOUGH TO MEET ANTICIPATED DEMAND. WHILE GROWING OUR LAUNCH CAPACITY THIS DECADE IS ACHIEVABLE, THERE ARE SEVERAL GEOGRAPHIC AND LOGISTICAL CONSTRAINTS THAT WILL MAKE SUCH AN EFFORT EXTREMELY CHALLENGING, MOST NOTABLY:

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Due to the inherent performance limitations of horizontal launch, the future space economy will be dependent on vertical launch. However, there are only five FAA-licensed vertical launch sites located in the U.S. (plus SpaceX’s private Boca Chica spaceport).

All of these sites are strategically placed adjacent to large bodies of water or in remote locations (Spaceport America) due to the fact that vertical launch vehicles drop one or more stages downrange, creating a hazard to life and property in the drop zones.

Although the FAA has licensed numerous inland spaceports, these sites cannot support vertical launch unless the U.S. is willing to accept the risks associated with the uncontrolled reentry of rocket bodies into populated areas (which we believe is highly unlikely).

The one possible exception is Spaceport America, which abuts a large, restricted airspace associated with White Sands Missile Range. This site could theoretically be used for orbital launch, but only if carried out by a reusable vehicle where the first stage returns to the launch pad. This flight profile would inevitably penalize the vehicle’s launch performance and could also compel a substantial insurance premium.

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Since the 1960s, Cape Canaveral is responsible for ~96% of all launches to equatorial and inclined orbits, and 100% of all launches to GEO from the U.S. The only other East Coast launch site, the Mid-Atlantic Regional Spaceport, has conducted 39 launches since 1957, primarily to LEO.

Two launch sites (Vandenberg and Pacific Spaceport Complex – Alaska) provide ready access to polar orbits but have been hamstrung in recent years by environmental and operational restrictions (i.e., the requirement to evacuate downrange West Coast oil rigs).

The FAA’s paper-based launch licensing system is cumbersome, contributing to market confusion and launch delays that cascade across commercial and defense customers.

Efforts to establish all-new vertical launch sites have historically encountered resistance from environmentalists and local citizenry. SpaceX’s Boca Chica launch site required about eight years from initial plans to the first experimental launch, and an effort to develop a new launch site in Camden, GA, has been ongoing since 2012.

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**IMPLICATIONS**

For an industry accustomed to overcoming “rocket science” challenges, the simple issue of spaceport access may seem like a routine matter, but it could singlehandedly throttle the industry’s long-term growth rate if not properly addressed and resolved. Fortunately, both the Space Force and the FAA are cognizant of these challenges and taking steps to expand the domestic flight rate.

At Cape Canaveral, modernized range equipment and the implementation of automatic flight termination systems are expected to boost the site’s flight rate to 48 times per year on an interim basis, and perhaps twice per day in the long run. Likewise, the FAA is proposing streamlined (Part 450) launch and reentry licensing requirements, and just began using its new Space Data Integrator (SDI), a tool that is intended to provide air traffic controllers and pilots with near-instant information on launch activities, reducing the size and duration of airspace restrictions.

While these efforts should enable the FAA to support a two- to three-fold increase in the annual launch cadence, the U.S. will still remain precariously dependent on a handful of key spaceports – a dependency that, if not resolved, will undermine U.S. interests strategically and commercially in the next decade.
ORBITAL TRANSFER VEHICLES

OVERVIEW
Orbital Transfer Vehicles (OTVs) are propulsive spacecraft designed to ferry satellites to their intended destinations in space after separation from a launch vehicle. OTVs can deliver spacecraft to a variety of Earth orbits or to more distant locations such as Lagrange Points, cislunar space, or interplanetary locations.

The space industry has sporadically pursued with OTV concepts for decades, from NASA’s 1960s Space Transportation System to Lockheed Martin’s 2015 Jupiter space tug. None of these concepts advanced very far due to high technology costs and limited market demand for large orbital payload transfers. This dynamic has shifted dramatically in recent years as the explosive growth of the smallsat industry, coupled with the growing popularity of rideshares, produced a flood of innovation and new entrants into the OTV market.

In total, more than a dozen companies, mostly located in the U.S. and Europe, have introduced an OTV product in just the past five years. Most of these companies are specialists in satellite propulsion, rideshare aggregation and/or launch vehicle production.

As of mid-2021, only three of these companies have successfully demonstrated OTVs in orbit – Spaceflight, D-Orbit, and Rocket Lab – but more than a dozen could reach orbit within the next three years.
(Note: Northrop Grumman’s MEV-1 satellite servicing vehicle is discussed in the OSAM section of this report).

### Commercial Orbital Transfer Vehicles in Development

<table>
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<tr>
<th>COMPANY</th>
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<td>Spaceflight</td>
<td>Washington</td>
<td>Rideshare aggregator</td>
<td>Sherpa</td>
<td>January 2021</td>
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<td><strong>REST OF WORLD</strong></td>
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<td>France</td>
<td>Rocket manufacturer</td>
<td>Astris</td>
<td>2024</td>
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<td>D-Orbit</td>
<td>Italy</td>
<td>Smallsat propulsion and components</td>
<td>In-Orbit Now</td>
<td>September 2020</td>
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<td>Germany</td>
<td>Rideshare aggregator</td>
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<td>Lúnasa Space</td>
<td>United Kingdom</td>
<td>OTV</td>
<td>Via</td>
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<td>Germany</td>
<td>Launch provider</td>
<td>Rfa Orbital Stage</td>
<td>TBA</td>
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<td>Skyrora</td>
<td>United Kingdom</td>
<td>Launch provider</td>
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<tr>
<td>Space Machines Company</td>
<td>Australia</td>
<td>OTVs</td>
<td>Optimus</td>
<td>2022</td>
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</table>
AGILITY
OTVs use smaller engines than rocket upper stages, enabling the execution of more versatile orbital insertion maneuvers. This includes precise changes in orbital attitudes and inclinations for individual satellites and for constellations, deploying satellites in different orbital rings (planes), and populating an orbital plane at a set altitude.

DURATION
OTVs can operate for months or years in space, whereas a typical rocket upper stage is only designed to run on battery power for several hours until a mission is completed. As such, OTVs can function as hosting platforms for sensors and other payloads. For large deployments of smallsats, telemetry-hosted payloads can support spacecraft identification and critical Launch and Early Operations Phase (LEOP) activities.

MULTI-MISSION CAPABILITIES
The longer life of an OTV also opens up new types of in-space logistics services, such as refueling, assembly, debris removal, and more. Many OTV companies have roadmaps that include one or more of these additional services.

We expect OTVs will find healthy utility by extending the satellite rideshare business as smallsat operators make use of the opportunity for increased orbital insertion accuracy. OTV operators will initially focus on demonstrating their smallsat deployment services and gaining heritage on critical hardware, especially propulsion.

Frontrunner OTV companies are seeking to quickly reach a regular launch cadence of at least three to five launches per year. Some launch companies developing OTVs are leveraging vehicle-agnostic designs, decoupling OTV programs from new launch vehicle development to boost their flexibility and viability.

WE EXPECT OTV COMPANIES TO GAIN FUNCTIONALITY OVER THE COURSE OF THE DECADE VIA THE FOLLOWING UPGRADES/DEVELOPMENT PATHS:

<table>
<thead>
<tr>
<th>FIVE YEARS</th>
<th>TEN YEARS</th>
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<tbody>
<tr>
<td>Increased carrying capacity to accommodate deploying larger microsats.</td>
<td>Multipurpose OTVs with robotic extensions for services including in-space manufacturing, repair, and active debris removal.</td>
</tr>
<tr>
<td>Larger power supplies to support hosted payloads for TT&amp;C, SSA, and other applications.</td>
<td>Deep-space OTVs optimized for cislunar and interplanetary missions (radiation-hardened components, larger propellant tanks, etc.).</td>
</tr>
<tr>
<td>Maturred subsystems to support multi-year operations around Earth, plus upgrades for lunar and interplanetary travel.</td>
<td>Long-duration OTVs running five to 10+ year missions, possibly supporting fuel depots.</td>
</tr>
</tbody>
</table>
CHALLENGES

By their very nature, OTVs are dependent on the health of the smallsat market, which appears poised for rapid growth in the years ahead. Nonetheless, OTV manufacturers will face two direct market challenges over time: (1) onboard spacecraft propulsion and (2) dedicated small launch vehicles. Both alternatives could be considered a near-direct substitute for OTVs, although each approach has distinct benefits and drawbacks.

Cubesats rarely carry onboard propulsion, and when they do it is generally used for basic maneuvering and end-of-life deorbiting, not high-energy maneuvers (i.e., orbit raising or plane adjustments). OTVs can address these latter requirements, but if the service is too costly, satellite manufacturers may elect to install larger, more capable propulsion systems to perform these functions.

Small, dedicated launch vehicles represent yet another threat to the OTV market. Although typically more expensive than a rideshare opportunity, small launch vehicles can place satellites directly into their intended orbit, thus saving both fuel and time.

Based on current launch prices, the combined cost of an OTV and a rideshare are likely less expensive than a dedicated launch or onboard propulsion. If these technologies manage to significantly improve their price/performance, however, demand for OTV services could suffer.

To defend against these challenges, OTV manufacturers could add new capabilities such as robotics or expand deeper into space to serve the GEO market. Both of these strategies, however, entail risk, including the need to upgrade from COTS to radiation-hardened components, and the uncertainty of still-developing markets such as active debris removal, OSAM, and life extension.

IMPLICATIONS

OTVs have emerged as a multipurpose platform that could mark the beginning of a much broader in-space transportation economy. While early OTV services are primarily focused on taxiing spacecraft in low-Earth orbit, future OTVs are already being designed for a wider range of services. These services could include debris removal, spacecraft inspection, fuel delivery, or operating as an orbital testbed.

With OTV efforts in their infancy, it is unclear how robust the OTV business case is as a standalone last-mile service. Most OTV companies have additional sources of revenue, such as selling components or offering rideshare or launch services, and are using OTVs as an expansion strategy. Their early success growing beyond the smallsat market will determine how much capability OTVs gain in the years to come.

Finally, the ability to adapt to changing market needs will be a key competitive factor amongst the many companies entering the market. Not all will succeed, but those that do could spur demand for adjacent services (for example, propellant depots), thereby helping to foster a healthy and thriving cislunar economy.
ON-ORBIT SERVICING, ASSEMBLY, AND MANUFACTURING

OVERVIEW

On-orbit Servicing, Assembly, and Manufacturing, or OSAM, encompasses a broad range of technologies used to produce and/or sustain off-world assets. OSAM activities generally fall into one of three categories: (1) manufacturing, servicing and assembly of hardware in orbit, (2) building products in space for return to Earth, and (3) In-Situ Resource Utilization (ISRU). This report focuses solely on the first category, as the latter two categories are unlikely to scale commercially for many years.

OSAM capabilities are not new, but until recently were exclusively carried out by NASA and the DoD. The first recorded OSAM activity occurred in 1973 when astronauts conducted a spacewalk to deploy a sunshade and a stuck solar array on the Skylab space station. Later missions to fix the Solar Maximum Mission in 1984 and the Hubble Space Telescope throughout the 1990s and 2000s showcased how astronauts could conduct complex repairs in space. Crewed repairs eventually gave way to robotics, most notably MDA Corp.’s Dextre and Canadarm2, which demonstrated how robotic systems could support in-space assembly and refueling.

Commercial interest in the OSAM market eventually began picking up during the 2010s. In 2011, MDA announced a $280 million agreement with Intelsat to service and refuel Intelsat’s satellites, but the agreement was scrapped due to regulatory pushback. Despite the setback a number of companies, including Orbital ATK, Effective Space, and Skycorp, continued investing in OSAM technology. In 2020, these efforts finally culminated in the world’s first successful commercial OSAM mission when Northrop Grumman’s Mission Extension Vehicle (MEV) paired up with an Intelsat satellite in GEO to provide station-keeping services (Northrop Grumman purchased Orbital ATK in 2018).
All spacecraft, regardless of purpose, orbit, or manufacturer, must adhere to two critical design criteria: (1) they must be sized to fit within the diameter of a rocket’s payload fairing, and (2) they must be ruggedized to withstand the g-forces, acoustics, and vibration experienced during the violent transit to space.

But what if it were possible to manufacture spacecraft and structures on orbit rather than transporting them to orbit? The obvious answer is that traditional design limitations could be entirely avoided, thus enabling structures to be produced in new and novel ways. Two technologies leading this revolution are 3D printing and robotics.

Currently, there are only two U.S. companies, Made In Space and Tethers Unlimited, that have successfully 3D printed spacecraft hardware in orbit. Both companies were recently acquired (by RedWire and Amergint, respectively), providing some indication that investors expect the OSAM market to gain traction in the near term.

Meanwhile, robotics has been regularly used in space since the U.S. Shuttle program but remains costly and limited in adoption. U.S. heavyweights Lockheed Martin and Maxar Technologies have contributed robotic arms to several NASA space exploration missions, demonstrating capabilities that could be reapplied to in-space manufacturing and in-situ resource utilization. Northrop Grumman plans to build on the success of its Mission Extension Vehicles with the future “Mission Robotic Vehicle,” which will use robotic arms to attach smaller Mission Extension Pods to satellites. Airbus in July announced installation of the European Robotic Arm it built onto the Russian Nauka ISS module, which is planned to launch later this summer.

When paired together, robotics and 3D printing could help create new in-space manufacturing products and services. Key amongst the current applications would include building solar arrays, deployable booms, reflectors, and radiators, with an eye toward more comprehensive manufacturing once components gain heritage.
IN-SPACE ASSEMBLY

Much like with 3D printing in space, self-assembling satellites have the potential to avoid volume constraints associated with rocket payload fairings. Self-assembling satellites can be divided into two categories: monolithic satellites with attachable elements and “satlets” that combine to form a larger spacecraft.

Monolithic satellites would use robotic arms and/or 3D printers to assemble partially or completely once launched. NASA’s OSAM-1 mission will test a series of technologies for assembling monolithic satellites in orbit. While OSAM-1’s primary mission is refueling the Landsat-7 satellite, the servicer will also carry a robotic arm from Maxar Technologies and a fabricator from Tethers Unlimited. Maxar’s Space Infrastructure Dexterous Robot (SPIDER) arms will demonstrate in-space assembly and manufacturing, and will support Tethers Unlimited’s MakerSat in manufacturing a carbon fiber composite boom. NASA expects delivery of OSAM-1 to its Goddard Spaceflight Center in 2022.

The satlet approach uses small, self-contained mini-satellites that link together to form a larger spacecraft. Each satlet has components to support basic functions like power and communications, providing redundancy in the event of failures.

COMMERCIAL MODULAR SATELLITE ARCHITECTURES IN DEVELOPMENT

NovaWurks/Saturn Satellite Systems
Developed with the aid of DARPA, NovaWurks’ Hyper Integrated Satlets (HI-Sats) will be used to build “small GEO” satellites for Saturn Satellite Systems, which acquired NovaWurks in 2019 to gain access to the technology. Although initially focused on the small GEO market, the technology can address a number of market applications.

AST Space Mobile
For its constellation of 168 satellites, AST SpaceMobile plans to use “micron” spacecraft that link together in space to form large telecommunications satellites. Each micron is essentially a mini-satellite, using one side to communicate to Earth with a phased-array antenna and its other side to generate power with solar cells. Built by Japanese supplier NEC, the microns link to a central chassis from NanoAvionics that acts as the control unit.
CHALLENGES

Like any emerging market, the OSAM market faces the classic chicken and the egg problem of convincing potential customers to commit to a service that does not currently exist. Fortunately, this holding pattern is slowly beginning to dissolve as NASA actively contracts tech demos with a handful of well-capitalized space companies, signalling their commitment to the market. Still, the following challenges remain:

LEO VS. GEO
Large GEO satellites have been the mainstay of the satellite industry since it first emerged. Designed to last ~15 years and costing up to several hundred million dollars, these satellites represent an ideal market for OSAM services. In more recent years, however, the industry has shifted dramatically toward proliferated LEO constellations comprised of hundreds or even thousands of “throw-away” satellites. Should this trend continue, long-term demand for OSAM services could wane dramatically.

CUSTOMER BUY-IN
As it stands today, satellites are not designed for servicing, and the industry is yet to settle on the standards for attachment points, refueling ports, and other service-friendly features needed to advance the market. Even with the adoption of these standards, service-ready satellites won’t launch for at least three years and may not require servicing for another decade.

SCALABILITY
Key OSAM technologies, including robotics and 3D printing, remain expensive and rare technologies that can only address premium market applications today. These technology providers must identify and capitalize on higher-volume market opportunities that lead to a virtuous price/volume cycle, or they could become forever trapped as providers of expensive, bespoke test equipment.

SPACE ENVIRONMENTAL RISKS
Robotics, 3D printers and other hardware have different challenges in space compared to their terrestrial counterparts. Some of the unique environmental challenges that must be overcome include microgravity, vacuum conditions, steep temperature changes, high radiation levels, and solar eclipses.

IMPLICATIONS
OSAM technologies are at the beginning of commercial adoption, but progress remains slow. The industry’s transition to smallsats and multi-orbit architectures has weakened the business case for some services, but expansion into cislunar space could create new sources of demand.

Specialized satellites and other high-value assets will find utility from OSAM technologies. Companies are poised to expand from demonstrations and early services to more robust OSAM capabilities, but major transitions like moving from component production to full spacecraft manufacturing in orbit are likely still several years away.
OVERVIEW
The "tyranny of the rocket equation" represents the single greatest obstacle to unencumbered human space travel. This mathematical axiom asserts that 85-90% of a launch vehicle's mass must be comprised of fuel, leaving at most ~2% of the total mass for the actual payload going to orbit. Or, as author Robert A. Heinlein put it, "get to low-Earth orbit and you're halfway to anywhere in the solar system." Halfway, that is, with a near-empty fuel tank.

\[ \Delta v = v_e \ln \frac{m_0}{m_f} = I_{sp} g_0 \ln \frac{m_0}{m_f} \]

The implications of this reality are evident throughout the space industry. In order to save fuel, many GEO satellite operators elect to perform orbit raising using electric propulsion even though this choice delays the satellite's operational service date (and revenue generating capability) by several months. Even so, an estimated ~85% of all GEO satellites are retired not from hardware failures, but simply because they ran out of the fuel needed to maintain their orbital slot. The implications for deep space missions are even more acute.

Absent the development of nuclear propulsion, chemically propelled rockets will remain the key means of reaching orbit for the foreseeable future. Consequently, efforts focused on storing, transferring, and creating fuel resources in orbit should arguably be viewed as a key investment priority.
Nonetheless, interest in orbital refueling has continued to grow in recent years, propelled by a growing acknowledgement that the technology will play a critical role in the future space economy. Key benefits of orbital refueling include:

**Opportunities**

The concept of orbital refueling has not always been warmly received. When satellite operator Intelsat announced in 2011 that it signed a $280 million contract with MDA to refuel and service its satellites on orbit, David Thompson, the CEO of (satellite builder) Orbital Sciences joked that Orbital would consider welding shut the fuel caps on its satellites. Thompson eventually reversed course and spearheaded the development of the world's first commercial satellite servicing vehicle (the now-Northrop Grumman MEV-1), albeit with an approach that externally controls a satellite's movement as opposed to direct refueling.

**Cost Savings.**
Refueling a perfectly functioning satellite is cheaper than replacing it, if fuel can be delivered at a sufficiently attractive price.

**Mobility and Maneuverability**
Unencumbered by fuel constraints, satellites would have increased flexibility to change their orbit or inclination to optimize revenue generating opportunities. From a military perspective, increased maneuverability greatly increases a satellite's ability to defend against hostile actions.

**Asset Recovery**
Launch vehicles sometimes experience partial failures that leave a satellite stranded in the wrong orbit. If not deemed a total loss, these satellites can sometimes be raised to their targeted orbits using onboard thrusters, but the maneuver typically reduces the satellite's effective life by several years. With orbital refueling, these satellites could be returned to their full service life.

**Reduced Space Debris**
Theoretically, the presence of a robust fuel depot architecture would discourage today’s “throw away” satellite culture, prompting satellite operators to refuel and re-use their existing satellites rather than launching new satellites. In addition, fuel depots would significantly lower the cost of active debris removal, thus prompting more companies to participate in the market.

**In Situ Resources**
Any effort to create a sustained human presence off-planet will require the exploitation of local resources, including the ability to create, store, and transfer fuel. Lessons learned from servicing satellites can eventually be applied to future in situ efforts.

**Deep Space**
Due to the tyranny of the rocket equation, large-scale interplanetary missions are effectively impossible without orbital refueling.
Echoing this final point, NASA has taken an increasingly active role in supporting orbital refueling research, with a particular emphasis on cryogenic (i.e., supercooled) systems. Nearly 70% of the agency’s October 2020 Tipping Point contract awards were directed at cryogenic fluid management technology demonstrations:

### 2020 NASA Tipping Point Cryogenic Contract Awards

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<th>COMPANY</th>
<th>AWARD</th>
<th>AWARD FOCUS</th>
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<tr>
<td><strong>Eta Space</strong></td>
<td>$27 M</td>
<td>Small-scale flight demonstration of a complete cryogenic oxygen fluid management system. As proposed, the system will be the primary payload on a Rocket Lab Photon satellite and collect cryogenic fluid management data in orbit for nine months.</td>
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<tr>
<td>Merritt Island, Florida</td>
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<tr>
<td><strong>Lockheed Martin</strong></td>
<td>$89.7 M</td>
<td>In-space demonstration mission using liquid hydrogen – the most challenging of the cryogenic propellants – to test more than a dozen cryogenic fluid management technologies, positioning them for infusion into future space systems.</td>
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<td>Littleton, Colorado</td>
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<tr>
<td><strong>SpaceX</strong></td>
<td>$53.2 M</td>
<td>Large-scale flight demonstration to transfer 10 metric tons of cryogenic propellant, specifically liquid oxygen, between tanks on a Starship vehicle.</td>
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<tr>
<td>Hawthorne, California</td>
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<tr>
<td><strong>United Launch Alliance</strong></td>
<td>$86.2 M</td>
<td>Demonstration of a smart propulsion cryogenic system, using liquid oxygen and hydrogen, on a Vulcan Centaur upper stage. The system will test precise tank pressure control, tank-to-tank transfer, and multi-week propellant storage.</td>
</tr>
<tr>
<td>(ULA)</td>
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<tr>
<td>Centennial, Colorado</td>
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But not every orbital refueling technology is based on cryogenics. Startup Orbit Fab is focused on storable propellants such as hydrazine and xenon, which are the most common propellants used by satellites in orbit today. The first propellant tanker was launched by Orbit Fab in mid-2021. The company expects to perform on-orbit refueling in 2022.

Orbit Fab is also spearheading the development of an orbital refueling system that can produce the nontoxic monopropellant HTP (high-test peroxide) from nothing more than water and electricity, which they see as key to a viable long-term storable propellant architecture. Orbit Fab has partnered with Rice University’s Wang Lab on HTP production, and the smallest propulsion company Benchmark Space System, which has developed a family of HTP-based thrusters, and has successfully recruited additional partners for their vision, including Spaceflight Industries and SCOUT. Maxar Technologies is building the OSAM-1 spacecraft (formerly Restore-L) for NASA that will load the hypergolic fuel hydrazine into the 20+ year-old Landsat-7 satellite. Hydrazine is the most common propellant for geostationary communications satellites and large imaging satellites in LEO.
CHALLENGES

Aside from a handful of government-funded demonstrations, most notably DARPA’s 2007 Orbital Express experiment and NASA’s 2011 Robotic Refueling Mission, orbital refueling remains a largely aspirational technology. Some of the primary challenges to greater acceptance include:

**TECHNICAL IMMATURITY**
Cryogenic fuels are volatile and notoriously difficult to transfer and store for extended periods of time due to the boil off of stored fuel. Orbit Fab has an operational HTP tanker in orbit but has yet to launch hydrazine or xenon systems and has yet to perform in-orbit refueling. Similarly, Orbit Fab’s PEM cell technology, used to convert water into HTP, is currently at TRL 3.

**CHICKEN AND THE EGG**
Orbital refueling companies face the classic “chicken and the egg” conundrum of convincing potential customers to adopt refueling-friendly technologies (i.e., refueling ports) when the underly service does not yet exist.

**INDUSTRY STANDARDS**
Closely aligned with the above point, the industry currently lacks universally accepted technology standards for hardware or fuel type amongst the dozens of satellite manufacturers and propulsion companies.

**PRICE DISCOVERY**
The decision to refuel vs. replace a satellite should be a fairly straightforward economic decision once reliable fuel prices are established. Until the industry gains scale, however, prices are likely to remain high and uncertain.

**NETWORKING EFFECT**
Similar to gas stations on Earth, an orbital refueling network must achieve a minimum critical mass in order to stimulate adoption. This challenge is compounded by the fact that space is big and refueling operations must be conducted across multiple dimensions, namely altitude, inclination and speed.

**RAFTI FUELING PORT**
Source: Orbit Fab.
CRYOGENIC REFUELING HAS ANOTHER LESS OBVIOUS CHALLENGE: UPPER STAGES. At present, rocket upper stages are the primary cryogenically propelled vehicles in space, but upper stages are only designed to last hours before running out of power and shutting down. Refueling an upper stage is only one part of the process to make such vehicles functional. Future upper stages will need solar arrays, upgraded batteries, thermal insulation and radiation protection, plus other upgrades so that adding fuel actually gives life to an otherwise dead spacecraft.

THE THREE NEXT-GENERATION U.S. HEAVY LIFT VEHICLES CURRENTLY IN DEVELOPMENT ALL HAVE PLANS FOR LONG-DURATION UPPER STAGES THAT COULD BE REFUELED AND/OR SUPPORT CRYOGENIC FUEL TRANSFERS.

SPACEX’S Starship, currently in prototyping, is designed as an upper stage capable of cryogenic fuel transfer. As a fully reusable vehicle, Starship avoids the aforementioned limitations of existing upper stages. Starship’s first orbital launch is projected for late 2021.

ULA continues to study a long-duration cryogenic upper stage despite shelving plans for its Advanced Cryogenic Evolved Stage in 2019. ACES was planned to operate for a week or longer, and came with a lunar lander concept called XEUS that would have required in-orbit refueling. The company’s next-generation Vulcan rocket, slated to launch in 2022, will use an upper stage called Centaur-5 that expands on the capabilities of the Atlas 5 rocket.

BLUE ORIGIN also has plans for a long-duration upper stage for its heavy lift vehicle, New Glenn. Scheduled to launch in 2022, New Glenn’s upper stage uses two BE-3U cryogenic engines to place spacecraft in orbit. Like ULA, Blue Origin has not disclosed a timeline for a long-duration upper stage. Blue Origin has studied reusable upper stages with NASA, as well as ways its upper stage could support diverse missions like building space stations.

IMPLICATIONS

Propellant depot and orbital refueling concepts are not new, having been studied extensively since the 1960s. Historically, technology hurdles represented the primary barrier to adoption, although one could also question the economic use case at a time when launch activity remained rare and expensive.

No such excuse exists today. Launch costs have been lowered by an order of magnitude, opening up space access to a broadening range of actors and activities. And these activities will move deeper into cislunar space, bolstering the need for orbital refueling services.

As demand gradually moves into alignment, technology hurdles are also falling, aided by advances in materials science, manufacturing techniques, and the ability to safely conduct rendezvous and proximity operations. The final, and perhaps most vexing challenge is executing the business model. Establishing a new industrial base is a daunting challenge even when macro forces are aligned in its favor (for example, electric vehicles). The challenge is easily an order of magnitude more difficult when extended to outer space.
DEEP-SPACE COMMS AND SDA

ALL HUMAN COMMERCE, WHETHER ENABLED BY TRUCK, RAIL, SHIP OR AIR TRANSPORT, IS DEPENDENT ON COMPLEX, GLOBAL LOGISTICS NETWORKS.

These networks, in turn, are dependent on standardized rules of the road combined with accurate tracking and communications systems to ensure the safe and orderly movement of goods.

The cislunar space economy will be no different. In fact, the inherent complexity of space travel, including the high rates of motion, extreme travel distances, and the challenges of space debris, will necessitate an extensive network of sensors and tailored communications services rivaling today's global air traffic control system.

Historically, responsibility for these functions fell squarely on the shoulders of government agencies, primarily the FAA, DoD, and NASA. These government-funded and operated systems, such as the 1950s-era Deep Space Network, have not aged well, and are wholly unprepared to meet the demands of a rapidly expanding cislunar economy. A failure to plan, develop, and build this needed infrastructure will inevitably constrain the growth potential of the future space economy.
Governments have traditionally taken on responsibility for the gritty and unheralded work of building sewers and sidewalks, although these projects can also be funded through public-private partnerships (PPPs) and direct commercial investment (e.g., toll roads). The merits of the former include neutral ownership of critical infrastructure and certainty of financing, while the commercial path generally promises (significantly) lower costs and a faster path to market.

The cis-lunar space economy, which is currently more PowerPoint than pavement, represents a largely open-book opportunity for policymakers to architect a 21st-century space infrastructure that can both support government needs while promoting the growth of commercial activities. Key elements of this infrastructure include:

**POSITION, NAVIGATION AND TIMING (PNT)**
A GPS-like system designed specifically to provide PNT services to spacecraft operating in cis-lunar space.

**LOGISTICS AND MANUFACTURING**
An assortment of space vehicles used to perform manual tasks in space, including orbital transfer vehicles (OTVs), and orbital servicing, assembly, and manufacturing (OSAM).

**SPACE DOMAIN AWARENESS (SDA)**
Space vehicles configured with one or more sensors to identify, track, catalog, and inspect objects in cis-lunar space with greater accuracy than terrestrial sensors.

**POWER**
Refers to energy sources, most notably chemical, solar, and nuclear, used to power spacecraft in cis-lunar and deep space.

**DEEP SPACE COMMUNICATIONS**
For the purposes of this report, refers to all communications carried out beyond the GEO orbit. NASA’s definition encompasses two discrete regions, the Near Space Network (NSN) and Deep Space Network (DSN), with a dividing line at two million kilometers from the Earth.

Which of the above infrastructure elements merit the government’s most immediate attention? Aside from OTVs and OSAM, which we have already profiled, our subjective recommendation would focus on two areas: (1) deep-space communications, and (2) Space Domain Awareness (SDA), both of which represent an immediate government need along with a demonstrated commercial appetite for investment.

Existing government capabilities in these two areas (see table below) are currently limited to terrestrially based systems that are inherently constrained by atmospheric challenges and limited physical site diversity. The U.S. Space Force’s newly commissioned $1.7 billion Space Fence, for example, is currently comprised of a single location, thus lacking redundancy and the ability to track objects from multiple look angles. Fortunately, existing commercial SDA providers, including LeoLabs (S-band radar) and ExoAnalytic Solutions (optical telescopes) have services that rival and/or exceed current government capabilities.
CHALLENGES

As human activities expand from LEO to cislunar and beyond, terrestrially based SDA and deep-space communications systems will inevitably reach their practical limits, thus requiring the development of new space-based sensor and communications networks. Who should build this infrastructure, and should it be owned by the government, commercial operators, or some combination of the two?

In the SDA domain, the Space Force has already taken initial steps toward a government-owned model with the deployment of four Geosynchronous Space Situational Awareness Program (GSSAP) satellites between 2014-2016, and the yet-to-launch Cislunar Highway Patrol System (CHPS) experiment. Nonetheless, at least two commercial operators, Guardian Space Technology Solutions and NorthStar Earth & Space are developing commercial SDA constellations (in GEO and LEO, respectively) targeting commercial satellite operators, insurance providers, and government customers alike.
Meanwhile, a similar debacle is brewing in deep-space communications, where NASA-and ESA-led efforts to develop lunar relay networks (LunaNet and Moonlight, respectively) could run afoul of the private efforts of CommStar Space Communications and Aquarian Space to place data relay satellites at Lagrange Point 1.

From this perch, CommStar’s optical/RF relay satellite could enable high-speed lunar communications while freeing lunar missions from the cost and weight of a direct-to-Earth communications system. Similarly, Aquarian’s deep-space relay satellite could enable unencumbered communications with NASA’s ~$10 billion James Webb Space Telescope, which is currently limited to 1 Mbps by the agency’s Deep Space Network.

Typical SDA Activities

- Identification, classification and tracking
- Conjunction analysis
- Identify problematic behaviors
- Accident forensics
- Threat deterrence
- Aid rendezvous and proximity ops
- Space weather monitoring
- Cislunar traffic control

IMPLICATIONS

More than 100 lunar missions and 40,000 satellites are expected to launch over the next decade, fundamentally transforming the operating environment in space. These activities are expected to generate significant science and wealth creation, but will also result in new resource and security concerns. The infrastructure needed to sustainably support this growth simply does not exist today, and the failure to establish “smart” infrastructure could crimp these growth efforts or result in even more dire outcomes.

Can the private sector be relied upon to underwrite this needed infrastructure? While the technical challenges would appear to be manageable, raising the necessary investment capital could prove challenging given the scale of required capital outlays, the long investment cycle, and the novel/unproven nature of the emerging cislunar space economy. That said, large government-run space programs have a long history of significant cost overruns and multiyear schedule delays, suggesting a higher probability of success for the commercial route – if funding can be secured.

The government can and should play an active role as an advocate and anchor customer, while also advancing neutral regulations and standards that mitigate investment risks. Finally, a thorough review of past government efforts to stand up new industries such as the commercial remote sensing sector, should be pursued to glean important lessons.
COMMERCIAL LUNAR UTILIZATION

OVERVIEW
Nearly 50 years after the end of the Apollo program, government and industry leaders are again focusing on returning astronauts to the surface of the Moon. According to NSR, 83 missions valued at $50 billion have been contracted to send spacecraft, infrastructure and crew to the Moon since 2016. While most of this investment is being underwritten by civil space agencies, dozens of commercial companies are supporting these efforts, and no less than a dozen are pursuing full-fledged commercial lunar business models.
WHY THIS SUDDEN RESURGENCE IN ACTIVITY?

Google’s Lunar XPRIZE, announced in September 2007, arguably planted the seeds for the current renaissance in lunar activity. Although ultimately unsuccessful, the competition attracted the efforts of 20 teams and directly spawned more than a half dozen rovers/landers that have either attempted or plan to attempt Moon landings over the next two years.

Meanwhile, long-dormant great power competition between nations has once again emerged as a driving force for U.S. space policy. Policy makers are closely following China, which has included the Moon in its Belt and Road Initiative and discussed the potential for a $10 trillion/year Earth-Moon space economic zone by 2050. Lunar program benefits include not only international prestige and possible economic wealth (e.g., energy, mineral resources) but also the ultimate high ground from which a military force could monitor the entirety of cislunar space and sweep all satellites out of Earth orbit with a directed energy and or kinetic weapons.

The final piece of the puzzle fell in place in December 2017 when then President Trump signed Space Policy Directive 1, establishing the goal of returning humans to the Moon “for long-term exploration and utilization.” In the wake of SPD-1, NASA established the Artemis Program along with a series of multi-billion technology initiatives (the Lunar Gateway, Commercial Lunar Payload Services program and the Human Landing System) to support the goal of returning astronauts to the Moon by 2024.

ASTROBOTIC PEREGRINE LANDER

Source: Astrobotic
OPPORTUNITIES
Fifty years ago, nation-state efforts were required to reach the Moon. Today the rapid growth of space technologies has made lunar missions a possibility for developing countries, private companies, and even crowdsourcing scientists. Currently, 17 countries and at least 10 companies are developing, or have proposed, missions to the Moon. Today the rapid growth of space technologies has made lunar missions a possibility for developing countries, private companies, and even crowdsourcing scientists.

But why go to the Moon? While some countries are seeking to promote STEM education and foster national pride, the prevailing rationale has categorically shifted toward a sustained human presence on the lunar surface. The strategic and commercial rationales for these efforts include:

COMMUNICATIONS
Enabled by large surface antenna arrays, the Moon can be used for high-data-rate direct or relay communications with the Earth or satellites in any Earth orbit.

RESOURCE EXTRACTION
Pummeled by asteroids for eons, the surface of the Moon has amassed valuable minerals that can be employed in situ or (with sufficiently low transportation costs) shipped to Earth or other locations. An estimated 600 million metric tons of water ice can be used for rocket fuel and human life support.

SPACE DOMAIN AWARENESS
The Moon's position astride the Earth and its orbital belts provides an ideal platform for observing commercial and military activities via optical, radar, electronic intelligence and other sensors.

ASTRONOMY
The moon's longer nights, lack of atmosphere and the absence of human radiofrequency sources make it a unique vantage point for studying the cosmos.

DATA STORAGE AND COMPUTING
In addition to offering the ultimate air gap, lunar-based storage and computing hold an immense operational cost advantage since certain terrestrial costs (HVAC, land, etc.) would not be present.

HUMAN PRESENCE
Although challenged by foreboding cost, risk, and regulatory policies, potential long-duration human activities on the Moon could include biomedical research, commercial R&D efforts and tourism.

ENTERTAINMENT/ADVERTISING
Why is the internet free? Advertising.

PARTNERSHIP BUILDING
As China promotes its economic model through the Belt and Road Initiative, a U.S.-led effort to develop and settle the Moon can represent a powerful opportunity to enlist the participation and contribution of partner nations.
CHALLENGES

While it may no longer require an Apollo-like program to reach the Moon, transit to the Earth’s largest satellite remains expensive, risky and rare. Backed by billion-dollar budgets, government-led science and technology programs can clear these hurdles, but commercial entities, which must demonstrate a viable investment return, face a more difficult fundraising path. Here are some steps government leaders can take to lower these investment hurdles:

GOVERNMENT AS AN ANCHOR CUSTOMER.

While commercial business models must eventually stand on their own two feet, programs such as NASA’s Commercial Lunar Payload Services, or CLPS, can play a critical role in achieving flight heritage, validating end-market demand, and establishing a revenue base for early-stage companies and business models.

REGULATORY CLARITY.

Commercial lunar activity is currently governed by the 1967 Outer Space Treaty, which lacks specificity regarding issues of private property and commercial activity. NASA’s Artemis Accords, currently comprised of 12 signatories, have enhanced policy clarity but not necessarily legal certainty.

COMMITMENT TO ENDURING INFRASTRUCTURE.

While inspiring, temporary boot prints on the Moon do not engender the confidence necessary for investors to undertake long-term capital commitments. Investments in long-lived infrastructure, including power sources, communications, and even orbiting gateways, help to create a self-sustaining lunar ecosystem.
IMPLICATIONS

Sometimes portrayed as a mere steppingstone to Mars, the Moon is in fact the key proving ground for humankind’s ability to develop a self-sustaining presence beyond Earth. Equally as important, the Moon holds tremendous military-strategic value and could become a source of significant national wealth creation, economic security (e.g., rare earth metals), and benefit to our planet (science, communications, space weather, etc.).

The counterfactual argument also bears consideration. If the U.S. cedes the lunar opportunity to China, the U.S. will be permanently disadvantaged militarily and economically. China’s Chang’e lander program has already proven out much of the technology needed to move forward with commercial efforts, and the Chinese state has committed to a human presence in the 2030s (the next Spratly Islands?). The U.S.’ key advantage is its capitalist system, entrepreneurial culture and proven record in space-based innovations. Any efforts directed at lowering investment risks and assuring a robust demand for lunar-derived products and services will inevitably represent the U.S.’s best prospect for success in a competition with China that we cannot afford to lose.

CHINA’S CHANG’E 4 LANDER
Source: Xinhua/China National Space Administration.
RECOMMENDATIONS

Every honest discussion of the space industry must begin with the same basic premise: space is hard. Any proposition that suggests otherwise is likely to result in a bitter dead end. Key attributes of the space industry that set it apart from most other industries include:

**PROTRACTED DEVELOPMENT CYCLES.**
Flight heritage, which can only be achieved in the vacuum of space, does not come often or cheaply. Unlike terrestrial products that can be cycled through labs in days, gaining access to space has traditionally been measured in months or years.

**OPEN-LOOP TESTING.**
Prior to SpaceX’s successful recovery of a first-stage booster in 2015, the “absence of failure” was the primary means of measuring a rocket’s design sufficiency. All other space hardware suffers the same constraint due to a limited ability to observe, manipulate, repair, and test hardware once launched to space.

**HIGH CAPITAL INTENSITY.**
Space hardware requires careful and specialized design techniques to survive the ride to space, as well as the harsh thermal and radiation environment once there. A trip to space traditionally costs $10,000 to $20,000 per kilogram.

Not surprisingly, these high barriers to entry result in limited market competition compared to other tech industries. Throughout the space industry’s history, most commercial startups were either spun out of larger A&D contractors, funded through direct government investment, or slowly bootstrapped, leveraging government contract dollars. Venture capital and financial sponsor funding were almost non-existent, amounting to perhaps ~$100 million per year and an average of five funded startups per year prior to 2010.

Declining launch costs and increasing launch frequency should gradually lower these barriers to entry, but helping companies gain access to space should be considered one of the government’s top investment priorities. By helping companies overcome the “TRL Valley of Death,” competition should increase, and prices should decline, potentially leading to a virtuous cycle.
HOW AND WHERE SHOULD THE GOVERNMENT INVEST?

The options are numerous and potentially overwhelming, including contracts, direct investment, public-private partnerships, export finance, tax credits, commodity exchanges, and startup accelerators, amongst others. At the risk of oversimplifying a complex challenge, we offer three unostentatious recommendations:

JUST BUY STUFF AND BUY OFF THE SHELF:
Avoid the temptation to create soul-sucking programs of record. Become a buyer of products and services. Wherever possible, select off-the-shelf products and solutions that meet 80% or more of mission requirements instead of spending exorbitant amounts for 100% effective solutions.

SPREAD THE WEALTH, MOVE FAST.
Engage with a broad cross-section of small-to-mid-sized innovative companies using acquisition approaches that minimizes paperwork and knowledge of government procurement systems. Emphasize annual technology “sprints” that emphasize government technology priorities, emphasize a rapid tech refresh cycle, and provide an opportunity to gain heritage through “free rides” into space.

BUY STUFF FROM ALLIES AND PARTNERS.
While buying American should be the top priority, don’t overlook the potential contribution of friends and allies that both need U.S. security support and are capable contributors in the space domain. This concept is not inherently in conflict with “Buy American” priorities in cases where suitable technologies are not available domestically. In fact, sending a buying signal to the market will induce further domestic investment in relevant technologies and capabilities.

Collectively, these recommendations are intended to convey a simple but important message. To remain relevant in the rapidly transforming space industry, the government must move away from its traditional acquisition approach and adopt a more venture-like attitude toward investment and acquisition. This transition could entail suffering some outright failures to achieve one spectacular home run.

Understandably, the concept of “acceptable failure” is discomfiting for government program managers and taxpayers alike. That said, even with byzantine procurement rules and armies of auditors to plan, test, and validate every major acquisition program, high-profile failures are unavoidable, as evidenced by programs like TSAT, Crusader, Comanche, FCS, and NPOESS. While an aggressive commercial procurement approach may entail higher front-end technology risk, the avoidance of traditional programmatic and funding cycle risk should still leave the government customer better off on a full-cycle basis.
Headquartered in St. Petersburg, Florida, Quilty Analytics provides research, strategy, and investment banking advisory exclusively for the Satellite & Space industry. Drawing on decades of experience and in-depth knowledge of Satellite & Space markets, we offer an unmatched combination of financial, technical, and strategic insights that helps our clients – leaders in government and industry – make better investment and policy decisions.

**Quilty Analytics has Prepared this Report at the Request of the Defense Innovation Unit (DIU)**

The report supplements and builds on a presentation that Chris Quilty, Partner of Quilty Analytics, is making at the State of the Space Industrial Base Hybrid Workshop, 14-16 July 2021, Albuquerque, New Mexico. The report is intended to provide attendees at the Workshop with a summary of emerging commercial space activities so that government and military planners can focus U.S. space priorities in ways that support our nation’s strategic and commercial interests.

**This Report, Its Findings and Conclusions are Those of Quilty Analytics and Are Not Endorsed or Approved by DIU of any US Government Agency**