Strategic Framework for NASA's Space Technology Mission Directorate

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In October 2016, NASA's Space Technology Mission Directorate (STMD) began adopting a new strategic framework that focuses investment prioritization and communication on impacts, outcomes, and challenges. The structure of the framework has been modeled after one successfully pioneered by NASA's Aeronautics Research Mission Directorate over the past five years, incorporating lessons learned and changes where appropriate. The Framework is driven by two major factors: (a) dialogue with the community and (b) analysis of the overarching trends shaping the course of civilian space research. These factors are captured in the Framework as Mega-Drivers, which represent major axes of change within the space industry and are characterized by a collection of industry trends and projections. In response to these Mega-Drivers, STMD has developed its understanding of the vision for the future of civilian space relative to STMD space research, captured in five Strategic Thrusts that represent the major lines of investment within STMD's portfolio. Within each of these Strategic Thrusts, multiple measureable, community-level goals have been established that STMD chooses to pursue as part of a joint effort across the community. STMD chose these goals based upon their potential impact, refers to them as Outcomes within the Framework. These Outcomes are decomposed into the products and/or capabilities that will be delivered by STMD, represented in the framework as Technical Challenges. This paper will further describe the framework structure and the progress that has been in defining each of the above elements to date.

Acronyms

ARMD	=	Aeronautics Mission Directorate
CH_4	=	Methane
CMOS	=	Complementary Metal Oxide Semiconductor
COTS	=	Commercial Orbital Transportation Services
CSLI	=	CubeSat Launch Initiative
ELaNa	=	Educational Launch of Nanosatellites
ESA	=	European Space Agency
GEO	=	Geosynchronous Earth Orbit
GSO	=	Geosynchronous Orbit; Geostationary Orbit
HEOMD	=	Human Exploration and Operations Mission Directorate
ISRU	=	In-situ Resource Utilization
LEO	=	Low-Earth Orbit
LH_2	=	Liquid Hydrogen
LLO	=	Low-Lunar Orbit
LOI	=	Lunar Orbit Insertion
LOx	=	Liquid Oxygen

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MD	=	Mega-Driver
NASA	=	National Aeronautics and Space Administration
SAA	=	Space Act Agreement
SBIR	=	Small Business Innovation Research
SEP	=	Solar Electric Propulsion
SMD	=	Science Mission Directorate
SPI	=	Strategic Planning and Integration
SSO	=	Sun Synchronous Orbit
STMD	=	Space Technology Mission Directorate
STTR	=	Small Business Technology Transfer
TBD	=	To Be Determined
TBR	=	To Be Revised
TEI	=	Trans-Earth Injection
TLI	=	Trans-Lunar Injection
ULA	=	United Launch Alliance

I. Introduction

NASA's Space Technology Mission Directorate (STMD) is a dedicated technology organization within NASA that is responsible for identifying and developing cross-cutting, pioneering, and new technologies and capabilities needed to achieve NASA's current and future missions. In its unique position as a standalone technology organization, STMD can develop multi-purpose and multi-application technologies; reducing costs across NASA's missions. In order to deliver on its mission, the Space Technology Mission Directorate (STMD) must formulate and execute a relevant technology portfolio; addressing the near-term technology needs of current missions while also anticipating and responding to needs of future missions and trends within global space industry.

To better support those portfolio formulation and execution activities, STMD began adopting a new Strategic Framework in October 2016; responding to the space industry and community needs by articulating STMD's vision for the future of civilian space technology. That vision is then decomposed to identify the Capabilities required to make that vision a reality, and direct investments towards those critical capabilities. By identifying the impacts and outcomes desired by the community first, and then discussing the enabling technologies and systems being developed by STMD second, STMD leadership can structure the framework to better communicate with STMD's stakeholders, both inside and outside NASA. The structure has also internally provided traceability from those community-desired impacts and outcomes to the required Capabilities and technologies, providing context for how a particular investment fits within the community's plans, which is critical to informing investment prioritization and technology development planning.

In developing this new strategic framework structure, STMD has been able to heavily leverage work done within and lessons learned from NASA's Aeronautics Research Mission Directorate (ARMD). Starting in 2013, ARMD initiated a rework of their own strategy, pioneering the community- and trend-driven framework structured around community-level Outcomes that STMD has been able to largely adopt [1]. Over the past six years, ARMD has made that framework an integral part of their operations: with framework elements integrated into their communication materials, organization roles & responsibilities, and portfolio formulation and evaluation processes. The lessons learned and best practices from this integration have been an integral to the discussions within STMD about its own implementation.

This paper will provide an overview of STMD's strategic planning process and the associated strategic framework, describe in detail the framework's individual elements implementation (i.e. Mega-Drivers, Strategic Thrusts, and Outcomes), and provide an overview (with an example) of how Outcomes are decomposed into Technical Challenges. Though the Framework is still under development, significant analysis has been completed to define a set of Outcomes and associated Capabilities. The currently defined Outcomes will not be discussed individually but are available in the Appendix.

II. STMD Strategic Planning Process and Framework

As directed by the National Space Policy [1] and NASA's Strategic Plan [2], STMD's strategic objective is to "develop and transfer revolutionary technologies to enable exploration capabilities for NASA and the Nation". To accomplish that objective, the overall goal of STMD's strategy is deliver a high-performing space technology portfolio; delivering technologies in the near-term that directly address customer needs, while identifying and developing the immature technologies that will address future, anticipated customer needs and transform the industry. STMD's process to accomplish this is shown in Figure 1. The process starts with development of an understanding of current plans across the civilian space industry, which grounds STMD's strategic planning in the needs of the community and the strategic trends driving the evolution of the industry.

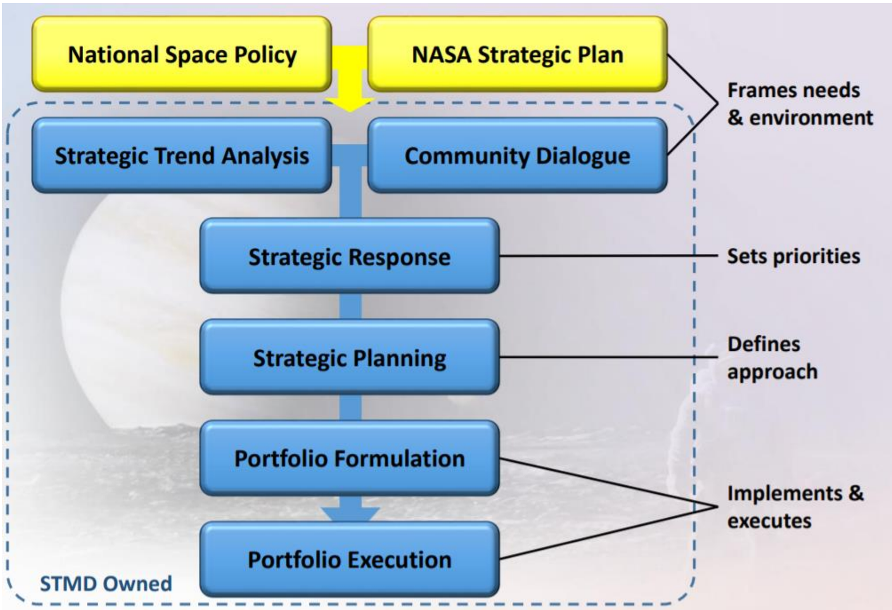

Figure 1: STMD's strategic planning process.

Over the past ten years, the space industry has transformed through the introduction of new technologies, systems, and operating models. For example, the average cost of accessing space is falling through commercial space's introduction of lower cost operating models and reusable launch systems. CubeSats have also begun to transform the remote sensing industry, providing a low-cost platform that can be deployed in constellations that, in aggregate, can more reliably provide high repeat imagery of the surface. While anticipating the long-term impacts of specific innovations is a challenge, identification and examination of the global trends can provide insights into the types of technologies that may have a major impact on the industry. To this end, STMD has identified sets of trends that represent major axes of change that have shaped, are shaping, and will continue to shape the course of civilian space research over the next several decades. These Mega-Drivers are then used to inform strategic planning.

As shown in Figure 2, in response to these Mega-Drivers and community input, STMD has provided a Strategic Response; developing its understanding of the vision for the future of civilian space relative to STMD space research. The vision is decomposed into Strategic Thrusts, around which STMD has formed major lines of investment within the STMD portfolio. Within each Strategic Thrust, STMD has then identified prioritized areas for investment, represented by Outcomes. These Outcomes are measurable, community-level achievements that STMD chooses to pursue as part of a joint effort with the broader community because of their potential impact and the importance of space technologies to their achievement.

In order to achieve this vision and these priorities, STMD conducts Strategic Planning to identify and develop credible approaches and paths to addressing the Outcomes. As part of developing this plan, the Outcomes are decomposed into the different technical and programmatic approaches to achieve this outcome and the products and/or capabilities required to make those approaches possible. STMD can then identify roles and responsibilities with respect to delivering those products and capabilities with its customers and strategic partners . The products and capabilities pursued by STMD are then documented as Technical Challenges.

The Technical Challenges developed as part of STMD's Strategic Planning will serve as the basis for Portfolio Formulation and measuring progress and success during Portfolio Execution. STMD projects and solicitations will be framed to directly address Technical Challenges. Portfolio selections for execution will be informed by the importance of the Technical Challenges to achieving the Outcomes, the expected cost required to address the Technical Challenge, and the likelihood that a project and/or activity can address the Technical Challenge within the expected cost. Selected projects in execution will be continue to be evaluated, with progress and success measured with respect to Technical Challenge achievement.

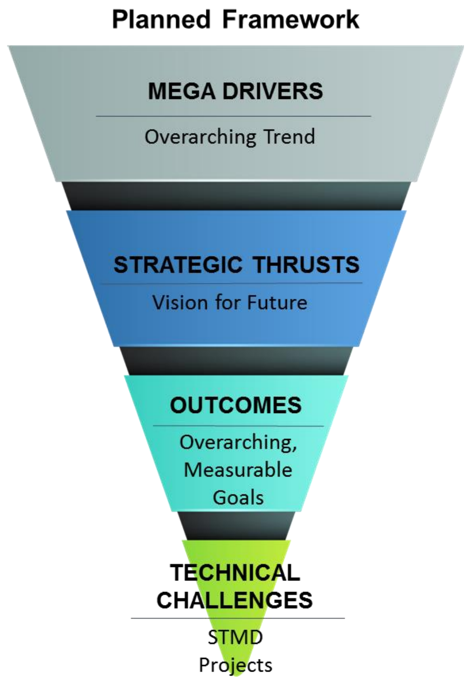

Figure 2: STMD's Planned Strategic Framework.

III. Global Trends and Mega-Drivers

STMD defines Mega-Drivers as sets of trends that represent major axes change that have shaped, are shaping, and will continue to shape the global civilian space industry and civil space research over the next several decades. These Mega-Drivers, in combination with dialogue from the community, serve to ground STMD's strategic framework in the near- and long-term needs of the space industry. Based on trend analysis, STMD has identified four Mega-Drivers: Increasing Access, Democratization of Space, Accelerating Pace of Discovery, and Growing Utilization of Space. These Mega-Drivers are highly interrelated. Given the implications of each, STMD has made the decision to define them separately [3].

A. Increasing Access

Over the past two decades, space has become increasingly accessible; making it easier for both traditional and new players to get assets into space, move around in space, and land/operate on other planetary surfaces. On average,* commercial cost to access space on a per kilogram basis has decreased by approximately 50% (see Figure 3) in response to increased international and private sector competition, higher launch rates, introduction of new technologies (e.g. reusable rockets, additive manufacturing, improvement propellants, modular systems), and regulation changes. Growth and diversification in launch vehicle options has increased the availability and customization available to launch customers, with large number of commercial flights, new launch providers entering the market, and significant increases in the use of rideshares. Miniaturization of satellite components and systems has resulted in deployment of new small, affordable platforms (e.g. small, mini, micro, and nanosatellites) that have reduced barrier of entry to new players and enabled deployment of new distributed architectures to provide services. In space, the increasing availability of new high efficiency and scalable in-space transportation systems (e.g. electric propulsion) is reducing transportation cost and mass requirements, while allowing systems to be leveraged across

* Average price is defined as the total dollars spent in a particular year, divided by the total kilograms launched in that year, as opposed to the average of the price per kilogram for each launch in that year.

multiple mission classes. Additionally, technology advances within entry, descent, and landing are allowing increasingly capable systems to be deployed to planetary surfaces.

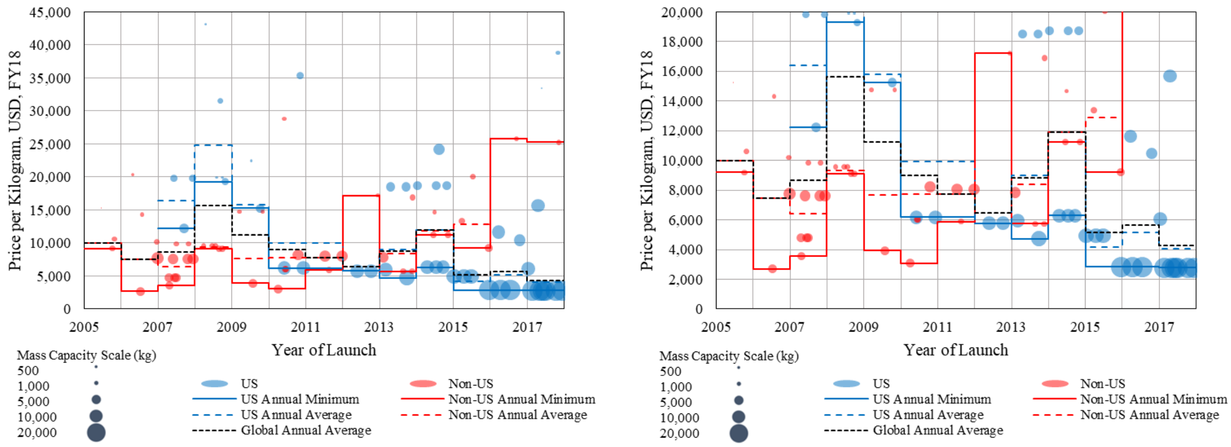

Figure 3: Commercial launch prices per kilogram to LEO, (a) total range and (b) zoomed-in range, with the annual minimum and the annual average by US and non-US and the global annual average, sized by launch mass capacity [4]-[52].

This Increasing Access has broad implications across the space community. Lower prices to launch and move through space are allowing traditional space players to offer more cost competitive and/or capable systems. Lower prices are also resulting in new commercial uses of space becoming economically viable, which will be discussed more in the Growing Utilization of Space Mega-Driver. Lower barriers of entry resulting from lower prices and platform innovations are resulting in an increase in who can use space, with new commercial, academic, and governmental entities deploying assets, which will be further discussed in the Democratization of Space Mega-Driver. Additionally, the drive to reduce costs across the industry, which is expected to continue for some time, has often been driven by the introduction of new technologies. Often, the solutions result in major changes to how things have been historically done, either at the subsystem or system level. For example, the introduction of small satellites has in turn led to the deployment of distributed, many-satellite constellations that are capable of performing similar services to larger historical platforms for lower cost. STMD's mission includes identifying and developing these type of game-changing technologies and capabilities, while also ensuring that the technology needs resulting from these changes are also addressed.

B. Accelerating Pace of Discovery

Scientific observations, deep space robotic exploration, and human exploration of space are driving new technologies that lead to an Accelerating Pace of Discovery. Robotic exploration of Mars is driving research into in-space optical communications technologies that could increase the amount of data transmitted between planetary destinations and Earth by orders of magnitude [53]. Likewise, exploration is driving research for technologies like hypersonic inflatable aerodynamic decelerators (HIADs) that enable high mass landings at destinations with atmospheres (e.g. Mars, Titan, etc.) and can also be used at Earth for sample return [54]. The near future should also see the launch and deployment of larger observatories such as the James Webb Space Telescope and Wide Field InfraRed Survey Telescope and new interplanetary missions such as Europa Clipper which will open the doors of discovery even further.

In addition, advances in data gathering and processing technologies are expected to grow the rate of discovery as these technologies find new applications in robotic and human exploration. Advances in computational hardware and data processing algorithms result in better analysis of data and pattern identification. In June of 2018, an Oak Ridge National Laboratory super computer demonstrated 1.8 x 10^{18} calculations per second capability while analyzing genomic information [55]. This increased computing power along improved software engineering will enable data assimilation systems and forecasting models to reach levels of complexity and temporal accuracy never before seen.

Advances in sensor technology also implications on spaceflight and exploration. For example, chip-based, solid-state lidar technology [56][57] that has been largely motivated by the autonomous vehicle industry is enabling smaller, inexpensive spacecraft sensor packages that can gather more data than traditional lidar packages and find uses in planetary exploration. The increased processing power combined with the growth in the number of space assets and accompanying returned data are fueling the acceleration of discovery.

C. Democratization of Space

As space has become increasingly accessible, there has been an increase in the number of entities using space, from national governments to private investors to individual citizens. One result of this change has been a shift over the past 20 years from an industry dominated by investment from a few governmental players to one with a mix of government and commercial investment. Commercial revenues from privately-funded space enterprises are now on par with governmental investment [58], resulting from substantial growth in commercial services while annual investment by governmental expenditures have largely remained steady [59]. Private investment has also increased significantly over the last 10 years. Of the $18.4 billion investment being made in start-up space between 2000 and 2017, 60% of that investment has occurred since 2015 [60], [61]. The number of governments making investments in space has also increased substantially over the last 50 years, growing from 11 with space programs in the 1960s to over 68 countries today; with increasing cooperation between different countries (see Figure 4) [62]. There has also been a growth in government spending on programs that enable small businesses and academia access to space, such as through the Small Business Innovation Research (SBIR), Small Business Technology Transfer (STTR), and NASA and NSF CubeSat Launch Initiative (CSLI) programs.

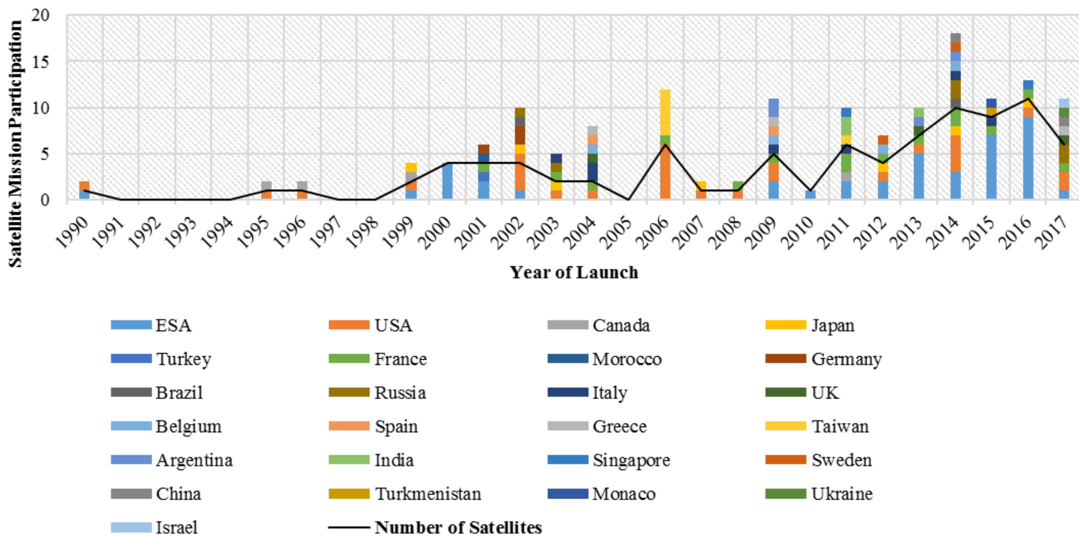

Figure 4: Number of currently operational Earth satellites with multinational collaboration [62].

This Democratization of Space is changing the landscape of the space industry. Historically, due to their large expenditures, national governments have had a significant influence on the evolution and direction of the industry. As private investment and commercial revenues have increased, that influence, while still significant, has been reduced. Private investment is increasingly resulting in innovations with significant potential to change the market, such as Planet Labs deployment of high-frequency imaging, low cost, and resilient nanosatellite constellations and SpaceX's demonstration of reusable orbital launch vehicles. Corporations have also been increasingly willing to define aggressive visions of the future of space, independent of national space programs. Examples include SpaceX's plans for human exploration of Mars, Blue Origin's vision for large scale use of Low Earth Orbit, and United Launch Alliance's vision for cis-lunar economy. This shift represents an opportunity: the increasing number of players provides opportunities for more partnerships, increasing private investments means government investment does not need to drive all growth/innovation and can be more strategically focused, and privately-funded innovations and architectures can be increasingly leveraged to enable to government-directed missions.

D. Growing Utilization of Space

As the barriers of entry to space and cost to operate in space have decreased, the use of space has continued to grow, in the form of increasing use and reliance on existing capabilities and opening of new markets. The NASA Authorization Act has outlined a Human Exploration Roadmap and science exploration goals, which push operations deeper into space and onto planetary surfaces. The 2000s have been characterized by substantial growth in existing space sectors (i.e. communication, navigation) and establishment of remote sensing as a multi-billion dollar market; growth that is reflective of the increasing demand for accessible data and knowledge. The global satellite industry almost tripled its revenues in the last 20 years, from $101B in 2000 to $275B in 2017 [63]. As seen in Table 1, new markets are being established, including the areas of space tourism, resource prospecting, and in-space manufacturing. In addition, there has been an observable growth in unique space-related services. Through private investment, aggressive strategies have emerged to drive low-cost, effective solutions to existing challenges, as well as new capabilities such as in-space manufacturing, large-scale habitation for tourism, and resource prospecting. Improving understanding of the Earth as a globally-integrated system presents another challenge that can be met with increasing utilization of space (e.g. resource monitoring, remote measurements, extraterrestrial resource extraction).

Table 1: New and existing space markets in Q4 2017, with number of companies and total investment [60].

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

This Growing Utilization of Space is leading to significant growth within the industry, reflecting our increasing reliance as a society on assets in space. A by-product of the overall growth is increasing revenues in secondary space markets (e.g. satellite manufacturing, launch), which provides increasing opportunities to leverage the growing scale of those markets to deploy new innovative solutions. The potential for new markets opening in areas such as in-space manufacturing, space tourism, and resource prospecting offer opportunities to further fuel this growth, while also providing increased opportunities to leverage those markets to demonstrate new capability and technology solutions. STMD's mission includes identifying and developing the cross-cutting technologies that can be leveraged across all these existing and potential markets.

IV. Strategic Thrusts and Outcomes

In response to the Mega-Drivers and Community Input, STMD has formulated five Strategic Thrusts that represent STMD's understanding of the vision for the future of civilian space relative to STMD space research. These Thrusts represent major lines of investment within STMD's portfolio that are expected to have major impacts on space through 2040 and beyond. The Strategic Thrusts are:

- *Go*: Enable Safe and Efficient Transportation Into and Through Space
- *Land*: Increase Access to Planetary Surfaces
- *Live*: Enable Humans to Live and Explore in Space and on Planetary Surfaces
- *Explore*: Expand Capabilities Through Robotic Exploration and Discovery
- *Prosper*: Accelerate the Industrialization of Space

Within each of these Strategic Thrusts are Outcomes that represent the achievements STMD wants to see come to fruition. They are measureable, community-level goals that STMD chooses to pursue as part of a joint effort across the community because of their potential impact and the importance of space technologies to their achievement. The Outcomes are phased across three periods (the 2020s, the 2030s, and the 2040s and beyond), with the capabilities required to enable the earlier Outcomes driving the higher technology readiness level investments made by STMD, while the later Outcomes are used to drive the early-stage portfolio investments. As Outcomes are completed, investments can then be shifted to achieving other Outcomes. The Outcomes have been formulated to not prescribe implementations and carry the expectation that solutions will most likely be multi-disciplinary.

A. *Go*: Enable Safe and Efficient Transportation Into and Through Space

The ability to access and traverse space in an affordable and reliable manner is critical to accomplishing NASA's goals for human and robotic exploration, science, and enabling U.S. commercial space ventures. Exploration, led by NASA's Human Exploration and Operations Directorate (HEOMD), will require heavy-lift launch vehicles for accessing space as well as high-capacity, fast-transit in-space transportation systems for moving crews, cargo, and surface systems through space to their destinations. Science, led by NASA's Science Mission Directorate (SMD), needs more affordable access to space and higher capacity deep space transportation systems as a means of increasing mission cadence and delivering more capable systems throughout the solar system and beyond. Moreover, lowering the cost of deployment systems and establishing economically sustainable in-space transportation architectures will immensely benefit commercial space ventures and allow U.S. companies to better compete and enter new markets. Meeting these needs will require the development of new transportation technologies for HEOMD, SMD, and U.S. companies.

After identifying Outcomes associated with the *Go* Thrust, they were structured into two themes: Launch and In-Space Transportation. Two of the identified Outcomes are presented in Table 2. For a full list of Outcomes, see the Appendix.

Table 2: *Go* Strategic Thrust Example Outcomes.

Theme	Timeframe	Outcome
Launch	2020s	Affordable and responsive launch systems introduced for delivering the next generation of small and cube satellite platforms to space.
In-Space	2040s +	A propulsion technology is demonstrated in space that enables rapid interplanetary missions and relativistic interstellar flight.

After identifying and decomposing all the Outcomes, STMD's strategic vision within this Thrust is to play a central role in facilitating and developing technologies that reduce the cost of space access and provide cost efficient, reliable transportation solutions that dramatically enhance fight capability and support a vigorous deep space agenda. Specifically, the capabilities that STMD is looking to advance include, but are not limited to the ability to autonomously transfer and store cryogenic propellants both in-space and on the surfaces of the Moon and Mars; high-power (hundreds of kilowatts), low-thrust propulsion systems; high-efficiency, high-thrust propulsion systems that can reduce interplanetary transit times; and deep-space autonomous navigation.

E. *Land*: Increase Access to Planetary Surfaces

Along with the ability to access and travel through space, the ability to affordably and reliably access the surface of other planets and moons, and return samples to Earth is also critical to accomplishing NASA's human exploration and science goals. Within NASA, HEOMD seeks to enable human access to the surface of the Moon and Mars and return them safely to Earth, and SMD seeks to gain access to high-value sites throughout the solar system (e.g. Mars, Moon, Venus, outer planet atmospheres, and icy moons) in order to enable its planetary science program which is guided by the Planetary Science Decadal Survey.

In response to these Agency goals, STMD identified Outcomes that fit within three themes: Crew Delivery, Cargo Delivery, and Science Payloads. Three example Outcomes are as follows in Table 3 with a full list of Outcomes in the Appendix.

Table 3: *Land* Strategic Thrust Example Outcomes.

Theme	Timeframe	Outcome
Crew	2020s	People safely and precisely landed on the Moon.
Cargo	2030s	Precisely and affordably land commercial and NASA payloads on Mars.
Science	2020s	Return industrial/scientific samples to Earth with high reliability.

Following the decomposition of these and the other *Land* Outcomes, STMD's strategic response is to focus on technologies that will enable safe and efficient delivery of mass to planetary surfaces, allow precise landing at more interesting and hazardous sites, and increase the reliability of sample returns to Earth. Key identified Capabilities in this Thrust include, but are not limited to the following: precisely landing large payloads on the Moon and Mars with an accuracy better than 50 m; safely delivering human-scale (on the order of 20 t) systems to the surface of Mars; providing scalable entry systems allowing for a broad range of Earth-return and interplanetary missions.

F. *Live*: Enable Humans to Live and Explore in Space and on Planetary Surfaces

In December of 2017, the President signed Space Policy Directive - 1 which stated "…the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations" [64]. Within NASA, HEOMD is currently executing projects to develop a heavy-lift launch vehicle and crew capsule, studying the establishment of a crewed deep-space habitation capability in cis-lunar space, and trading options for Moon and Mars transportation and surface architectures [65]. The establishment of new capabilities, through the development of advanced technologies, will be required to enable the exploration of the Moon as a necessary step for the future human exploration of Mars.

This Thrust, however, is not limited to satisfying NASA's goals. It also includes Outcomes that capture the broader civilian space community, and humans living and working in Space for any purpose. With that broad reach in mind, Outcomes were fit into three themes: In-Space, Moon, and Mars. Example Outcomes are presented in Table 4 with the remaining Outcomes available in the Appendix.

Table 4: *Live* Strategic Thrust Example Outcomes.

Theme	Timeframe	Outcome
In-Space	2020s	People living and working beyond low-Earth orbit.
Moon	2030s	Routinely visit new sites across the Moon to conduct exploration and science.
Mars	2040s +	Routinely visit new sites across Mars to conduct exploration and science.

Following the decomposition of these and the other *Live* Outcomes, STMD's strategic response is to focus on technologies that will support in-space and surface habitation, provide scalable support infrastructure to sustain those habitation capabilities, and enable systems to permit exploration and investigation of diverse, high-value sites by U.S. astronauts. Key identified Capabilities in this Thrust include, but are not limited to the following: providing highly-capable, autonomous robotic assistants and rovers to support exploration and discovery; demonstrating key ISRU systems on the Moon that will be needed to support future human exploration; and remotely locating potential resources and other exploration and discovery interests on the surface of the Moon and Mars.

G. *Explore*: Expand Capabilities through Robotic Exploration and Discovery

The continued growth of human exploration and discovery capabilities will rely on growth in capabilities of robotics. With the ability to operate in extreme environments for durations that exceed human limits, along with the ability to augment human performance, robotics enable discoveries that would not be possible with humans alone. Robotics are also critical to expanding exploration by providing services and consumables to support crew and enable them to live and work in-space and on planetary services. In-situ resource utilization (ISRU) and reliable power sources that can support crewed activities during eclipses are critical to future crewed deep-space exploration.

This Thrust was formulated to emphasize the far-reaching importance of robotics to the future of exploration and discovery. Outcomes for the Explore thrust were focused on demonstrating and relying upon these robotic capabilities and were organized in to three themes: Moon, Mars, and In-Space. Example Outcomes are giving in Table 5 with the remaining Outcomes available in the Appendix.

Table 5: *Explore* Strategic Thrust Example Outcomes.

Theme	Timeframe	Outcome
Moon	2020s	Autonomous, reliable robotic mobility and sensing systems exploring large regions of the Moon with potential applicability to Mars and beyond.
Mars	2030s	ISRU propellant production, storage, and transfer demonstrated on Mars.
In-Space	2020s	Cislunar assets autonomously maintained and utilized to enable discovery with applicability to deep-space transit and surface assets.

Following the decomposition of these and the other Explore Outcomes, STMD's strategic response is to focus on technologies that will support sustainable, long duration human habitation and exploration of the Moon and Mars and augment human capabilities in order to enable future discovery. Key identified Capabilities in this Thrust include, but are not limited to: providing continuous multi-kW power in any lighting condition; provide reliable, secure, high-rate (>200Mb/s) communications from in-space locations as well as the surface of the Moon and Mars; and producing, storing, and transferring oxygen and water for crew consumption on the surface of the Moon and Mars.

H. *Prosper*: Accelerate the Industrialization of Space

The economic potential of space is substantial, with the global commercial space economy valued in excess of $344B [66] and growing at twice the rate of the U.S. economy [67]. To realize this potential, private investment in the past five years has been in excess of $10.6B, which is an increase of almost 40% from the previous 5 years [60]. Development of new technologies is critical to sustaining this rapid economic growth. STMD recognizes this potential and plays a significant role in developing these technologies.

Performing functions in space rather than on the ground could provide dramatic benefits in space operations and the design and deployment of structures that cannot be launched from Earth. Emerging technologies such as on-orbit servicing, assembly, and manufacturing will lower operating costs and create market opportunities through the establishment of commercial research and industrial facilities in space. The Outcomes within the thrust have been structured around three themes: Assembly & Manufacturing, Space Infrastructure, and Servicing. Example Outcomes are presented in Table 6, with the others listed in the Appendix.

Table 6: *Prosper* Strategic Thrust Example Outcomes.

Theme	Timeframe	Outcome
Assembly & Manufacturing	2030s	Manufacturing of components and robotic assembly and reconfiguration of systems in space is routine.
Space Infrastructure	2040s +	Industrial-scale, sustainable in-space commodity markets established.
Servicing	2020s	Reliable, industrial-scale, in-space refueling, reconfiguration, and maintenance services introduced.

Following the decomposition of these and the other Explore Outcomes, STMD's strategic response is to focus on technologies that will foster sustainable new in-space markets and increase the lifetime and capability of current space assets. Key identified Capabilities in this Thrust include, but are not limited to: refueling, maintaining, and servicing satellites in Earth orbit; assembling large assets in space; reliably manufacturing spacecraft components in-space; and highly capable robotics supporting, servicing, and maintaining in-space systems.

V. Outcome Decomposition and Technical Challenges

The Outcomes are decomposed into the products and/or capabilities that will be delivered by STMD to enable those Outcomes, represented in the framework as Technical Challenges. These Technical Challenges will serve as the foundation for planning projects and tracking performance within STMD, with STMD projects and solicitations being formulated to directly address Technical Challenges. [1]Given their level of specification, the expectation is that they will continually evolve as they are achieved, as community needs change, as technologies advance, or as new issues emerge. In decomposing the Technical Challenges, some specificity is required in the type of approach or implementation pursued. Therefore, unlike for Outcomes, Technical Challenges will often prescribe or infer an implementation and may be restricted to a single discipline. The types of products that need to be delivered to address a Technical Challenge may range from complete systems (e.g. solar electric propulsion for NASA's Gateway [65]) to components, manufacturing techniques, and concepts. The expectation is that most Technical Challenges will involve delivering products and/or capabilities at or below the subsystem level. To develop these Technical Challenges, a systematic decomposition process is used, with that process shown in Figure 5. The intent of this process is to identify, explore, and evaluate different approaches that are being or could be pursued by the community to achieve these Outcomes to inform the key areas in which STMD can invest to have the greatest impact.

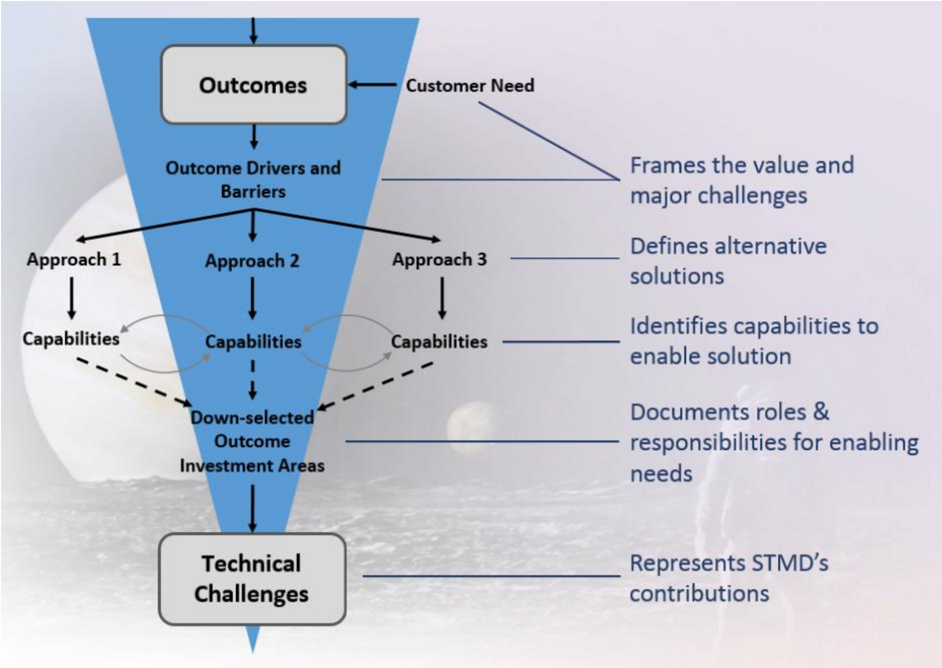

Figure 5: Outcome to Technical Challenge Decomposition Process.

To decompose the Outcomes, the context around each Outcome needs to be more clearly defined, with particular emphasis on the Customer Need and the Outcome's Drivers and Barriers. The Customer Need defines the value produced by the Outcome, provided in the terms of the members of the community affected, how the Outcome fits into the broader community plans, more detailed timeframes for achievement, and relevant policies and plans. In some cases, these need statements may relate to multiple different markets or communities, particularly where the Outcome has cross-cutting applicability. The Outcome's Drivers and Barriers represent the technical, programmatic, operational, and policy factors that will strongly drive achievement of the Outcome. The intent is to identify the factors that need to be accounted for in formulating the subsequently defined approaches. Each driver/barrier should be addressed in some way by each approach.

While Outcomes are implementation agnostic, in order to identify meaningful Technical Challenges around which technology development activities can be formulated, some implementation definition needs to be specified. Within the Outcome decomposition process, these implementation definitions are defined as Approaches. Given that multiple implementation alternatives may be pursued in order to achieve a particular Outcome, each Outcome has an infinite number of potential Approaches. Each Approach represents a collection of capabilities that when addressed in total by the community, would result in the Outcome being fully achieved. These capabilities may be either technical or programmatic in nature and can be used to inform discussions with customers and development of Technical Challenges. Certain capabilities, or portions of capabilities, may be identified as the responsibility of other organizations, while others may be identified as STMD's responsibility and turned into Technical Challenges. Over time these Technical Challenges will be continually evolving as they are accomplished, Outcomes change, technologies progress, or new technologies are introduced. This structure was chosen to allow STMD to better define two key factors driving how it invests its limited resources to have the greatest impact:

- STMD wants to invest in capabilities and technologies with broad applicability across a range of Outcome and associated Approaches

- STMD wants to invest in capabilities and technologies that are critical to achieving NASAs goals where other organizations are not investing and thus would not be achieved without STMD involvement.

STMD may also elect to pursue Technical Challenges that enable multiple approaches within a single Outcome, whether as a hedging strategy or because a downselect has not occurred, in order to keep the option space open for the community.

To illustrate the decomposition process the Outcome "People safely and precisely landed on the Moon" is decomposed as a notional example. The customer need is a simple statement that includes: the customer, deadline, and driving direction; "The National Space Council directed NASA to return to the Moon at their first meeting in 2017. HEOMD is currently working on crewed lunar missions to begin in the 2020s." The drivers and barriers are organized into programmatic, technical, and operational categories:

- Programmatic
  - interfacing with other programs
  - uncertainty in the lunar architecture
- Technical
  - largest indivisible system delivered to the surface
  - global access
  - anytime abort
- Operational
  - landing site location
  - surface mobility range, which informs landing precision and accuracy requirements

As previously discussed there are an infinite number of alternative Approaches, as examples a few notional Approaches to achieve "People safely and precisely landed on the moon" include:

- Gateway-centric
  - A launch vehicle delivers payloads through Trans-Lunar Injection (TLI), from which a Solar Electric Propulsion (SEP) or hypergolic stage is used to insert and rendezvous with Gateway. From there a reusable hypergolic ascent module is used to transfer crew to Low Lunar Orbit (LLO) to rendezvous with a LOx/CH_4 descent module and deliver the (two) crew members to the surface for a seven day stay. Finally, the ascent module delivers the crew back to Gateway.
- Constellation-like:
  - A LOx/LH_2 upper stage delivers lander and crew capsule (w/service module) through TLI. The LOx/LH_2 descent module performs Lunar Orbit Insertion (LOI) into a 100 km LLO and descent to a polar location with four (4) crew and 20 t of cargo for a seven day stay. The hypergolic ascent module rendezvous with the crew capsule where the hypergolic service module performs TEI.
- Apollo-like:
  - A launch vehicle delivers the ascent & descent modules, along with a crew module, direct to lunar orbit. A hypergolic descent module descends to equatorial location with two crew members for a three day stay. The hypergolic ascent module returns crew to lunar orbit.

Next, each Approach consists of a collection of capabilities, which each, when possible, have a numerical target tied to them. The specific value of these targets are still in the process of being analyzed. Recall that to achieve an Outcome, all the capabilities associated with (at least) one approach must be fulfilled. The capabilities required for the Gateway-centric Approach include:

- **Precision Landing:** Ability to deliver payloads to Moon within 50 (To Be Revised [TBR]) m of desired landing location.
- **Landed Mass Capacity:** Ability to safely deliver a 20 (TBR) t system as a payload to the lunar surface in a single flight.
- **Hazard Detection and Avoidance:** Ability to detect hazards of 0.5 (TBR) m or less from a distance of 200 (TBR) m or more and divert landing path to a safe location.
- **Landing Site Slope Accommodation:** Provide controlled, stable landing on local slopes of up to 15 (TBR) deg.
- **Crew-rated Lander:** Provide a lander capable of delivering up to 4 (TBR) humans to the surface.
- **EVA:** Provide crew members with pressure garments, portable life support, tools, and systems to perform EVA tasks on the lunar surface or in interplanetary space with (To Be Determined [TBD]) suited mobility rating and 12 (TBR) months lifetime of the suit, with frequency of 3 (TBR) EVAs per week.

- **Radiation Exposure:** Provide monitoring, mitigation, and operational strategies to limit radiation exposure to the crew to As Low As Reasonably Acceptable (ALARA) standards and increase tolerance in systems over short duration missions.
- **Dust Mitigation:** Protect crew and equipment from detrimental effects of lunar dust.
- **Power**: Provide reliable, sustained power 10-50 kW (TBR) for 28 (TBR) days in order to support crew systems.
- **ECLSS:** Provide monitoring, management, and control of environmental systems during human missions with (TBD) reliability with minimal maintenance required.
- **Thermal Control:** Maintain system temperatures within desired bounds in space and on the lunar surface during both day and night. Provide thermal management for human elements, robotic landers, long-term cryogenic storage, and other systems.
    - During the lunar day, provide waste heat rejection from landers and habitats with environmental sink temperature up to 300 (TBR) K.
    - During the lunar night, provide thermal management (insulators, heaters, louvers) to maintain equipment with environmental sink temperature down to 150 (TBR) K.
    - Thermal management to maintain cryogenic propellant tanks containing liquid oxygen and/or methane at 90 K, or liquid hydrogen at 20 K.

From these capabilities, or portions of these capabilities, STMD develops Technical Challenges around which it formulates projects and solicitations. The Outcome decompositions will continue to be updated and refined as a part of the Strategic Framework.

VI. Forward Work

The STMD Strategic Framework is still under development and is designed as a continually evolving structure allowing STMD to make strategic and transparent investment decisions. Moving forward, the Outcome Decompositions will be further vetted to assist in the selection of a prioritized set of Capabilities that STMD will pursue in the next round of portfolio formulation activities. As the Framework continues to be integrated into the Portfolio Formulation process and STMD Projects formulated to address prioritized Capabilities, Technical Challenges will be developed to guide the Projects and serve as a measure of their progress. On an annual basis, Outcomes will be reviewed to identify existing Outcomes no longer aligned with the NASA or STMD missions, or new Outcomes that need to be added to reflect changing priorities. Throughout this process STMD will continue to remain engaged with the broader space community to ensure that the Framework, and thus the STMD portfolio, evolves with changes the space community's needs.

VII. Conclusion

STMD has developed a Strategic Framework to better communicate with STMD's stakeholders and inform investment prioritization and technology development planning. The Framework is structured to be responsive to the Mega-Drivers that are currently shaping and will continue to shape the civilian space sector. The Framework articulates a vision for the space industry, organizing that future into five investment lines or, Strategic Thrusts. Within each of those Strategic Thrusts, STMD chooses to pursue community-level Outcomes which, through development and application of new space technologies, will have a significant impact on NASA's mission and the space industry. STMD has begun decomposing those Outcomes into the Capabilities required to achieve them, identifying the key areas of investment necessary to most effectively advance their completion. As this Framework continues to developed and refined and is further integrated into STMD's portfolio formulation process, STMD will be able to more clearly communicate the impact and rationale of its portfolio, demonstrating how STMD's investments not only advance the state of the art, but will also have a clear path to infusion in order to provide the most value and impact.

Appendix

Table 7 *Go*: Enable Safe and Efficient Transportation Into and Through Space Strategic Thrust Outcomes

Time Period	Outcomes
2020s	• Reusable commercial launch services fleets introduced. • Affordable and responsive launch systems introduced for delivering the next generation of small and cube satellite platforms to space. • Routine, affordable in-space transportation between the Earth and Moon. • Propulsion technology demonstrated to affordably deliver SmallSats and CubeSats to the inner planets and asteroid belt on demand.
2030s	• Space access cost, reliability, and availability improved by an order of magnitude. • High-speed propulsion systems demonstrated, providing more aircraft-like access to space. • Crew safely and rapidly delivered to and returned from Mars. • Cargo efficiently delivered to inner solar system destinations. • More efficient and affordable propulsion systems deployed to enable more capable and faster deep space robotic missions.
2040s+	• Robust, commercial up/down transportation market underpinning a vibrant and dynamic space economy. • High-speed propulsion systems introduced to commercial launch service fleets, resulting in more airport-like operations. • Routine, low-cost transportation to and from Mars. • Large quantities of resources efficiently moved within the solar system. • A propulsion technology is demonstrated in space that enables rapid interplanetary missions and relativistic interstellar flight.

Table 8 ***Land*****: Increase Access to Planetary Surfaces Strategic Thrust Outcomes**

Time Period	Outcomes
2020s	• People safely and precisely landed on the Moon • Precisely and affordably land commercial and NASA payloads on the Moon • Double the landed mass capability to the Mars surface • Return industrial/scientific samples to Earth with high reliability
2030s	• Routine landings of people on the Moon • People safely and precisely landed on Mars • Precisely and affordably land commercial and NASA payloads on Mars • Increase the landed mass capability to the Mars surface by an order of magnitude • Fly affordable, long-duration science payloads through the atmospheres of multiple outer planets • Land the first ever U.S. scientific payload to operate on the surface of Venus • Land science payloads on previously unexplored icy moons and ocean worlds
2040s+	• People landed safely, routinely, and affordably on the Moon and Mars • Science payloads landed precisely on previously-inaccessible planetary destinations

Table 9 *Live*: Enable Humans to Live and Work in Space and on Planetary Surfaces Strategic Thrust Outcomes

Time Period	Outcomes
2020s	• People living and working beyond low-Earth orbit • People living and working in low-Earth orbit for commercial purposes • People exploring previously inaccessible locations on and around the Moon
2030s	• A sustainable and increasingly independent outpost established on the Moon • Routinely visit new sites across the Moon to conduct exploration and science • Deploy and operate assets that will allow humans to live on Mars • Initial Human presence on the surface of Mars
2040s+	• Expanding human settlement on the Moon • Continuous and sustainable human presence on Mars • Routinely visit new sites across Mars to conduct exploration and science

Table 10 *Explore*: Expand Capabilities through Robotic Exploration and Discovery Strategic Thrust Outcomes

Time Period	Outcomes
2020s	• Lunar resource availability characterized • Production of consumables and/or propellant using lunar resources demonstrated • Autonomous, reliable robotic mobility and sensing systems exploring large regions of the moon with potential applicability to Mars and beyond • Robotically scout and prepare potential sites for future human missions to the Moon • Demonstration of surface radiation protection solutions • Critical system survival of the lunar night demonstrated (e.g. batteries, propulsion, thermal control, ECLSS) • Return the first Martian soil sample to Earth • Cislunar assets autonomously maintained and utilized to enable discovery with applicability to deep-space transit and surface assets • Space weather (e.g. SPE) prediction and warning capabilities developed in support of crewed missions
2030s	• First manufactured goods produced on the Moon using lunar resources • ISRU propellant production, storage, and transfer demonstrated on Mars • Robotically scout and prepare potential sites for future human missions to Mars
2040s+	• Technologies demonstrated to support a sustained human presence on Mars and beyond • Characterize the dynamic geologic and meteorological circumstances on Mars

Table 11 *Prosper*: Accelerate the Industrialization of Space Strategic Thrust Outcomes

Time Period	Outcomes
2020s	• In-space robotic assembly of pre-manufactured components demonstrated • Component-level manufacturing demonstrated in space • Commercially viable research and manufacturing infrastructure deployed in near-Earth space for terrestrial uses • Near-earth space infrastructure and utilities support multiple independent users • Reliable, industrial-scale, in-space refueling, reconfiguration, and maintenance services introduced
2030s	• Manufacturing of components and robotic assembly and reconfiguration of systems in space is routine • Commercially viable research infrastructure deployed in cislunar space • Commercially sustained debris mitigation services
2040s+	• Demonstrated robotic assembly of systems in space using parts manufactured with space resources • Commercially viable research infrastructure deployed in deep space • Industrial-scale, sustainable in-space commodity markets established • repurposing, manufacturing markets

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