CONNECTING SPACE RESOURCES TO THE NEAR-EARTH ECONOMY: PROPELLANT DISTRIBUTION, STRATEGIC MODULARITY, AND A CONCEPT OF SPACE SUPPORT

by

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ABSTRACT

This thesis describes the importance of space resources to national power. It introduces methods of distributing propellant derived from space resources in the cis-lunar system and recommends methods that the United States and its Allies can take to achieve interoperability and strategic modularity. The thesis reviews The General Theory of Space Power, first described by Lt. Col. Brent Ziarnick, Army Doctrine Publication 4-0 Sustainment, and aviation and airport management principles, and then applies the reviewed concepts to establish a concept for setting a space theater and establishing a concept of space support. The thesis concludes with an imperative: America and its Allies must study and invest in in-space sustainment coupled with in-space resource utilization. These capabilities represent the foundational ability to act in space: they are the key to enabling an Earth independent supply chain.

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For my son.

CHAPTER 1.

INTRODUCTION

> "In order to grow space power, space officers need to become space enthusiasts, and enthusiasts need to adopt military terminology to better work together to promote their common interests in space development."
>
> -Brent Ziarnick [1]

Sustaining and servicing satellites is not a new idea, nor is prospecting for, extracting, and processing propellant sourced from space resources. Nor indeed, is it a new idea to transport propellant to Earth orbit to refuel space vehicles. However, sustaining satellites for use in Earth orbit utilizing space resources, rather than to enable deep space exploration missions, represents a new application and a fusion of several new and old ideas. NASA initially considered refueling spacecraft in orbit in 1969 with the Report of the Space Task Group that conceptualized the Space Transportation System, delivered in the months following the successful Apollo 11 Moon landing. The report repeatedly emphasized the importance of commonality, reusability, and economy in its vision to expand the manned space program all the way to Mars. It also articulated a three-phase program to get to Mars, similar to today's Artemis plan: first leverage and expand upon existing technology; second live sustainably in the Earth-Moon system; and third, use that knowledge gained to get to Mars [2,3]. The difference between the 1969 concept and the 2020 plan is the details and technology readiness. The philosophy of living off the land is forefront: NASA along with its partners have resumed the work they started in 1963, exploring how to extract water and oxygen for human sustainment from Lunar regolith; how to build facilities on the Moon for Humans to live and work in from the materials present on the Moon; and determining how best to get astronauts to and from the Moon [3,4].

What NASA lacks is a clear tie-in to the economics of space. It is not NASA's fault – they are bound by the Congressional legislation forming NASA: NASA's purpose is to pursue peaceful scientific inquiry and exploration. They also are not allowed to advertise on their own behalf, much like all government agencies [5]. At the time of NASA's formal creation America

lacked a clear theory of space power—but its importance was not lost on the 1969 Task Group: they believed that one of the key returns from the space program was a "…non-provocative enhancement of our national security [2]." Space power as a theory malingered in low Earth orbit since the end of the Apollo program—was it more like sea power, or air power, or something else entirely [6,7]?

Space power does not appear to follow sea power: Admiral Alfred Thayer Mahan compared the sea to a "wide common, over which men may pass in all directions, but on which some well−worn paths show that controlling reasons have led them to choose certain lines of travel rather than others [8]." It included the use of ports and colonies for trade, defense, and production of supplies. A Navy can remain deployed at sea for months at a time, and it can be replenished at sea or at a friendly foreign port. Because of limited technology, limited staying power, and the restrictions of orbital mechanics in the proximity of Earth, space could clearly not fit into the sea power model. Air power seemed more appropriate then. Air travel was much more transient. An airplane could remain in the air for only as long as its fuel allowed it to remain aloft. An aircraft had to return to base to be repaired or resupplied beyond aerial refueling. You could not establish floating drydocks in the sky.

But once one includes the Moon and the Solar System and its resources, the application of Mahanian concepts of sea power to space power begin to flourish—you can have lines of communication connecting the Earth to the Moon or to Mars, or from near-Earth asteroids to Earth, or from the Moon to Earth orbit. The planning Naval logisticians undertook in preparation for World War II (WWII) can be overlayed onto and translated into the requirements for the space environment. To operate in the Pacific, the Navy had to design or contract for the design and construction of equipment that was not yet commercially available but that had been conceived of to support rapid base formation.

> "Example[s] of this work were the floating drydocks, pontoons, portable housing, portable power plants, stills for producing fresh water from sea water, and other equipment which made possible the rapid advance of our forces into the western Pacific [9]."

The inclusion of the modern space resources and space transportation industries opens a new logistics paradigm. The industry is developing the ability to extract oxygen, water, and

construction materials from the Lunar surface [10,11,12]. They will be able to further manufacture rockets, buildings, and launch pads on the Lunar surface [13,14,15,16,17]. SpaceX' Elon Musk is taking the long-term vision of perfecting rapid reusability of rockets [18]. From here, it is up to logistic planners and their application of the sustainment arts to decide how to further apply these capabilities. The industry, in partnership with the US Space Force (USSF) and NASA can establish a material distribution and space shipyard industry in space by launching materials from the Moon for the further construction of logistics hubs, factories, and facilities to house its personnel, and provide supplies for the sustainment of human activity in the solar system and towards Earth's orbits.

Sustainment enables access. It allows industry, people, and the government to act in space. Brent Ziarnick developed the General Theory of Space Power, based on sea power. He defined space power as "the ability to do something in space [1]." Space power, just like sea power, is based on economics: trade centered around a triad of production, colonies, and shipping. This triad is the grammar of space power, from which one applies it to the logic triad, for a political, economic, or military purpose, where the economic purpose is the most important. "Space power's ultimate purpose is to generate wealth from space activities, and commerce is the true path to national greatness in space [1]."

Space resources fit nicely within the grammar of Ziarnick's theory of space power. Space resources explores the creation of production capabilities, the establishments of spaceports and shipyards, and the use of space tugs for the transport of goods and people. Ziarnick's logic describes how to emplace those capabilities. Military sustainment requires the effective application of logistics: forecasting the sustainment needs for "beans, bullets and bandages" across time, space, and purpose.

> "Logistics is planning and executing the movement and support of forces. It includes those aspects of military operations that deal with: design and development; acquisition, storage, movement, distribution, maintenance, and disposition of materiel; acquisition or construction, maintenance, operation, and disposition of facilities; and acquisition or furnishing of services [19]."

It is between the now well-developed theory of space power and the emerging technology of in-space sustainment that this thesis was developed. The model of Army sustainment applied to

space operations allows for a pragmatic look at what space resources can do for the space economy, and thus for national power in space.

It is my hopes that through this work the space industry will consider the sustainment of satellites during the contracting and engineering phases of acquisitions and embrace deliberate interoperability across sustainment functions, so that our space capabilities become more robust, resilient, useful, and ideally cheaper to operate. Sustainment maintains combat power, enables operational reach, freedom of action, and prolongs endurance – all worthy goals of operating in the space domain [19].

1.1 Thesis

Space Resources can and must be used and logistically integrated with a coherent concept of space support to enable full spectrum space operations that span the range of military operations, with or without human presence.

This thesis focused on: 1) how space resources impact national power, 2) refueling satellites with space resources derived propellant, 3) establishing a fully modular sustainment system, and 4) defining the concept of space support. These topics are covered in chapters two, three, four, and five, respectively.

1.2 Importance

The purpose of this thesis was to develop and describe systems for sustaining military operations in Earth orbit; to expressly integrate them with resources extracted from sources beyond Earth orbit; and to justify the need, feasibility, and utility of doing so. The foundation of military operations is sustainment. Sustainment enables operational reach, freedom of action, and prolonged endurance [19]. No element of sustainment can really be declared more important than another, however the biggest hurdle to being able to operate in the newly christened space domain has been transportation through the domain, that is, the cost of maneuvering. The tyranny of the rocket equation prevents one from significantly changing their satellite's orbit, let alone leaving the central celestial body to visit another. The rocket equation mathematically describes the ratio of propellant to payload needed to launch a vehicle from Earth. The overall mass fraction of the Saturn V was roughly 1:12. Twelve kilograms of propellant were needed for every kilogram of structure or payload. The Saturn V had a design wet mass of 6,102,000 pounds (lbs), to transport a payload of 96,900 lbs, giving the overall system an astounding need for 59

lbs of propellant needed to deliver a single pound of payload to its final destination [20]. The rocket equation has not changed in 60 years but advances in the production of the rockets themselves has lowered costs, but it is not by any means close to being free.

A further reduction in costs can be derived from refueling vehicles in space. Distributing space resources derived propellant to refuel space vehicles and satellites expands a supported vehicle's mission profile and reduces their cost to maneuver. A resilient propellant distribution architecture that enables reliable and regular resupply is required, but it is only as effective as its distribution nodes and edges, from the extracted or mined resource and the source of production through the end consumer. Once established propellant distribution systems move us closer to achieving "maneuver without regret." The recent spacecraft paradigm has been that a spacecraft is launched with all the propellant it will ever have. Each maneuver is a significant decision. Securing a low-cost source of propellant that can assuredly be resupplied eases the decision to maneuver. Low-cost maneuver then enables the transportation of other goods and services throughout the space domain, opening new markets: the production and transportation of manufactured goods made from space resources.

Space resources cannot just be considered from the operational or tactical level. They must also be considered at the strategic level, through the theory of space power, while remembering the ultimate strategic purpose of space power is fostering and defending the space economy. Ziarnick is not alone in declaring the economy to be the most important aspect of national power. His assertion is partially based on James Holmes and Toshi Yoshihara's analysis of sea power in Clausewitzian terms, in their article *Mahan's Lingering Ghost* [1]. It also agrees with Colin S. Grays's analysis on the importance of the economy in supporting strategy:

> "Strategy requires the use or development of scarce economic resources. It rests completely upon economic activity, and relies entirely upon logistical performance, i.e., the supply and movement of armed forces [21]."

Growing space power requires the deliberate effort on the part of space power planners. Ziarnick cites the economist, Joseph Schumpeter's theory of economic development, to define development as the effort of combining productive elements (production, shipping, and colonies) in new ways. Schumpeter provides five cases: the introduction of a new good (product or service), a new method of production, the opening of a new market, the conquest of a new source

of supply, or through the reorganization of an industry [1]. Space resources and its applications are the foundation of change—of generating new space access—space resources in their many forms are a new supply source, that can create new goods, by new means of production. Collectively they create a new market, requiring the reorganization of the entire space industry.

1.3 Chapter overviews

Chapter 2 thoroughly expands upon the importance of space resources in terms of national power. Chapter 3 introduces a potential framework for distributing propellant throughout cis-lunar space, establishing a near-term solution to the need for maneuver without regret. Chapter 4 builds upon the need for a propellant distribution architecture. To create an effective distribution network, the US Space Force must work with the US government to promote closer relations with the civilian sector and with whole of nation actors in allied countries. Chapter 5 expands upon how space resources generate space power access, including describing a concept of space sustainment to connect space resources at the industry level to the end users of space resources.

1.4 Methodology

The methods used during this research were: 1) problem identification, 2) literature review, 3) monitor current events, 4) conduct subject matter expert interviews, and 5) synthesize.

1.4.1 Problem Identification: Space Sustainment Paradigm

Satellites and satellite constellations continue to be designed for single use missions, without the intent for repair, refueling, or other refurbishment or planned upgrades. There are a few exceptions, but it is still far from the norm. Upon running out of propellant, satellites are disposed of, either by controlled (and sometimes uncontrolled) atmospheric reentry, or through disposal by placing the satellite into a disposal or graveyard orbit [22,23]. With the advent of mega constellations, such as SpaceX' Starlink constellation, the prospect of nearly ten satellites reentering Earth's atmosphere every day makes this deliberate choice alarming to some scientists [24].

SpaceX justifies allowing its Starlink satellites to reenter the atmosphere in high numbers (as they did recently when a solar storm increased atmospheric drag just before they launched 49 satellites) by declaring themselves a good steward of the environment. They plan on allowing their satellites to reenter both upon initial orbital insertion at low altitude to dispose of a satellite

that fails during checkout, and for planned end of life [25,26,27]. They are being good stewards of the environment. This is best practice for preventing Kessler syndrome (an exponential increase in space debris from chain reaction of impacts of dead satellites [28]). There is no enacted plan for either recycling used or failed satellites on orbit, or a plan to repair, service, or otherwise upgrade those satellites. Ideally that will change, as it is being actively considered by the European Space Agency (to repurpose space junk in support of a lunar base), among others [29,30].

A change to the in-space sustainment paradigm is needed but has been understudied. The reason for this, unfortunately, is due to the success of American logistics since WWII – excellent ubiquitous logistics: overnight shipping, cheap and reliable manufacturing coordinated with well-known standards, and just in time logistics. Planning for sustainment is left to professional logisticians alone and is generally overlooked or of minimal concern for other professions, as the cost to overlooking it is often so low—the logisticians will rapidly supply anything that was overlooked, and for the past 20 plus years, the United States has not been fighting near-peer adversaries, causing logistical oversights to become trivial, in spite of increased complexity [31]. The increased complexity of managing complex logistics operations—from source of supply through end user—on the ground increases the resistance to duplicating it in space. This is exacerbated by the aerospace engineering profession's divorce from the sustainment profession. As a further example of this, Army sustainment is often overlooked by the combat arms: it is just an expectation that food will be served, medical services will be available, ammunition and fuel will be provided, and vehicles and weapons will be maintained. The vast organizations dedicated to sustaining the Army, The Air Force, the Marines, and the Navy at first appears to have been overlooked by the Space Force upon its initial creation.

Instead, the Space Force has merely replicated the Air Force's sustainment philosophy. They have not considered the need for a new space sustainment and force projection paradigm, how that should tie into the Nation's strategy for extending its power into space, or how it will promote other government efforts for increasing national power in space. The Air Force operates from multiple air bases that serve as points of power projection for aircraft from which they are sustained (apart from in-air refueling). The Navy operates from ports, and contracts for port calls with host nations and performs resupply at sea. The Army performs sustainment operations

across the geographic area of the battlefield, historically delivering supplies to the front line of troops (during counterinsurgency operations where areas were not as well controlled, this devolved to point sustainment rather than area sustainment). The Marines have a slightly different sustainment philosophy: they are expeditionary and bring enough supplies to operate for a set period of time (usually less than 30 days, before they are expected to be replaced by follow on forces or be resupplied). The Air Force, until recently has been the primary military branch responsible for managing space activities; this imbued its sustainment philosophy upon the space domain. Reconsidering the philosophy of space sustainment is long overdue. The Space Force needs to incorporate sustainment cultures from the Army, Marine Corps, and Navy, not just the Air Force. Air Force sustainment models do not translate well to space operation beyond Earth orbit.

In this dissertation, in-space sustainment was considered from an Army, and at times, from a Naval officer's perspective. This includes considering the Army's concept of support (a method for planning sustainment at the operational level of war) and applying the principals and elements of sustainment outlined in the Army Doctrine Publication 4-0 Sustainment and Joint Publication 4-0 to in-space sustainment [19,32,33].

1.4.2 Literature Reviews

A literature review was used to identify and highlight space equivalent concepts for performing sustainment operations in space and establishing a supporting logistics infrastructure. The fields of study of space operations, orbital mechanics, space resources, aerospace engineering, and aerospace management have addressed the seven sustainment elements (maintenance, transportation, supply, field services, distribution, operational contract support, and general engineering support), but not in a deliberate or coordinated manner from a sustainment perspective [19]. Each element have begun to be addressed, including: conducting rendezvous, proximity operations, and docking (RPOD); on-orbit sustainment, assembly, and manufacturing (OSAM); orbital maneuvers to connect closed-circuit, fully reusable, sustainment architectures (orbital maneuvers to LaGrange points from low Earth orbit (LEO) and geostationary orbit (GEO) and back); in-situ resource utilization (ISRU); and NASA's contracting practices for securing space services (including transportation services and mining

and extracting resources for lunar surface construction and human sustainment [34,35,36,37,38,39,40,41,42]).

The literature review considered academic papers in peer-reviewed journals, conference papers, books, government funded reports, and government policy publications. Topic areas included investigating how satellites are currently serviced, how sustainment systems are structured to enable large organizations such as the military to operate, what national power and space power are, how and why we operate in space, with an emphasis on how space resources can contribute to those areas.

1.4.3 Interviews and Workshops

Conducting interviews was a key component of this research. Thought leaders and key players in the space sustainment sector and in the space resources sectors relevant to this research were identified and interviewed. Some of these interviews also supported related work for the advancement of Lunar Outpost's Cislunar Logistics Center (CLC) concept and customer outreach. Cumulatively, these interviews led to similar conclusions: that the current paradigm for conducting space sustainment is broken, and that it requires a national level, coordinated approach to overcome. Interviewed organizations and companies included: Altius, Bradford Space, Defense Innovation Unit (DIU), Lockheed Martin, Northrop Grumman, United Launch Alliance, the United State Air Force Research Laboratory, and the United States Space Force Chief Scientist Office. Some of the key personnel included:

Dr. Gordon Roesler, Space Robotics

Mr. Joe Anderson, Vice President, Space Logistics

B.G. John Olson, PhD, US Space Force

Dr. George Sowers, Professor, Colorado School of Mines

Dr. Michele Gaudreault, US Space Force

Mr. Peter Garretson, American Foreign Policy Council, Air Command and Staff College

Dr. Namrata Goswami, Author, Senior Analyst

Dr. Brent Ziarnick, Author, Air Command and Staff College

B.G. Steve “Bucky” Butow, DIU

Dr. Tracie Prater, NASA In Space Manufacturing

The author also participated in two of the US Space Force’s Space Future Workshops. These workshops were designed to help the Space Force Chief Scientist Office in determining future science and technology objectives and aid them in prioritizing efforts and resources to meet those needs. The workshop coordinated leading minds across the space industry to imagine what the future of space operations would be like across various future scenarios politically and scientifically. Efforts at these workshops distinctly influenced the author’s thoughts and views on the range and scale of in-space sustainment needs.

1.4.4 Relevant Current Events

Monitoring the current events in the field of in-space sustainment has contributed to maintaining situational awareness of the state of the industry and may facilitate other efforts at growing related capabilities further. Events that have taken place over the past few years have highlighted the potential future validity of some of the ideas and architectures proposed in Appendix A. Sustainment Models. This rapidly accelerating field demands monitoring, especially considering the interplay of astropolitical competition. China’s Chang’e-4 lunar lander was the first lunar lander to land on the far side of the Moon. More importantly from a sustainment perspective, it was also the first to germinate seeds – an early foray into establishing a national source of supply of class I supplies – food – for extended human operations beyond low Earth orbit [43].

Additionally, industry giants have rapidly outpaced academia. Mr. Joe Anderson graciously provided me a tour of SpaceLogistics’ facilities, to include the opportunity to see the first mission extension vehicle (MEV-1) before it was launched. MEV-1 and MEV-2 proved to be successful, and the company fully expects the follow-on concept of mission extension pods to be successful as well. OrbitFab launched the first propellant depot from a Falcon 9 in 2021 and has since announced a second one for GEO to deliver xenon propellant to AstroScale [44,45].

1.4.5 Synthesize

The final method used in completing this research was to synthesize the information gathered from multiple fields, sources, and professional subject matter expert opinions and then

apply and organize them to the elements of sustainment. Army Doctrine Publication 4-0 Sustainment was used as a guide to consider theater setting and the establishment of a concept of support. This was done while considering the wide view of potential futures presented in the USSF's Space Future Workshops and simultaneously considering the technologies that enable in-space sustainment, including manufacturing, in-space transportation, RPOD, OSAM, and space resources extraction. Future space operations could range from minimal to maximal robotic and human presence in space. The resulting space concept of support and sustainment overlay presented in Chapter Five is extremely general but depends upon and draws from the realities of the present work being done by the space resources and servicing industries and academic fields and connects it to the rich heritage of military sustainment planning and space strategy.

1.5 Findings: Theater Setting and The Space Concept of Support

Theater Setting and a space concept of support describes the deliberate planning for, development, emplacement, and utilization of a logistics system to support military operations in space. A logistics system includes production, staging, and transporting consumables, products, and systems, as well as the establishment and maintenance of those systems and the facilities, bases, and ports required to ensure the flow of all classes of supply to the location of need in the right quantity and at the right time. To establish this system, an international coalition needs to focus on developing the sustainment nodes and capabilities detailed here, ensuring they have interoperability, and assured mobility (through on-demand low-cost refueling). The sustainment nodes and capabilities include basic extraction of resources from celestial bodies, the processing and production of those resources into useful products, and the supporting transportation system, inclusive of lunar surface and warehouse transportation systems, spaceports on the Moon and in Lunar orbit, deep space, and beyond GEO (XGEO). Transport capabilities must be mission and environment specific: space launch must focus on space launch and in-space transportation must focus on in-space transportation. Intermodal operations must be studied in earnest to facilitate quick and efficient exchange between modes of transportation. Spaceports should be established on the Moon and in space, similar to the way airports and seaports are established on Earth: as commercial endeavors owned by private parties that meet public needs with public oversight and cost sharing. Airport masterplans provide opportunities for partnership and de-risking partnered

business plans. The government is currently lacking administrative organizations that can provide oversight for spaceports off-world, or for permanent civilian operations in space.

1.6 Contribution to the Field of Space Resources

This is the first thesis submitted for consideration for the newly minted field of Space Resources, from the first program specifically dedicated to the study of Space Resources. This work was designed to consider the logistical possibilities of space resources for the immediate and future needs of the Space Force – the youngest branch of the military. The Space Force is still determining what it needs for its force structure, and what mission sets it may have; it appears to expect its mission set will eventually expand to human travel in space [46]. Its present mission set is focused on being a capability provider for the Geographical Combatant Commanders, while assuring its own ability to operate in space [47].

This thesis establishes that logistical infrastructure development in space for the express purpose of extracting space resources and utilizing them in the near-Earth economy should be prioritized as a collaboration between civil government, industry, and the military. Lunar and NEA resource extraction and utilization enables further space activities and the development of a space economy. The investment in Lunar space ports and space stations for their logistical importance has civil and military implications. First, the Moon and NEAs are a significant source of resources. Second, space operations are dependent upon and empowered by their ability to sustain themselves—refuel, repair, or exchange parts and payloads, and supply food and other consumables for human and robotic missions. Good sustainment planning is just as necessary for military activities as it is for NASA's science and exploration programs. Distribution and sustainment planning in space is not addressed, and may be completely overlooked at present, in the military space structure.

US Transportation Command (USTRANSCOM) is the non-geographic Combatant Command charged with worldwide distribution and sustainment planning. It provides airlift, sealift, and surface lift capabilities to transport Soldiers, Sailors, Airmen, Marines, and now Guardians as well as their equipment, families, and household goods anywhere a servicemember is needed. It facilitates the intermodal working group to shape international standards and define Department of Defense (DoD) standards and related doctrine, and hosts working groups with domestic aviation, rail, trucking, and shipping industries to maintain a strategic relationship with

those industries—ensuring future partnership possibilities if the need arises [48]. Notably, USTRANSCOM does not manage space lift, and in general, space lift is limited to considerations for launching satellites into orbit, not for transportation of supplies in and around space, let alone to and from other celestial bodies.

This thesis may be the first step in considering in-space logistics as a feature, rather than as a cost, as a contribution to space activities in near-Earth and as a generator of wealth for the nation. Space stations and Moon bases should be considered critical national infrastructure: as enablers of space access, rather than as destinations. They should be included in national transportation and logistics planning—with decades of foresight—and funded at similar levels as other national transportation infrastructure hubs. This thesis establishes four critical factors that underpin this assertion: 1) that space resources and the production of goods via in-space manufacturing are foundational to national power, 2) that space resources derived propellants enable low-cost space mobility – enabling the distribution of other resources and products in space, including resources derived from the Moon and near-Earth asteroids (NEAs) to Earth orbits, 3) that interoperability and strategic modularity is a necessary prerequisite for a successful system-of-systems, and 4) that the long term planning and investment in logistics nodes, including infrastructure development, sets the theater for the sustainment of all future space activities.

1.7 Conclusion

The importance of the Moon and NEAs to establishing an operational foothold in space is a result of the potential they provide in off-worlding industrial production. Both the Moon and NEAs provide a source of resources that are gravitationally closer to GEO and LEO than the Earth is, despite the relative distances. Critically, the Moon and NEAs are also closer to each other gravitationally. The establishment of an in-space logistics system that works in space for space functions and ultimately reduces the cost of services for people will facilitate and benefit all of humanity, from the production of space based solar power reducing the cost of electricity and reducing pollution, to the production of satellite systems that facilitate communications providing high speed internet and communications to the remotest parts of Earth. Fifty-five years after Sputnik was launched, we are still launching everything up the gravitational well and then letting it fall back to Earth, rather than invest in new logistics infrastructure. The concept of

space support described here could help to advance the development of the space superhighway. It requires our leaders to invest in utilizing the Moon and other space resources.

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CHAPTER 2.

SPACE RESOURCES: EXTENDING NATIONAL POWER INTO SPACE

> "Teddy Roosevelt created the great white fleet at the turn of the century, and he did it with a purpose. The purpose was to let everyone in the world know that our [U.S.] commercial activities will not be threatened by pirates or foreign sovereigns that want to do us damage. The great white fleet was not just to protect our commerce, but it was to wave the white flag to say: 'our commerce will be protected…'
>
> "Just like the Navy protects commerce on the seas, we need a Space Force to protect commerce in space."
>
> -NASA Director Jim Bridenstine, 5 May 2020 [1]

2.1 Introduction

NASA Administrator James Frederick "Jim" Bridenstine demonstrated an unusual level of openness about the geopolitical and astropolitical implication of NASA, space resources, and the ongoing space race in an online presentation on NASA's Moon to Mars Plan to the Center for Strategic & International Studies' Aerospace Security Project on 5 May 2020. Throughout the interview, Administrator Bridenstine consistently drew the viewer to understand that there is a consensus on the hill: that NASA's Artemis program is important to advancing the wellbeing of America; that it sends a message to our strategic competitors that America has the technological, political, and economic power to achieve its goals in space. He clearly saw NASA's path to Mars as being inclusive of space resources, commercial partnerships, and the Space Force. He only alluded to our strategic competitors who were defined in the 2017 National Security Strategy as China and Russia and are clearly referenced as such in subsequent documents, including the 2018 National Defense Strategy and 2020 National Defense Authorization Act:

> "The central challenge to U.S. prosperity and security is the reemergence of long-term, strategic competition by what the National Security Strategy classifies as

> revisionist powers. It is increasingly clear that China and Russia want to shape a world consistent with their authoritarian model—gaining veto authority over other nations' economic, diplomatic, and security decisions." -2018 NDS [2, 3]

Extending "veto authority" over another nation's decisions is a direct attack on that nation's sovereignty and legitimacy. Pierre Bourdieu a renown modern social theorist created the most coherent definition of a state, building on classical (Marx, Weber, and Durkenheim) and modern (Elias, Tilly, and Corrigan and Sayer) theorists. He defined the state as:

> "…[A]n X (to be determined) which successfully claims the monopoly of the legitimate use of physical and symbolic violence over a definite territory and over the totality of the corresponding population...
>
> "The state is the culmination of a process of concentration of different species of capital: capital of physical force or instruments of coercion (army, police), economic capital, cultural or (better) informational capital, and symbolic capital [4]."

This chapter explored the intertwined history of space resources and American national power; the space resources value chain; and why the Space Force should be absolutely fascinated by space resources as a means to enhance the government's ability to project force in the celestial sphere.

The United States has become increasingly open to publicly discussing space as a warfighting domain, as an investment opportunity explicitly disavowing the 1979 Moon Agreement, and now, as an insurance policy to ensure Western values, namely capitalism and the rule of law, extend into space [5,6,7,8]. President Trump's administration was highly supportive of the industry and took decisive action to secure America's lead in space [6]. They took steps to secure domestic law for space resources, and advanced international law, through the Artemis Accords, a treaty meant to establish norms of behavior on the Moon in regards to extracting and utilizing space resources [9]. The Artemis Accords now has nearly 20 signatory nations [10].

2.2 Space Resources

Space resources are the natural and man-made resources found in space. They include minerals, metals, ices, and volatiles including water, methane, and nitrogen. NASA and other

members of the international community have found these resources on the Moon, Mars, and the asteroids. Space resources are also intangible consumables such as frequency allocations or orbital slots that provide specific views of the Earth or another celestial body. Once occupied or consumed, it is not available for another's use. Other space resources should not be ignored, including solar energy and the material emitted by the solar wind, abandoned spacecraft, and trash in orbit. A resource is anything that can be used; it acquires value through its utilization [11].

The space resources industry is currently creating and contributing to new markets, including space mining, space manufacturing, and spacecraft servicing (refueling, repairing, and station keeping) and on orbit assembly. The products of these efforts could be for use in space, at the point of extraction (in-situ resource utilization), or for return to Earth. However, the vast expense required to exit Earth's gravity well and return products to Earth's surface limits the return-to-Earth business plan to data and low-mass/high value-added products. The expenses of space flight have further prevented the business plans of space companies from exiting Earth orbit and abandoning the single use satellite design. Though that paradigm has been deteriorating over the past decade. NASA is no longer owning and operating its own transportation: it is now hiring commercial services to deliver astronauts, supplies, and equipment to the international space station (ISS) in low Earth orbit (LEO); to deliver supplies and astronauts to the Gateway space station, and from there to the Moon [1]. The competition for NASA service contracts has resulted in novel ways of overcoming the rocket equation.

The rocket equation describes Newton's laws of motion as applied to a rocket, relating the change of velocity, or delta-V, of a rocket to the mass of expelled propellant.

$$\Delta \mathrm{V} = I_{sp} * g_0 * \ln(\frac{\mathrm{mf}}{mi})$$

Change in Velocity is equal to the specific impulse times gravity (at the Earth's surface) times the natural log of the mass fraction of the rocket (residual mass over initial mass [12]). It is widely accredited to Tsiolkovsky for his 1903 work, though multiple authors have described it independently [13,14]. The mass ratio required to propel a rocket to orbit has prevented humans from expanding our presence beyond low earth orbit, apart from briefly visiting the Moon. At 2020 market rates to get a kilogram (kg) of mass into low Earth Orbit (LEO) costs $3,000, and to

get a kg to the Moon result in staggering costs, on the order of $1 million per kg [15,16]. Space exploration has been hampered by the fact that until it can become profitable, it will be limited to government projects—until recently.

Deep Space Industries and Planetary Resources were among the first wave of serious space resources companies to believe they could overcome the high costs of space. They succeeded in attracting a significant amount of venture capital. However, the wave receded when the venture capitalists revealed the fundamental flaw in the two companies' space resource plans. According to Peter Marquez, Planetary Resources' Washington Policy advisor, on the topic of why they were unable to raise more funding in the summer of 2018:

> "There was more of a focus on the religion of space than the business of space. There's the religious [segment] of space people who believe that almost like manifest destiny, we're supposed to be exploring the solar system—and if we believe hard enough, it'll happen. But the pragmatists were saying there's no customer base for asteroid mining in the next 12 to 15 years [17]."

To have an effective space resources plan, one needs a clear goal, knowledge of a space resource to extract, technology to execute the plan, and a customer. "Of these, the customer is the most important [18]." The lack of focus on securing a customer in Planetary Resources asteroid mining venture hampered the company from establishing a prospect of profitability and scared away potential investors. However, in the words of one of Space Resource's founders, Rick Tumlinson, "We didn't fail, we were too early!" He argued that there was a successful sale of the company, its business and intellectual property [19]. In spite of these examples, the next surge of the space resources industry is emerging, this time with the advantage of customer demand and clearer understanding among the industry of the variety of positions within the space resources value chain.

2.3 The Space Resources Value Chain

A value chain, in general, describes how a resource is turned into a product and delivered to a customer. The Oxford Dictionary defines a value chain as "[t]he processes or activities by which a company adds value to an article, including production, marketing, and the provision of after-sales service [20]." Dr. Dreyer combined the terrestrial mining and manufacturing value

chains to establish a generalized space resources value chain: (1) prospect, (2) explore, (3) establish feasibility, (4) mine, (5) process, (6) manufacturing, (7) distribution, and (8) sales [18].

Multiple space companies are posturing themselves as customers within the space resources value chain right now. Intelsat became the first customer to have Space Logistics, a wholly owned Northrop Grumman subsidiary, augment their station keeping capability for Intelsat IS-901, a 15-year-old geostationary communications satellite. Space Logistics' Mission Extension Vehicle-1 successfully docked with IS-901 on February 25, 2020 and is expected to extend the satellite's mission for five years before providing service to a second customer [21,22]. Meanwhile, ULA and SpaceX see the tyranny of the rocket equation as an opportunity: refuel—or refill, as both the oxidizer, O_2, and fuel, H or CH_4, need to be resupplied—their rockets in orbit [23]. ULA led the Commercial Lunar Propellant Architecture study to determine the cost and feasibility of mining propellant on the Moon, tentatively declaring it both technically and economically feasible. They then announced a price point they would purchase water for in orbit [24]. OneWeb Satellites designed in an emergency handle for potential future servicing satellites to latch onto their LEO mega constellation satellites in anticipation of an emerging LEO servicing economy [25]. Tethers Unlimited Inc. (TUI) is interested in providing LEO satellite servicing and is investing in technologies to that end, including providing refueling capabilities with water as a propellant and providing other repair, servicing, and augmented station keeping services, as well as investing in aspects the in-space manufacturing supply chain, and in supporting space robotics [26,27]. SpaceX's Starlink mega constellation could become a future customer too, depending upon the economy of scale for their satellites and Elon Musk's business plan for the constellation. Amazon indicated interest in getting into the mega constellation business when it filed its intent to purchase Oneweb's assets, spectrum rights, and the future looking designs [28]. in 2021 Amazon contracted with ULA to launch its Kuiper mega constellation satellites with a planned 590 km orbital altitude an end-of-life deorbiting plan would have to avoid other satellites, including SpaceX' Starlink satellites, and the ISS which orbit at lower altitudes [29]. All of the mega constellation owners could utilize space tug services, which could eventually utilize in-space refueling services, which itself has the potential to be sourced from space resources. Collectively, these potential space resources customers are seeking to expand the robustness of the services they provide. Space resources provides these companies an opportunity to increase their systems survivability and to refresh their technology

on orbit. This increases their ability to compete with other providers and simultaneously reduce their costs. These forward-looking space companies are generating demand for services that the space resource industry can provide.

Emerging space resources companies can set up shop in multiple places along the value chain or span multiple sections of the chain. Often, they can borrow technology or concepts from their terrestrial mining and manufacturing sector. TransAstra has designed a plan to find, identify, mine, and deliver water to a customer in cis-Lunar space. TransAstra plans on accomplishing this with their Sutter Survey and Asteroid Provided In-Situ Supply system. The Sutter Survey will identify near-Earth objects (NEOs) that can later approach with minimal delta-V. They have conducted feasibility studies with the Colorado School of Mines (CSM) Department of Space Resources to develop optical mining techniques that ablate the surface of the asteroid, fracturing the rock and releasing volatiles [30,31]. Mining prototypes, including drills and excavators, for use on the Moon, Mars, and/or the asteroids have been variously developed by Astrobotic, Honeybee Robotics, Kleos Space, OffWorld, NASA, and others. Terrestrial mining companies such as Caterpillar have started showing their interest in space resources. Caterpillar partnered with Astrobotic to work on adapting some of their technology in remotely operating mining equipment and robotics for use in space [32,33].

On the other end of the value chain, several companies, including Made In Space, TUI, Ultratech, and Cornerstone Research Group, are already working with NASA to design and test in space manufacturing and assembly technologies and techniques. Made In Space spans the spectrum of manufacturing in space for use in space, but have also identified products for sale on Earth, including their ZBLAN high speed optical fiber. The NASA ISM team is investigating activities such as constructing plastics, metals, electronics, health and medical products, recycling materials, conducting robotic manufacturing, assembling space structures, and additive manufacturing of buildings [34].

Niki Werkheiser and Dr. Gordon Roesler have argued that the advantage of in space manufacturing (ISM), robotic servicing, assembly, and construction—collectively referred to as On-Orbital Servicing, Assembly, and Manufacturing (OSAM)—will create a fundamental paradigm shift in conducting space activities. Niki Werkheiser, the former program manager of the In-Space Manufacturing Team at NASA Marshall Space Flight Center authored or

coauthored numerous papers on her team's work and their vision. A major goal for her and NASA is to reduce the logistical requirements of space travel in terms of mass launched from Earth. She believes ISM provides methods to reduce the amount of bench stock mass required for routine maintenance activities. Mass reduction techniques include the recycling of materials from discarded items, and through the planned commonality of feedstock materials (i.e., minimizing the number of materials and number of fabrication processes). This reduction of total up-mass from Earth will ultimately lead to successful missions to Mars [35]. Dr. Roesler, the former program manager of DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) argued in his August 2018 article "The Robotic Space Station" that a permanent on orbit unmanned robotic space station is necessary for the testing of advanced robotic manufacturing and assembly techniques in space to reduce cost due to commonality and modularity among other benefits. Dr. Roesler promotes this idea as an alternative to hosted payloads on the International Space Station (ISS). The Robotic Space Station, he points out would not need to stipulate human life compatibility requirements onto a hosted payload [36].

At a recent interagency Science and Technology (S&T) Partnership Forum, held November 2018, the concept of a robotic space station for OSAM was discussed seriously among NASA, the US Air Force Space Command, the Naval Research Lab, and the National Reconnaissance Organization. In its current incarnation, the interagency forum now includes the US Space Force, according to NASA's interagency forum website, which remained active as late as April 2020, and hosted a NASA Langley concept video of the robotic space station featuring OSAM capabilities as the future of space [37,38].

The emerging capabilities available to the government are historical achievements. However, removed from the geopolitical context these achievements lose their true significance. These are not just technological achievements but are part of the US's historical strategy to expand the country's national power into space.

2.4 Space Resources History

Asteroid mining and Lunar mining have been a part of science fiction for well over 150 years and scientific supposition for 100. Edward Everett Hales is credited as the first documented writer to discuss a space colony in his book Brick Moon in 1869; he was followed by Jules Verne in 1878 and Kurd Lasswitz in 1897. Konstantin Tsikovski wrote more technically on the

ideas of space colonization and contemplated what ores existed on the Moon in his own science fiction stories in the 1890s [39]. Garrett P. Servis may have been the first to write about mining asteroids in his independent science fiction sequel to H.G. Well's The War of the Worlds, titled Edison's Conquest of Mars in 1898 [40]. Later, in 1920, Robert Goddard calculated the amount of propellant needed to send a pound of mass an infinite distance from the Earth, and to the Moon in his technical paper "A Method of Reaching Extreme Attitudes." NASA credited Goddard with suggesting the use of extraterrestrial resources to manufacture structures and propellants shortly after WWI [39].

Robert Goddard was ridiculed for his ideas at the time, but rockets, space, and eventually space resources become more militarily and geopolitically (and now astropolitically) relevant over the course of the following 100 years. At the end of WWII, The Pentagon's Joint Intelligence Operations Agency launched Operation Paperclip to capture and employ German scientists, inclusive of the rocket scientists who designed the V-1 and V-2 rockets at Peenemünde. The desire to prevent them from falling into the Soviet's hands was so great that the Secretary of War approved the operation despite considering them enemies and believing that hiring and forgiving the men for their war crimes would be counter to democratic ideals [41].

Wernher Von Braun – one of those captured Nazi-scientist-cum-US-national-hero – wound up working for the US Army [42]. While working at the White Sands Missile Range, he proposed an orbiting space station, from which to launch nuclear first strikes against the USSR, as early as 1945 possibly coining the term "space superiority." He may have been ignored, but over a decade later—and eight months before Sputnik was launched—Maj Gen Schriever said: "In the long haul our safety as a nation may depend upon our achieving 'space superiority [43].'"

The October 1957 launch of Sputnik motivated the U.S. to seriously consider the military potential of space. The U.S. Army proposed establishing a lunar base in their proposal Project Horizon in 1959 with approval from Von Braun and in competition with various proposals from the U.S. Air Force, the newly established ARPA, and the private sector [44]. A key concept of the proposal called for the construction of a lunar orbiter with a refuellable in space segment, and the use of space resources.

> "Every conceivable solution for minimizing the logistic effort must be explored. Maximum use of any oxygen or power source on the moon through regenerative or

> other techniques must be exploited. Means of returning safely to Earth must be available to the occupants of the outpost [44]."

The U.S. Military seriously considered using in-situ resources, on orbital servicing, manned space stations, and lunar bases at the beginning of the space age. The motivation was purely geopolitical.

The Project Horizon proposal explicitly called out the threat the USSR posed by being the first to establish a Moon base. They indicated the Soviets would declare sovereignty over the Moon and deny, militarily or politically, the free world access to the Moon, its resources, and military potential. If the Soviets got to the Moon first, then they could threaten the U.S.'s claim on their monopolies on the use of physical and symbolic violence, delegitimizing the U.S. Government, the Western way of life, and the liberal western order. Project Horizon's authors discussed these political and security implications along with the state of space law at the time of the writing. Their discussion on space law preceded the 1967 Outer Space Treaty (OST) and the US' 1969 Moon landing by nearly a decade. They touched on several topics that would later be codified in the OST and subsequent treaties, characterizing the state of space law as:

> "The plethora of writing on the subject [of space law] and the variety of opinions expressed reveal that, as of this present, what is regarded as international law, and its presuppositions and prerequisites in the field of outer space activity, are nothing more than the wishes or pious thoughts or aspirations or fears of the writers. They cannot bind, control or even limit states and nations in the new dimension [44]."

The authors considered preexisting international law the U.S. could use, including discussions by eminent Soviet legal scholars on the use of anti-missile missiles on either country's sputniks; America's position on Antarctica sovereignty claims by the King of Norway; as well as the return of astronauts and space objects. One question they posed dealt with the right to claim resources on the Moon: how does a country preserve a claim on resources? They concluded that it requires continuous occupancy. On legal defense against trespassers, they wrote:

> "Obviously… It must be recognized that there will probably be no tribunal to which the conduct of the alleged intruder could be submitted for judicial resolution… the case would be one for diplomatic or political negotiation; more likely, and for the

> worst, it would be for resolution by the more violent form of political action known as war [44]."

They also discussed the possibility that the Soviets would declare the need to destroy US resupply vehicles due to them posing a safety concern to their outpost [44].

The use of Space resources were planned and considered as a part of the Apollo Application Program and Apollo Extension Series following the manned lunar landings, however, because of early decisions by the Kennedy Administration decisions, budgetary requirements due to the Cold war, and a loss of public support for the space program's costs the Nixon administration cancelled the remaining Apollo missions [45]. President Kennedy infamously said to the NASA director James Webb that he was "not that interested in space." JFK saw space solely as an opportunity to compete with the USSR to "demonstrate that democratic capitalism was superior to Soviet-style communism as a form of societal organization." JFK wanted to prioritize, within the NASA budget, everything that directly contributed to the Moon Landing over everything that did not [46].

Since then, NASA has conducted additional research in space resources, but without the geopolitical threat focusing the national budget on it, space resources have been relatively short funded. Even with meager funding, NASA was able to produce fantastic theoretical work, such as NASA's Space Settlements: A Design Study (NASA SP-413), Space Resources and Space Settlements (NASA SP-428) and Space Resources (NASA SP-509), which NASA published in 1975, 1979 and 1992 respectively. Over the past two decades, more resources have been provided toward remote sensing and to establish prototypes and hardware to begin mining resources. It is only within the last decade, formally with the pivot to the Pacific, that the U.S. woke up to the threat that the Chinese Communist Party (CCP) posed as a revisionary and rising power (or potentially, as a peaked and declining power [47]). Today, the CCP is America's pacing threat, and Taiwan is the Pacing Scenario [48,49].

As early as 2001, in spite of the recent trade normalization with China, there was an awareness that China perceived itself as a competitor with the US, that China was an eventual near-peer competitor to the US, and that China was developing its own counterspace capabilities, including space and ground based kinetic and directed energy weapons [50,51]. Since then, the CCP has cyclically released white papers on its activities in space in coordination with its five

year plans. In its most recent paper, released January of 2021, the CCP has announced its interests in space resources, highlighting its recent successes in its Lunar and Martian exploration missions, and its intent to continue investing in "…the leapfrog development of space science and technology, which spearheads overall technical advances [52]."

2.5 Using Space Resources to Enhance National Power

The message from NASA Administrator Jim Bridenstine on 5 May 2020 demonstrated that the past administration adopted a position similar to that of Kennedy with two key differences: the U.S. is now competing with the CCP in Space, and the U.S. will use space resources to win. The existence of the Artemis Accord, a treaty on space resources and establishing norms of behavior in space, was leaked to the public only three hours after Administrator Bridenstine finished his presentation. Its purported "Safety Zones" draw eerie parallels to Project Horizon's concerns about the USSR attacking U.S. supply vessels, and the fears the Trump administration may have had about the CCP. It also raised new concerns about de facto declarations of sovereignty [9]. The only ride to the Moon available at the time of Bridenstine's talk are the U.S.'s Space Launch System, potentially Space X's Starship, the CCP's Long March 5, and more recently the CCP's planned Long March 9, reportedly being modeled after SpaceX's Starship [53,54]. The CCP has declared its intent to establish a Moon base by 2030, and they are well on their way. The Long March 5B, a single stage variant, just had its first successful launch with their man-rated crew capsule designed to go to the Moon, it is conjectured that the CCP will not announce a manned lunar mission until 2026 [55,56]. The Apollo Accord is drawing a line in the sand: go to the Moon with the U.S. or be considered a bad actor in space. Bad actors will be denied partnership access to the space domain and the beneficial aspect towards a state's prestige and national power.

Administrator Bridenstine made this position clear by referencing his military experience and quoting Joint Publication 1 which shares the DIME mental model of exercising national power (diplomatic, informational, military, and economic power) used by interagency planners to exercise the governments monopoly on physical and symbolic violence [57]. He pointed out that NASA shares a significant role in promoting U.S. national power in space through diplomatic, informational, and economic power, and then pointed out that NASA is partnering with the Space Force for space situational awareness. Bridenstine mentioned that NASA is a

diplomatic partner to over 700 agreements with foreign countries. He pointed out that the Moon Landing was seen by one out of one person on Earth, and that when Curiosity landed on Mars Tehran's National Guard glowingly wrote about it and America's international partnerships. Bridenstine clearly laid out his vision for the Artemis Program being an economic success by commercializing as much of the process as possible, specifically laying out the role of Space Resources:

> "We're going to the Moon. We're going sustainably. We're going with international partners and we're going with commercial partners. We're gonna go and learn how to live and work on another world using the resources of that other world—namely the hundreds of millions of tons of water-ice on the south pole of the moon. We're going to take that knowledge and go all the way to Mars [1]."

The Space Force can also take that knowledge and apply it to expanding its ability to work in Cis-Lunar Space and apply it to all the missions the nation may require it to do in the future.

Administrator Bridenstine thinks that the Space Force should protect space commerce like the Navy protects trade at sea. His idea is supported by Joint Publication 3-0, Joint Operations, which introduces National Power in conjunction with the range of military operations (ROMO) applied across a conflict continuum—from peace to war. By defining ROMO the joint chief of staff has established a requirement for the joint force, including the new Space Force, to be able to perform missions such as ensuring freedom of navigation and overflight, sanction enforcement, enforcement of exclusive economic zones, protecting shipping and deterring piracy, and humanitarian relief operations [58]. OSAM will enable the Space Force to rearm, refuel, and repair its satellites, manned spaceships, and unmanned weapon platforms with materials sourced from the Moon and Asteroids. Multiple opportunities exist to expand the Space Force's capabilities, these are "combat multipliers" in colloquial military terms: space resources will allow the Space Force to go farther, stay longer, and do more for less.

2.6 Conclusion

Space resources contribute to all elements of national power. NASA's use of space resources will enable the U.S. to sustainably land on the Moon and establish a permanent presence. Space resources will enable NASA to send humans to Mars and enable the commercial sector to establish an economy in cis-lunar space. The space resources economy will enable the

Space Force to operate effectively. Collectively these will give America a huge diplomatic, informational, economical, and military advantage over its strategic competitors: it will deny the CCP or the Russians the opportunity to beat the U.S.

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CHAPTER 3.

ORBITAL SUSTAINMENT AND SPACE MOBILITY LOGISTICS USING SPACE RESOURCES

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Alexander Jehle,[1] Dr. George Sowers[2]

3.1 Abstract

Water is the oil of space. It can be used as a steam or plasma propellant for spacecraft and space tugs and be split into hydrogen and oxygen as a chemical rocket propellant. Water is ubiquitous in the inner solar system and exists as ice on the Moon. Recent research indicates lunar water can be economically mined, processed, and exported into cislunar space. Refueling space vehicles using space-sourced propellant breaks the tyranny of the rocket equation, lowering the cost of missions beyond low Earth orbit. The cislunar propellant distribution architecture we describe is anchored by a logistics node at the first Earth-Moon Lagrange point. This node receives and stores propellant sourced from space and distributes it using tanker vehicles. Three use cases are described. The first is refueling launch vehicle upper stages carrying payloads en route to locations beyond low Earth orbit. The second is supporting space exploration activities on the Moon and missions to Mars. The third is refueling and servicing spacecraft in geostationary orbit. The fuel storage node occupies strategic real estate, providing space domain awareness and access to any point on the Moon, Earth orbit, and beyond.

> "…A peaceful, gain-loving nation is not far-sighted, and far-sightedness is needed for adequate military preparation, especially in these days."
>
> -Admiral Alfred Thayer Mahan [1]

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* See Appendix C for permissions and citation

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3.2 Introduction

One of the great planetary science discoveries of recent decades is that water is ubiquitous in the inner solar system. Water exists at the poles of Mercury and is chemically bound in hydrated minerals within C-type asteroids and near-Earth objects (NEOs [2,3,4,5]). Water is abundant on Mars, but most importantly, water exists in permanently shadowed regions (PSRs) near the poles of the Moon [5,6,7,8,9,10]. The existence of water on Earth's nearest celestial neighbor is of paramount importance for space exploration, space commerce, and defense. Water is the foundation of a space logistics chain enabling long term space sustainment and unprecedented space mobility. The core competencies of the United States Space Force (USSF) could all benefit from expanded space mobility [11].

Logistics capabilities are operational capability multipliers in that they are the systems that deliver sustainment. Effective sustainment is critical to enabling operations to go farther, do more, and stay longer. Sustainment exists in all phases of an operation—from preparation through operations to returning to a state of readiness for the next mission. Joint Publication 4-0, Logistics defines sustainment for the Joint force, now including the USSF, as:

> "Sustainment—one of the seven joint functions—is the provision of logistics and personnel services to maintain operations until mission accomplishment and redeployment of the force. Effective sustainment provides the joint force commander (JFC) the means to enable freedom of action and endurance and to extend operational reach. The relative combat power that military forces can generate against a threat is constrained by their capability to plan for, gain access to, and deliver forces and materiel to points of application [12]."

The USSF's capstone document defines Space Mobility and Logistics (SML)—a core competency of the USSF—as movement in, from, and to space [11]. They further define in-space logistics as orbital sustainment:

> "Orbital sustainment and recovery is another important application of SML. Already demonstrated in the commercial sector, orbital sustainment will allow military space forces to replenish consumables and expendables on spacecraft that cannot be recovered back to Earth. Orbital sustainment will also enable spacecraft

inspection, anomaly resolution, hardware maintenance, and technology upgrades [11]."

The USSF clearly envisions that orbital sustainment will expand to replenishing consumables and expendables, conducting spacecraft inspection, and technology upgrades. Looking farther into the future, building a logistics architecture in cislunar space to distribute water and propellant from the Moon and elsewhere will greatly enhance sustainability and mobility of assets in geostationary orbit (GEO) and across the space domain.

As the USSF's logistics doctrine evolves, it must be integrated with its entire operational concept. A valuable source of thought in this arena is found in the U.S. Army's principles of sustainment, depicted in Figure 3-1, and underlying logistics culture, partially defined in the Army Doctrine Publication 4-0 [13]. This paper suggests that a particular technology—lunar-sourced, on-orbit-stored propellant—could be a key enabler of the USSF's cornerstone responsibilities.

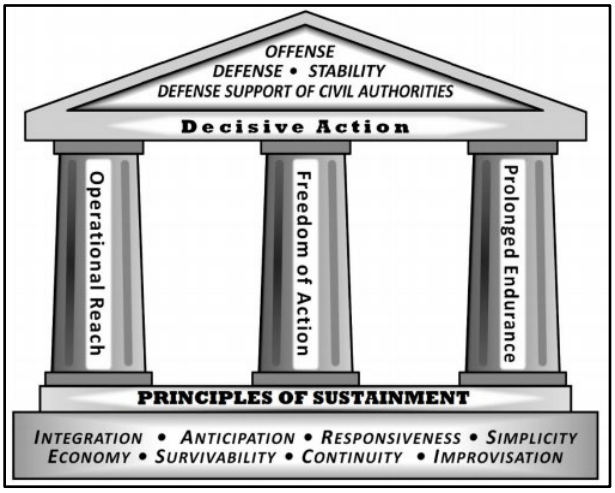


Figure 3-1. The US Army's Principles of Sustainment, from ADP 4-0.

3.3 The Water Resources on the Moon

Water has many uses in the context of space exploration and development. It is essential for human life and agriculture. Oxygen, one of its constituents, is a necessary component of breathing air. It is one of the most effective substances for radiation shielding on a per mass basis [14,15,16,17]. But perhaps its most valuable use is to support space mobility as rocket propellant. It can be used directly in the form of steam or plasma for low to medium thrust

applications. When split into hydrogen and oxygen and liquefied, it produces LO_2 (often called "LOX") and LH_2, the most efficient chemical propellant combination known. *Water is truly the oil of space.* And like oil on Earth, water will be the foundation of the space economy, underpinning all activities including those of the USSF.

There is overwhelming evidence that water exists near the poles of the Moon, trapped in PSRs. Most of this evidence comes from remote sensing observations although ejecta from the impact of a Centaur upper stage was observed by the LCROSS spacecraft indicating 5.6±1.9wt% water ice [6,7,8,10,18]. Figure 3-2 shows the extensive availability of lunar surface ice [10].

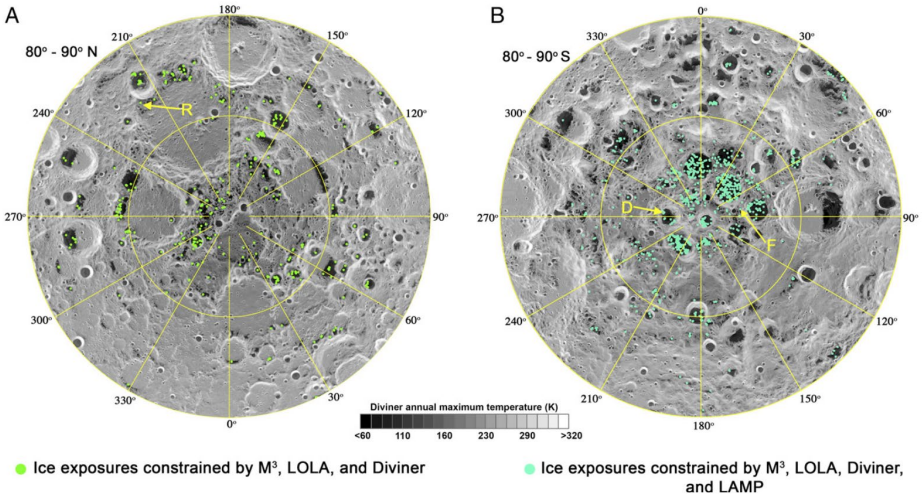


Figure 3-3. Ice exposures on the North pole (A) and South Pole (B) of the Moon. Used with permission from Li et. al., 2018.

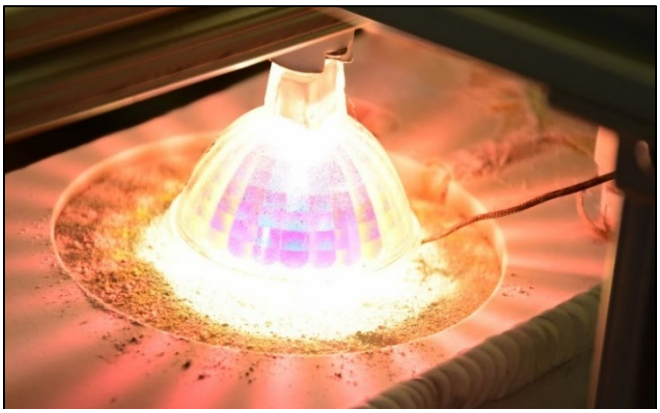


Figure 3-2. Heat applied to an icy regolith simulant sample under cryogenic vacuum conditions.

To be useful as an economic resource, the water on the Moon must be extracted and processed into propellant. One promising technique under development at the Colorado School of Mines (CSM) is called Thermal Mining. Thermal Mining applies heat in-situ to the water bearing lunar material. This avoids the cost, mass, and complexity of the more traditional excavation methods. A recent study indicates a 65% mass savings for in-situ Thermal Mining compared to excavation. The effectiveness of direct heat in sublimating ice from within icy regolith samples has been demonstrated in the laboratory at CSM [19]. Figure 3-3 shows heat in the form of simulated sunlight being applied to an icy regolith simulant sample under cryogenic vacuum conditions—the same conditions at the lunar poles [20].

In addition to proving the physical concepts underlying Thermal Mining, CSM has also developed an architecture for exploiting this technique in the lunar PSRs. CSM has developed a functional and physical architecture for a LO_2/LH_2 propellant production system anchored by a Thermal Mining based ice extraction system. Figure 3-4 is CSM's ice extraction concept described in the NASA Innovative Advanced Concepts (NIAC) phase I report [20].

Based on this architecture, a business model suggests that it can be profitable for a commercial mining and propellant production company to sell into a cislunar propellant logistics stream [21].

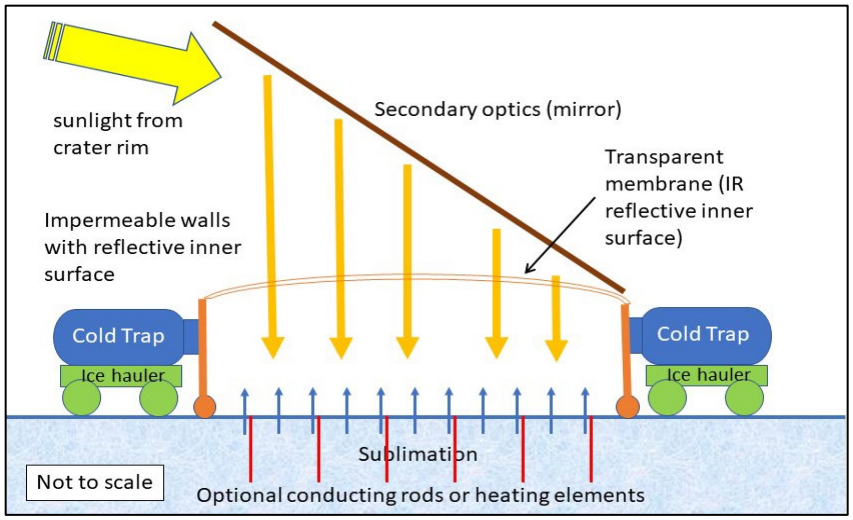


Figure 3-4. Ice extraction concept, from Sowers et al., 2020.

3.4 Benefits of Refueling and Propellant Sources in Space

The cost of most space activities is dominated by transportation cost. The energy to escape Earth's gravity well is enormous and the distances between interesting or valuable destinations in space is vast. For the sixty years since the first human mission into space, all space missions have originated on Earth with all propellants brought from there. This situation gives rise to what is known as the tyranny of the rocket equation. The rocket equation is simply written: $\Delta V = v_e \ln (m_i/m_f)$, where ΔV is the velocity added to the rocket, v_e is the exit velocity of the rocket engine, m_i is the initial mass of the rocket including propellant, and m_f is the final mass after all propellant has been expended. The difference between the initial mass and the final mass is essentially the mass of the propellant [22].

If one solves the rocket equation for propellant mass in terms of ΔV, the equation is exponential. In other words, the "farther" one wants to go in space (generally requiring more ΔV), the required propellant increases at an ever-increasing rate. This is the reason rockets leaving Earth consist mostly of fuel, and that a rocket going to the Moon and back must be the size of the Saturn V used in Apollo or the Space Launch System currently in development by NASA.

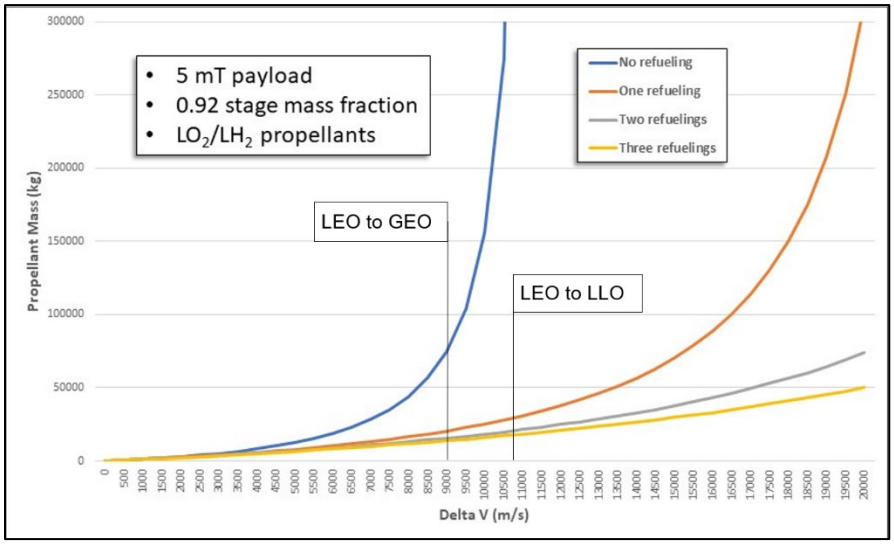


Figure 3-5. Benefits of refueling with space sourced LO2/LH2 propellant. A round trip from LEO to GEO costs nearly 9000m/s, while a round trip from LEO to low lunar orbit costs nearly 12,000 m/s: this results in a propellant mass savings of 75% for a round trip from LEO to GEO, and significantly more for LEO to LLO. Modified from Sowers, 2021.

However, if a spacecraft can be refueled en route, reusing the propulsion system through multiple refuelings, *the tyranny of the rocket equation is broken*. The exponential increase of propellant with ΔV becomes linear. Figure 3-5 shows the enormous benefit of one, two, or three refuelings in reducing required propellant for a given ΔV, while maintaining a stage mass fraction of 0.92 (The Saturn V's stage mass fraction was roughly 0.94, and the Space Launch System Block 1 has a stage mass fraction of .91 [23]). Furthermore, reduced requirements for propellant to do a given mission entails a reduction in the size of the rocket or the number of rockets required. Either of these situations results in a significant reduction in the cost of the mission. Table 3-1 shows the results of calculations based on the model of Sowers, 2021. The estimated costs saving benefits are based on propellant prices in figure 7 [21].

Table 3-1. Benefits of lunar-sourced propellants, from Sowers, 2021.

Space Activity	**Lunar-Sourced Propellant Benefit**
Transportation from Earth to Geostationary orbit.	10-20% lower cost.
Transportation from Earth to the lunar gateway.	2 times lower cost.
Transportation from Earth to lunar surface.	3 times lower cost.
Transportation from the lunar surface to the lunar gateway and back.	70 times lower cost.
Cost of a human mission to Mars.	2-3 times reduction.
In-space transportation.	Essentially the cost of lunar-sourced propellant.

3.5 Cislunar Propellant Economics

Given that the Moon is a viable source of water and thus LO_2/LH_2 propellant, it is uniquely situated to enable space activities in cislunar space and beyond. The Moon is the closest

source of resources to the Earth. Escaping the Moon's gravity well is far easier than Earth's. As shown in Figure 3-6, the ΔV from the surface of the Moon to the first Earth-Moon Lagrangian point (EML1) is a factor of five less than from Earth—inclusive of Earth to orbit (ETO) plus LEO to EML1—and launch from the Moon does not require flying through an atmosphere [21].

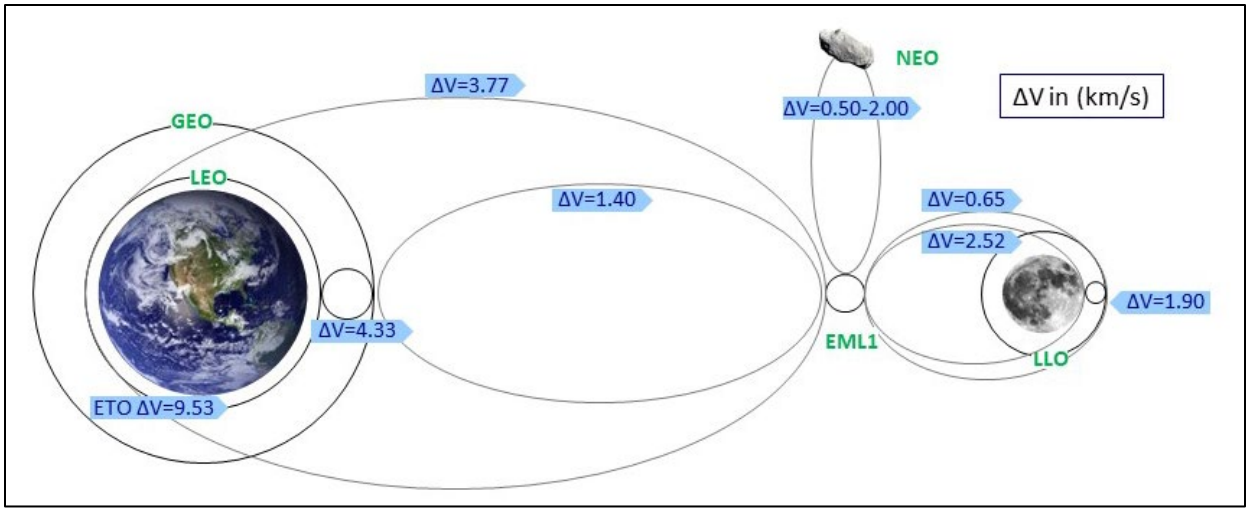


Figure 3-6. ΔV map of cislunar space.

Of course, a source of fuel is not valuable unless there is a refuellable space transportation architecture able to take advantage of it. Fortunately, there are several commercial companies working on refuellable upper stages and landers including SpaceX, Dynetics, Blue Origin, and ULA. As Chief Scientist of ULA, co-author Sowers made a public offer to buy propellant in space to support ULA's future upper stage, currently being designed to be refuellable. He presented prices ULA would be willing to pay at locations within cislunar space. These prices, depicted in Figure 3-7, reflect both the physics and the corresponding economics of propellant in cislunar space [21,24]. The blue bars represent the cost of propellant (or any mass) launched from Earth. The green bars were set by the criterion that the price of lunar propellant in low Earth orbit (LEO) be less than the price of propellant launched from Earth at the same location. The LEO price chosen was $3000/kg, lower than the $4000/kg to launch from Earth. If this condition is met, then ULA would be able to lower the cost to launch a payload from Earth to GEO, a critical piece of ULA's current market [25].

The price of propellant on the lunar surface required to ensure meeting $3000/kg in LEO is estimated to be $500/kg. This depends on several assumptions regarding transporting the propellant from the Moon to LEO. First, the transportation uses a vehicle that can store cryogenic propellants for long periods, such as ULA's Advanced Cryogenic Evolved Stage (ACES) upper stage and Experimental Enhanced Upper Stage (XEUS) lunar lander. Second, all maneuvers are propulsive. This assumption is very conservative, given that aerobraking using Earth's atmosphere to decelerate to LEO could reduce the cost by a factor of two. The other key location for pricing is EML1. This location is a good proxy for any location in high Earth or Lunar orbit, such as the orbit of NASA's proposed Lunar Gateway station. For EML1 propellant sourced from the Earth, the price is $10,000/kg. Sourced from the Moon, the price estimate is $1000/kg, a factor of ten reduction.

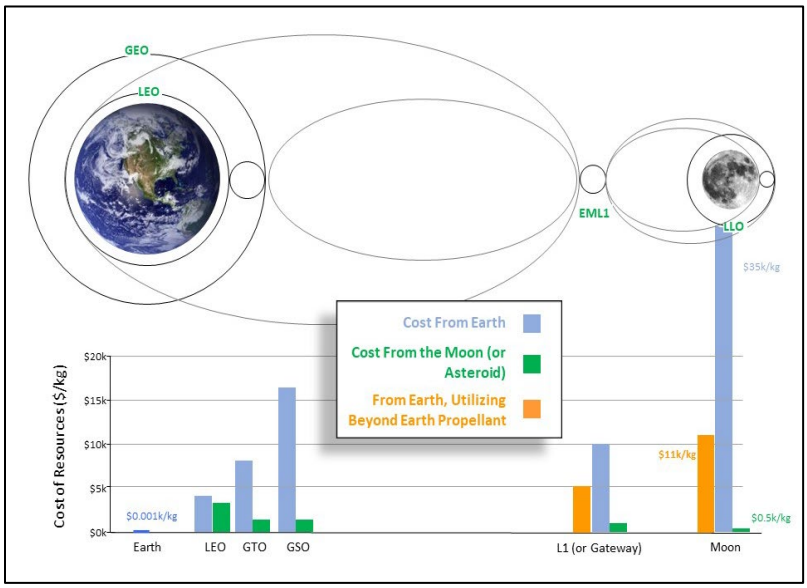


Figure 3-7. Propellant prices in cislunar space.

Finally, the orange bars in Figure 3-7 represent the price to move mass from Earth to EML1 or the lunar surface, *with a single refueling using propellant from the Moon.* The use of lunar propellant will reduce the cost to move mass from Earth to the lunar Gateway by a factor of two and reduce the cost to move mass from Earth to the lunar surface by a factor of three. These two facts make a compelling argument to move forward with lunar propellant production as a top priority. Every space mission beyond LEO could benefit from the use of refueling with lunar propellant.

3.6 Cislunar Propellant Logistics Architecture

Beyond supporting civil and commercial activities in cislunar space, a logistics architecture based on lunar water and propellant would enable long term sustainment of our critical space infrastructure in Earth orbit. It would provide key logistics support to enable unprecedented space mobility through the supply of propellant, both as water and as LO_2/LH_2. We envision a logistics architecture that consists of three basic elements, shown in Figure 3-8.

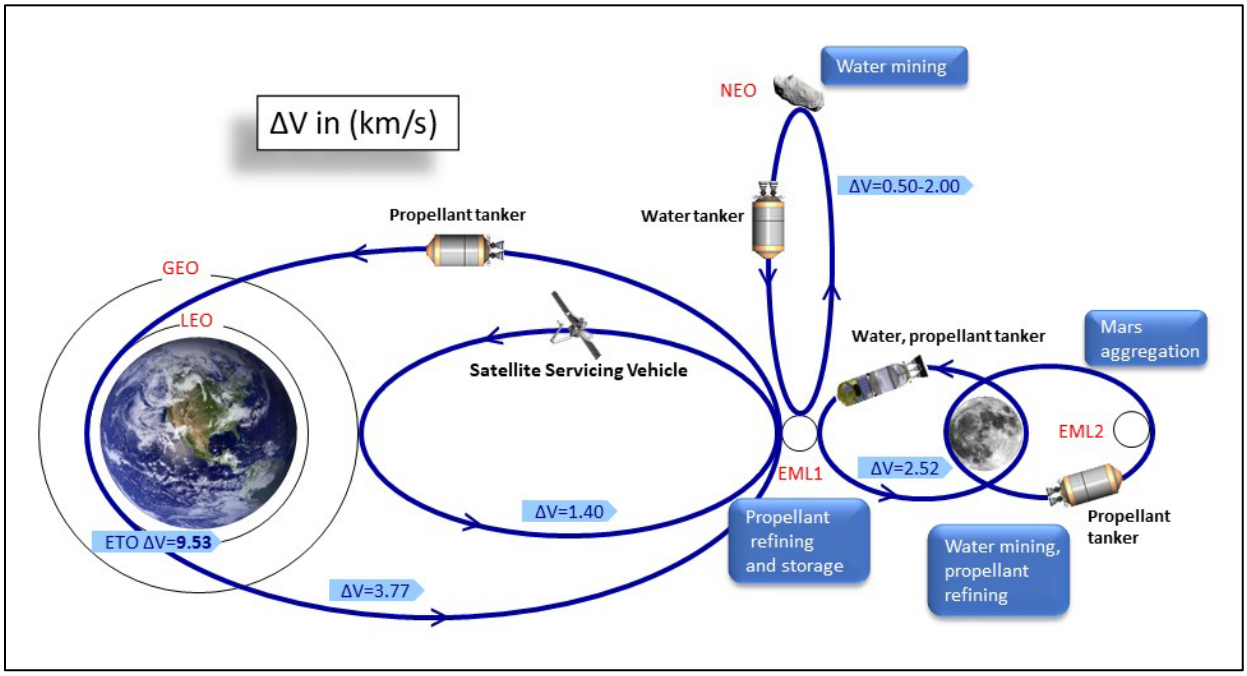


Figure 3-8. Water and LO2/LH2 propellant logistics architecture in cislunar space.

The first part of the architecture is the sources of supply. We discussed the lunar supply above. Other sources of supply include NEOs and the Earth itself. Once a robust water/propellant economy is established in space, water and LO_2/LH_2 propellant will become commodities and prices will be set by the market. Water and propellant prices will decrease due to competition between Earth, Moon, and asteroid sources of supply. The second component is the transportation system that moves propellant from the supply source to the point of demand. This will include tankers to carry either water or LO_2/LH_2 propellant, vehicles that can land and take off from the Moon, tankers to refuel launch vehicle upper stages and servicing vehicles that can refuel (and potentially repair) satellites in GEO. The third part is logistics hubs (or depots) that will include water and propellant storage and transfer, water to propellant processing, and transportation element servicing capability.

Consider an initial architecture with a single logistics hub located in the vicinity of EML1. This is a critical location in cislunar space for a number of reasons. First, EML1 is easily accessible from any point on the lunar surface with about the same ΔV. Second, EML1 is always in line of sight to the Earth, facilitating continuous communications. Third, tankers dispatched from EML1 are able to access almost every Earth orbit, enabling optimum refueling of launch vehicle upper stages en route to destinations beyond LEO. Finally, the ΔV from EML1 to GEO is modest, enabling efficient servicing of that critical domain. Since EML1 is an unstable equilibrium point, the logistics hub would consume a small amount of the propellant stored there to remain on station.

There are a number of practical delivery routes for both water and propellant. Water and propellant can both be delivered from the lunar surface to the logistics hub in EML1. Eventually, water may also come from NEO mining operations to EML1. From EML1, tankers can be dispatched into Earth orbit to meet and refuel upper stages delivering payloads to beyond LEO destinations. Satellite servicing vehicles will transit from EML1 to GEO carrying water to refuel GEO belt satellites.

3.7 The EML1 Propellant Depot

A conceptual design for an EML1 logistics hub is shown in Figure 3-9. It has a number of critical functions It stores both water and LO_2/LH_2 propellant. Once NEO mining begins, it will process water into propellant. It transfers both water and propellant from delivery tankers to storage and from storage to delivery tankers. It must maintain its attitude to keep the sunshade pointing toward the sun. It must harvest solar energy to power its operations and store enough energy to cope with periodic solar eclipses. Energy storage could be in the form of batteries and/or fuel cells. With a ready supply of water, hydrogen, and oxygen as well as electrolysis capability, generating energy through fuel cells is an attractive option.

The propellant storage tanks are placed into a transverse spin to facilitate transfer operations and to reduce boil-off of the cryogenic propellants. Preliminary estimates indicate cryogenic boiloff rates can be reduced to 10% per year through purely passive measures [26]. These include the sunshield, multi-layer insulation, and vapor cooling using hydrogen boil-off.

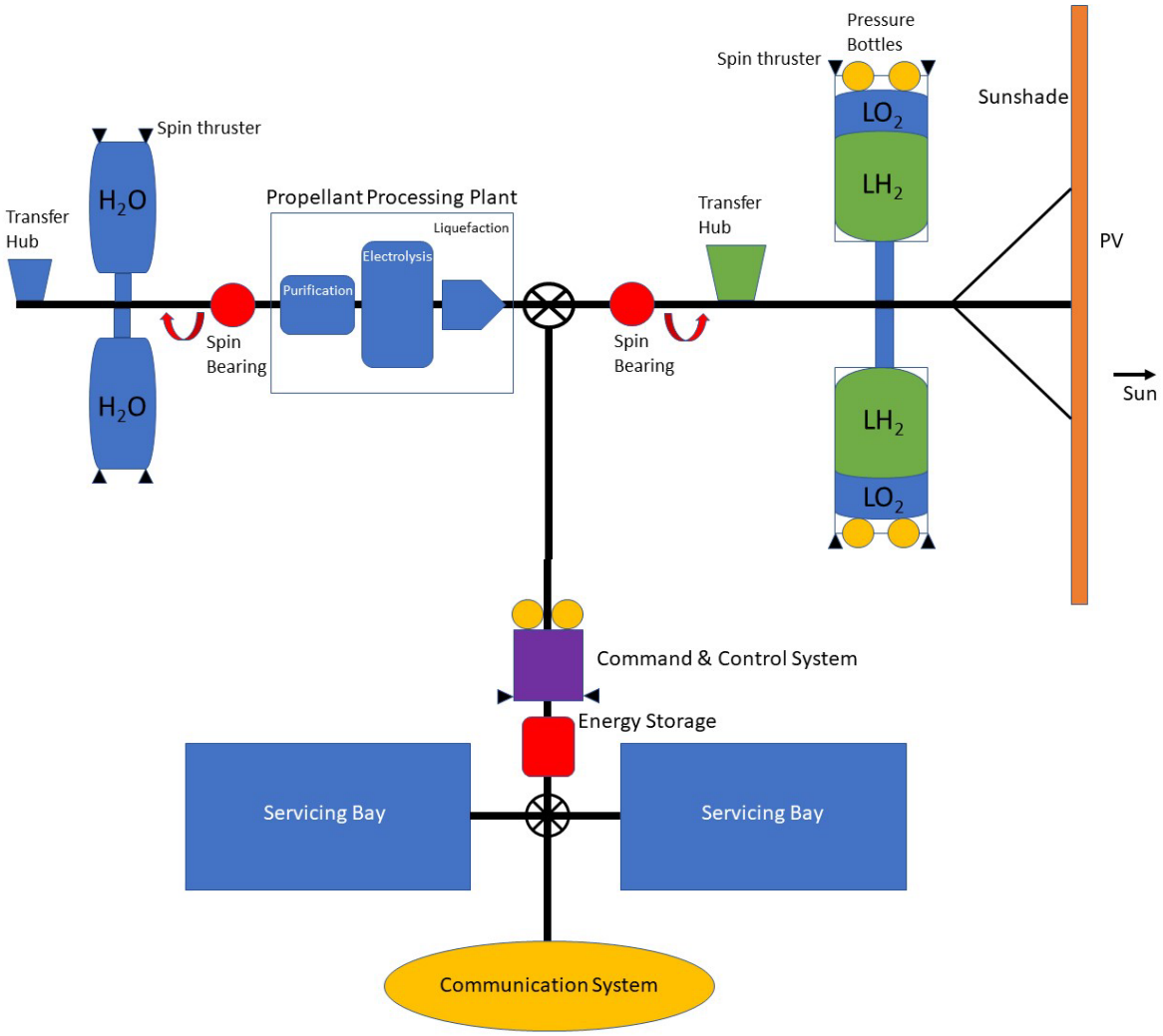


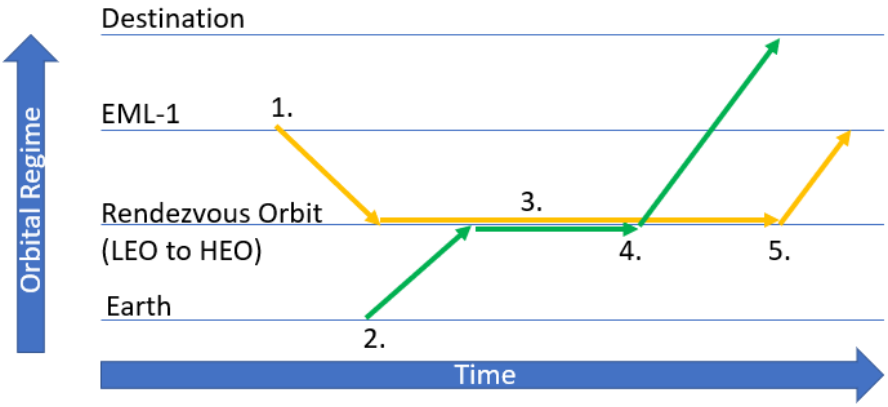
Figure 3-9. Preliminary system concept for an EML1 logistics hub. Work by authors.

3.8 Cislunar Propellant Use Cases

We consider three primary use cases that can be supported by the logistics network: refueling upper stages en route from Earth to destinations beyond LEO; supporting space exploration missions around the Moon, to Mars, and beyond; and providing orbit sustainment support to the GEO belt. As logistics operations become mature, costs will decrease opening up other activities such as permanent human presence on the Moon, asteroid mining, and in-space

manufacturing. These activities and more will be enabled by the wide availability of propellants sourced in space.

The concept of operations for the first use case, upper stage refueling, is straight forward. A tanker vehicle loaded with LO_2/LH_2 propellant is dispatched from the logistics hub to a predetermined rendezvous orbit around the Earth. This orbit is optimized based on the launch vehicle design and final destination of the payload. The rendezvous orbit will typically be an elliptical orbit similar to a geostationary transfer orbit. The tanker arrives in the rendezvous orbit before the payload is launched from Earth. Upon completion of the booster phase of flight, the upper stage and payload will reach the same orbit and rendezvous with the tanker. Propellant is transferred from the tanker to the upper stage and the upper stage proceeds to deliver the payload to its final destination. The tanker then returns to the EML1 logistics hub. This process is depicted in Figure 3-10. As calculations listed in Table 3-1 indicate, refueling can reduce the cost of these missions anywhere from 10% to 70% depending on the final destination.



1. Tanker depart EML-1 to predetermined rendezvous orbit.
2. Launch.
3. Cooperative RPOD and refueling.
4. Undocking and departure of upper stage to destination.
5. Tanker returns to EML-1 for refueling, preparation, and staging for next mission.

Figure 3-10. Preliminary system concept of operation for upper stage refueling.

The exploration use case has a number of scenarios. Missions leaving the surface of the Moon can be refueled directly on the lunar surface, saving a factor of 70 compared to bringing fuel from Earth. A single Mars mission can save $12B through the use of lunar propellant

compared to launching everything from Earth [20,21]. For a Mars mission, propellant will be shipped directly to the mission aggregation point (EML2 is a possibility). Mars mission hardware will be refueled en route to the aggregation point.

The third use case is the sustainment of satellites in GEO. This will consist primarily of refueling, but satellite maintenance and repair will also be enabled as these capabilities are developed. A critical prerequisite for enabling sustainment via the space logistics architecture is to transition satellites to a water-based propulsion architecture. This technology is well along in development by a number of companies including Bradford Industries (which acquired Deep Space Industries), Tethers Unlimited, and the Aerospace Corporation. In this case, a satellite servicing vehicle given a full load of water at the EML1 logistics hub transits to GEO. Since water is storable, the satellite servicing vehicle can linger in GEO or near GEO providing refueling services when needed. Once its supply is depleted, it returns to the logistics hub for another load.

Historically, satellites in GEO have been inserted by a launch provider into a geostationary transfer orbit. They then used their own apogee kick motor to raise their perigee from an altitude of 300 kilometers to GEO's 36,000 km altitude. This required on average 1.7 km/s of ΔV and, if using a chemical propellant, consumed roughly 2,000 kg. They then had a residual station keeping ability of ~500 m/s for the remainder of the life of the satellite (~55m/s per year). They either remain in the original orbital slot or consume a portion of their ΔV budget to move to another GEO belt slot. Additionally, a fraction of propellant must be preserved to dispose of the satellite at the end of its design life. However, if the satellite is refueled after reaching GEO, it will have roughly 5 times its previous ΔV budget and have the ability to maneuver as well as station keep. The GEO satellite now can reposition itself without regret.

Refueling or providing ΔV assistance—"final leg" delivery to upper stages or satellites destined for GEO, EML1 or beyond—has a similar economic incentive. Instead of paying to launch propellant from Earth, buy it in space. A typical satellite bound for GEO usually pays the launch provider to launch their payload mass (2,000 kg), plus the mass of their apogee kick motor and propellant combined (also just over 2000 kg). Instead, the satellite service provider could launch two 2000 kg satellites and purchase final leg services from a company like Momentus Space, who could purchase water from EML1. This would reduce the launch cost per

satellite in half, netting a 30% saving to the satellite operator after paying for the "final leg" services.

3.9 Legal Considerations

The legal environment surrounding extracting and utilizing space resources is moving towards increased clarity, promoting investor confidence. The international community and individual nations, including the United States, are collectively and independently working on legislation to define in space resource utilization ownership, property rights, and responsible activity, while upholding international agreements [27]. Under the Outer Space Treaty of 1967, all nations have agreed to disavow claiming sovereignty over celestial bodies or territories on those bodies. They still retain quasi-territorial jurisdiction and responsibility over their activities and objects launched into space, and personal jurisdiction and responsibility over their astronauts, citizens, and juridical persons, including non-governmental organization's activities launched into space [28]. The Hague International Space Resources Governance Working Group's recently released *Building Blocks for the Development of an International Framework on Space Resource Activities* are the first step to establish prospecting rights and property rights in space [29]. Jurisdiction, therefore, is going to extend to the activities involved in extracting the claimed resources and to the final products, vehicles, and facilities manufactured from these space resources. Sovereignty in space, as opposed to on celestial bodies, does not need to be claimed. By defining, occupying, and establishing logistical nodes American is projecting quasi-territorial jurisdiction and responsibility into space—establishing outposts of the law-abiding world with its Artemis Accords partner nations.

America and its allies can extend their reach, peacefully, or at least non-aggressively, into the cislunar system. This effort can and should be led by NASA, civilian providers of space capabilities, and the space resources industry; however, it will create operational capabilities that the USSF will leverage. The USSF should intently follow the progress of the space resources industry and be prepared to enable and protect its development, much as the U.S. Army served to secure, explore, and expand the economy of America into the western frontier.

3.10 Strategic Benefits

America has long realized that the nation does not need to have sovereignty over territory or colonial subjects to project force on the sea but that effective refueling and resupply stations

become the dominant consideration in achieving control [30]. When A.T. Mahan wrote *The Influence of Sea Power upon History* in the 1880s, he pointed out that America had no need of the Merchant Marines, as America had no threats to its naval commerce, and that its commercial ships could go to foreign ports—generally without fear—for refuge from storms, to repair, and to resupply. This is not always the case. When peace does not prevail, Mahan continued, the merchant seaman:

> "…intuitively sought at the far end of his trade route one or more stations, to be given to him by force or favor, where he could fix himself or his agents in reasonable security, where his ships could lie in safety, and where the merchantable products of the land could be continually collecting, awaiting the arrival of the home fleet, which should carry them to the mother-country [1]."

In space, the need to establish logistics hubs and the need to conduct space mission logistics is the same need the navies of the 1800s had for coaling stations, fresh produce, and safe harbors. Currently though, there are no friendly foreign ports—there are no in-space ports in which to refuel at all. There is a need to refuel our space vehicles, provide our astronauts with fresh food, and protect critical systems and humans from radiation and solar storms. The means of securing safe harbor in cislunar space are technically feasible, as discussed above. They are also legal under international law.

The cislunar logistics hub could eventually serve as a robotic space station, expanding over time to host more and more capability, eventually becoming an in-space fabrication laboratory to responsively manufacture and distribute repair parts, fabricate structures, subsystems, and components for tech refresh [31,32,33]. This concept is similar to the DoD's interest in pushing logistics as far forward as possible, as responsive as possible. Naval Additive Manufacturing, in the office of the Deputy Assistant Secretary of the Navy (Research, Development, Test and Evaluation), has a goal of establishing permanent additive manufacturing installations on multiple ship classes, with a 24-hour response time to additive manufacturing requests [34]. Coupled with an independent source of raw materials, establishing factories in space that can deliver components, and eventually satellites to Earth orbits would be a significant capability. The EML1 hub would serve as a foundational element for a future, incrementally evolving, industrial capability in space.

3.11 Operational Benefits

Beyond the direct benefits discussed above, the establishment of a propellant logistics architecture anchored by the EML1 logistics hub delivers other operational benefits. For example, the logistics hub at EML1 and at other future locations allows for resupply of maneuvering spacecraft without waiting for an Earth-based launch. A logistics hub coupled with a robotic servicing vehicle, space tug, or refueling spacecraft at a "High-GEO" orbit would increase the flexibility of mission planners. USSF spacecraft could be refueled at regularly scheduled intervals and be available for on demand or "emergency" resupply. Those spacecraft would then be at peak readiness.

The EML1 logistics hub also allows for the emplacement of other capabilities. The hub could host additional payload sensors to conduct passive space domain awareness activities, or with adequate power, conduct active space domain awareness activities including space object identification, cislunar orbital element set (ELSET) generation, and traffic management. Future versions of USSF spacecraft could be deployed directly from the hub for applications throughout cislunar space. This would inform the military with precise position and velocity information and could also publish ELSETs for the international community, without charge, similar to the way space-track.org currently functions.

In addition, by refueling communication satellites, the satellites gain the ability to reposition on orbit, either rapidly by a few degrees within a theater of operation, or between theaters as needed. Future USSF spacecraft could have the ability to reposition itself anywhere within the GEO belt within hours with high-ΔV transfers. Again, because of assured resupply, planners would be willing to conduct such transfers and increase the number of propulsive missions, including forced motion navigation inspections for cooperative and non-cooperative space domain awareness.

A space-sourced logistics supply line adds redundancy to the sustainment of our space infrastructure by establishing a new celestial line of communication (CLOC) from the Moon. A CLOC is a route used for the "movement of trade, materiel, supplies, personnel, spacecraft, electromagnetic transmissions, and some military effects [35]." Currently, we have only one CLOC: we must sustain all spacecraft and constellations via Earth launch, which is well understood, preplanned, and interdictable. The Missile Defense Agency's 2019 Ballistic Missile

Defense Review includes endorsement of a space sensor layer to detect ballistic and hypersonic missiles during the launch and flight phases and pass on targeting information to ground, air, or sea-based weapons to defeat the missiles over the launching nation's territory [36]. This capability could be expanded to prevent space launches. America's position on militarization of space does not appear to extend to conducting or endorsing space blockades in either the Defense Space Strategy or in the Space Capstone Publication [37]. The Space Capstone Publication takes a nuanced approach to achieving space superiority and supremacy:

Space superiority is a relative degree of control in space of one force over another that would permit the conduct of its operations without prohibitive interference from the adversary while simultaneously denying their opponent freedom of action in the domain at a given time. Space supremacy implies that one side could conduct operations with relative impunity while denying space domain freedom of action to an adversary. Space supremacy is not always desirable, or attainable against a peer adversary, and should not be the unconditional goal of military spacepower [11].

A space blockade would be one way to achieve space supremacy, however freedom of use of space is protected by the Outer Space Treaty (OST [38]). America's and the OST's stance on allowing space to be used for peaceful purposes explicitly includes using space for non-aggressive purposes, including missile warning [39]. America would be unable or unwilling to prevent an adversary from developing similar capabilities that could deny or disrupt its launch capabilities. Having a second celestial line of communication for propellant, and eventually in-space manufactured consumables and repair parts, would mitigate against the threat of an adversary targeting Earth-launch.

Finally, developing a strategic reserve of in-space propellant enables and enhances the maneuverability and extends the reach of all satellites and space vehicles. The water at EML1 could also serve as shielding for other prepositioned equipment, repair parts, and feedstock for advanced in-space manufacturing capabilities, or as radiation shielding for humans. Products and feedstock can be delivered to these nodes (whether launched from Earth or sourced from space) to test out capabilities and start building logistical staying power.

3.12 Tactical Benefits

The tactical benefits of a cislunar logistics system accrue to both commercial and military users. Rapid repositioning of a GEO satellite (as opposed to passively drifting near the GEO belt) enables commercial satellites to respond as the market or customer's needs change. Active station keeping can increase the number of satellites within the geostationary belt—if satellites maintained a smaller station keeping box, they could potentially reduce the space between satellites, although other factors may limit this.

Repositioning a satellite has multiple national benefits across the diplomatic, informational, military, and economic, "DIME," spectrum. Maneuvering satellites can serve as an indication that the military is planning to conduct an exercise or an actual operation. It could also be purely for diplomatic signaling. It could also serve to potentially break or disrupt an adversary's plan by disrupting their find, fix, track, target, engage, and assess processes—eventually even giving the satellite operator the "power of giving or refusing battle at will [1]."

The Geostationary Space Situational Awareness Program (GSSAP) Satellite has a unique mission that requires it to frequently reposition itself in the GEO belt to inspect other satellites, typically without their cooperation. The GSSAP system is highly classified except for its existence. Some conjectures are possible, however, and some estimates may be made simply based on open-source literature. Beyond mere station keeping, GSSAP must accomplish safe rendezvous and proximity operations (RPO), to include staging points, standoff, and mission abort capability, perhaps including forced motion circumnavigation and other propulsive events to ensure safe encounters. If the GSSAP launches with its lifetime supply of propellant, then mission planners are constrained in how they consume propellant, putting a high price on each kg of propellant. With an estimated program cost of $700 million, the six satellites each cost roughly $115 million. With an estimated total mass of 700kg and ΔV budget of 1000 m/s a GSSAP with a chemical propulsion system perhaps has 140kg of propellant [40]. Each kg of propellant is then worth $800,000 if the satellite cannot be refueled. However, if we can refuel GSSAP for $2,000/kg (the green bar above "GSO" in Figure 3-7, on page 43) or $300,000 total, we could save >99% percent of the cost of launching a replacement GSSAP. A propellant provider could charge up to $400,000/kg and still result in the USSF achieving 50% savings on replacement capabilities.

A more active GSSAP provides more intelligence, faster. With on demand refueling, GSSAP can maneuver across the GEO belt as needed. This can dramatically reduce the cost of intelligence while at the same providing increased operational flexibility. Further, maneuvering geostationary satellites defensively becomes a feasible, affordable option.

3.13 Conclusions

Establishment of a water and propellant logistics architecture has enormous benefits to the nation across the civil, commercial, and military space sectors. Refueling with space sourced propellants dramatically lowers the cost of every space mission beyond LEO. It is enabling for developing a sustained presence on the Moon and eventual exploration of Mars. It is also enabling for the establishment of commercial space mining, processing, and manufacturing businesses. Mining and processing lunar water ice for propellant and other uses is likely to be the first economically viable use of a space resource.

Perhaps most importantly in the near term, space sourced propellant logistics provides unprecedented sustainment and mobility capabilities for our national security infrastructure in GEO. A satellite that runs out of fuel will no longer be a "mobility kill." It will no longer be necessary to decide between preserving propellant or preventing intelligence loss. The Space Force's Core Competency of Space Mobility and Logistics is inclusive of movement from, to, and *in* space. USSF plans on taking advantage of recent advancements in on-orbit servicing; they should not overlook the benefit of sourcing propellants from space resources.

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CHAPTER 4.

IN-SPACE MILITARY SUSTAINMENT: THE NEED FOR AN INTERNATIONAL CIVILIAN LED LOGISTICS ARCHITECTURE

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4.1 Abstract

This paper considers the technical, policy, and military implications of establishing an in-space logistics system that delivers propellants made from space resources to spacecraft in cislunar space and beyond; and proposes establishing an international civil and military partnership to create shared standards, interfaces, and interoperability procedures to achieve strategic modularity. This paper starts by reviewing foundational aspects of space sustainment: first, the cislunar operating environment, inclusive of the physical, legal, and astropolitical environment; second, functional use cases for operating and refueling space vehicles; and third, the terrestrial petroleum industry and the Defense Logistics Agency's (DLA) method to connect national source of supply to the end user. The DLA's sustainment methods are used as a model to frame the establishment of a second celestial line of communication. The recommended method to achieve strategic modularity is then presented: an international, civilian run "In-Space Logistics Commission," which would map out the functional component of space logistics centers and networks, identify common interfaces and procedures, and then freeze those interfaces to create technical stability. The outcome of this commission would ensure allied nations have in-space logistic interoperability; resulting in an international commonality that serves the allied space economy and space forces' needs.

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* See Appendix C for permissions and citation

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> "Grand strategy—higher strategy—is to coordinate and direct all the resources of a nation, or band of nations, towards the attainment of the political object of the war—the goal defined by fundamental policy [1]."

4.2 Introduction

The United States is pioneering the creation of a space strategy that embraces international cooperation across civil and military space. The United States Space Force (USSF) is focusing on outreach towards allies worldwide with the goal of building what has been referred to as a "New Space Coalition" centered around the United States. International cooperation has been a cornerstone of successful space endeavors, especially regarding civil programs. These civil partnerships have influenced the boundary conditions for military space activities. With the "New Space Coalition" the USSF has stressed that American leadership in military space shall be built on close international cooperation. Allied nations now have the chance to actively shape the future of military space and play an essential role in the space coalition [2].

Allied grand strategy should pursue a future in space that is managed by rule of law (in the western liberal sense, rather than the Chinese philosophy of legalism) where capitalism flourishes, and people are able to live and work in space. This is the ideal vision of the future outlined by the Air Force Space Command in 2019 [3,4,5]. To achieve this future, the strategy requires a balanced trio of "ends, ways and means." Colin S. Gray asserts that when preparing for war, economics and logistics—the "means"—underpin strategy.

> "The economic resources of a polity supply and move a military machine that is directed by a strategy making organization, recruited, armed, and trained by military administration, ordered in accordance with intelligence information, educated and drilled respectively by strategic theory and doctrine [1]."

He continues by saying that "Strategy requires the use or development of scarce economic resources [1]." The development of the space resources economy and the establishment of an in-space sustainment infrastructure are necessary to achieve the Space Command's vision of the future, and to prevent darker futures. Ensuring allied forces have the means to project power in and from space is fundamentally dependent upon its ability to sustain their forces in the farthest reaches of space. Extracting propellant from space resources—establishing coal stations in

space—Is a fundamental first step towards establishing the means to achieve the desired future in space. Maneuver in space is fundamentally tied to the use of propellant.

All active, thrust-producing propulsion systems require propellant—propellantless propulsion technologies have not been successfully demonstrated [6]. Nuclear thermal propulsion, an excellent and promising advanced propulsion technology utilizes nuclear power to generate electrical or thermal energy to heat and accelerate a propellent—preferably hydrogen [7]. Past works have shown that water ice reserves on the Moon could be sourced and processed into propellant for in-space refueling in a commercially viable way, potentially within ten years, paving the way for further space resource extraction and utilization [8,9,10]. A corresponding architecture has been proposed to distribute water, as depicted in Figure 4-1 [8].

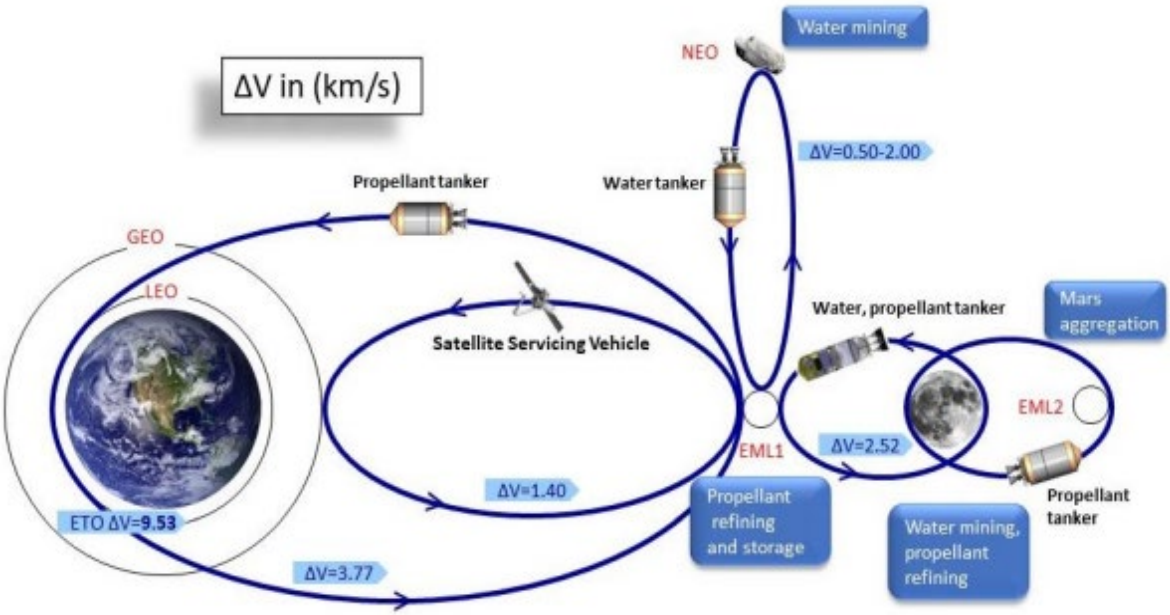

Figure 4-1. Water and LO2/LH2 propellant logistics architecture in cislunar space, from Jehle and Sowers, 2021.

This paper is structured around three broad areas. First, we review the operational environment of cislunar space, including the physics of maneuvering in space, the legal situation surrounding space resource extraction and utilization, and the astropolitical situation. The second

broad area is to consider the functional use cases of refueling space systems. This includes reviewing what propellant is used for in space but does not expound on how these uses relate to military planning considerations (namely: operational reach, culmination, the movement and maneuver and protection warfighting functions, and the space control space operational capability). The third section details what an in-space logistics system would consist of, and some considerations surrounding technical interfaces. We conclude with the recommendation that an international In-Space Logistics Commission be established with the purpose of achieving strategic modularity.

4.3 Cislunar Operational Environment

The cislunar operational environment includes considerations of the physical, legal, and astropolitical environment.

4.3.1 Propulsion

In June 2021, the AFRL published "A Primer on Cislunar Space." This primer provides a high-level introduction into the orbital mechanics knowledge needed for trajectory and maneuver planning in cislunar space along with the challenges of tracking and observing space vehicles in the domain [11]. Understanding the space "terrain" is a prerequisite to operating in cislunar space.

The fundamental argument for in-space refueling is based on the physics of maneuvering in space and can be found in the rocket equation. The rocket equation is written: $\Delta V = v_e \ln(m_i/m_f)$, where ΔV is the change in velocity of the spacecraft, v_e is the exit velocity of the propellant, and m_i and m_f are the initial and final masses respectively of the sum of the structure and propellant. The rocket equation results in an exponential requirement for propellant as the need for ΔV increases.

> "This is the reason rockets leaving Earth consist mostly of fuel, and that a rocket going to the Moon and back must be the size of a Saturn V used in Apollo or the SLS currently in development. However, if you can refuel enroute, and reuse the propulsion system through multiple refuelings, you can break the tyranny of the rocket equation. The exponential increase of propellant with ΔV becomes linear... [9]"

A reliable network of in-space logistics assets is an enabler for the mobility of all spacecraft—not just military spacecraft. Enabling low-cost or nearly free propulsion will enable the transport of other materials, and all other warfighting functions in space. Among all spacepower competencies, in-space sustainment holds the greatest potential to link the typically interconnected and international character of military, civil, and commercial space activities. A long-term objective of utilizing space resources for in-space sustainment is needed to enable large-scale access to low-cost, sustainable propellant for the space economy [8,9].

4.3.2 International Partnership

Existing and upcoming human exploration missions to cislunar space and Mars are built on models of international cooperation. The International Space Station is a noteworthy example, the 1988 Multilateral Space Station Agreement was signed by 15 international partners [12]. The Lunar Gateway is also being planned and executed by an international space agency consortium consisting of NASA, ESA, JAXA, and CSA with bilateral memorandums of understanding [13]. Such endeavors not only serve as legal models for an in-space sustainment infrastructure but could also serve as customers who would benefit from the delivery of space sourced water and its constituent elements (oxygen and hydrogen) for human sustainment, propulsion, or radiation shielding.

The possible interconnections between such highly internationalized space activities and an internationally operated in-space sustainment network become evident in the light of new civil space exploration doctrine. The "Artemis Accords," signed on 13 October 2020, represents the zeitgeist of international commitment to shape the future of human space exploration. Utilization of space resources is a core aspect of the Artemis Accords, which specifies international governance.

> "The Signatories intend to use their experience under the Accords to contribute to multilateral efforts to further develop international practices and rules applicable to the extraction and utilization of space resources, including through ongoing efforts at the COPUOS [14]."

A year prior, on 12 November 2019 "The Hague International Space Resources Governance Working Group" adopted the "Building Blocks for the Development of an International Framework on Space Resource Activities." The building blocks outline a potential legal

framework surrounding property rights, responsibilities, and limitations for governments to coordinate, extract, and utilize space resources, and the establishment of a forum and procedures to prevent and resolve disagreements consistently with existing treaties, including the Moon Agreement [15,16].

The Hague Building Blocks and multilateral space agreements provide policy and legal examples for establishing and maintaining an international in-space sustainment infrastructure. This spirit of international cooperation can be harnessed for defense-related purposes, but its primary use should be for establishing an in-space sustainment infrastructure and for building the space economy in general. A civilian led in-space sustainment infrastructure used by both government and private civil and commercial architectures to support the fulfillment of peaceful political goals in space. Further commercial services can be built on the foundation of the described infrastructures to service military spacecraft but will decrease the costs of space faring generally. Commercial space activities beyond LEO will be facilitated for all space players, amplifying digital services, communication, and connectivity on Earth, ultimately benefiting all consumers of space-based services [15].

These broad economic benefits serve the interests of everyone on Earth: they increase the quality of life of the individual consumer by reducing the cost of critical services; they lower the cost of doing business for companies operating in space or tangential to the space industry; and they lower the cost for governments utilizing space capabilities to govern and preserve their defense. An in-space sustainment architecture then, can serve as a roadmap for allied governments to invest in this area while adhering to their commitments to international space law. The most prominent treaty, the Outer Space Treaty of 1967 emphasizes that space activities are in "the common interest of all mankind… for the benefit of all peoples… [and that] co-operation will contribute to the development of mutual understanding and to the strengthening of friendly relations between States and peoples [17]."

In-space sustainment is a support function with immense dual-use potential that supports all stated ideals that the international community agreed to with the Outer Space Treaty. Although essential to military operations, it is not inherently aggressive or threatening, but can be an ideal focus point to maintain and promote positive norms and standards for international precedence in the context of the OST. An opportune moment has now arrived in the light of the

international activities of American Space Policy initiatives. The new space coalition has a common interest for an in-space sustainment infrastructure from a strategic and operational perspective: this is a unique opportunity to spark a demand signal for the space resources industry.

4.3.3 Strategic Considerations

Military space strategies must be derived from political and economic goals on Earth and in space and are constrained by the economic means available to the planners. Although consensus on the necessity of international cooperation in space becomes ever more obvious, it is questionable if all diplomatic signals in this respect are backed by a long-term strategic mindset. Allies to the US must evaluate their interest in participating in international space defense activities from a strategic perspective. Including allies from the beginning will allow for the creation of internationally accepted standards, therefore ensuring the willingness of allies to follow US leadership in space. Civil space exploration programs accompanied by commercial opportunities are adding further emphasis to international cooperation; the Artemis Accords explicitly deals with space resources utilization.

Several national space strategies must be coordinated into an overall model for international space defense cooperation. Cultural differences regarding the standing of space defense within national priorities should not be underestimated. Not only does this comprise of differences in spending but how military space activities are interconnected with overall space activities for national purposes. Unlike the US, the awareness of an operational demand for space is very young in many nations. Within NATO, space was accredited as an operational domain only in 2019, whereas the US considered the 1991 Persian Gulf War to be its first "space war [18]." Although states might be relying on large-scale commercial and scientific activities to maintain influence in space, the implications for defense and national security often remain unperceived outside the direct spheres of influence of military institutions.

A low national priority for space results in limited spending for space. Revenue for military government satellites in Europe amounted to a predicted $12 billion for the two decades from 2008-2017, while North America spent $60 billion [19]. However, commercial, civil, and scientific activities massively outweigh defense applications in most countries. Among allied nations, only the US has a significant portion of its space budget dedicated to the defense sector.

United States Space Command international engagements chief Lt. Col. Pete Atkinson stated:

> *"*But not all space partnerships are created equal. Where wealthier countries may have more established national security space needs, others may only have the budget or desire to pursue civil and commercial space programs. The U.S. is learning to meet everyone where they are [2]."

The US cannot assume that other nations' space defense ecosystems are identical to the US'. The USSF and NASA have broad bipartisan political and economic support and standing that enables the country's political leadership to formulate strategies relevant to its nation's space activities. For many partner nations the civil, military, and commercial space sectors do not garner political interest. In 2018 the FAA Office of Commercial Space Flight reported on the global space economy: the US government spending dominates global government spending ($47.5 of $82.9 Billion, or 57% of global government spending on space) with over half of that (NRO, MDA, and USAF) spending being military related [20]. However, the commercial satellite industry dominated the space economy's spending ($260B of $344.5B in global spending), with benefits spread across the world in the form of telecommunications, position navigation and timing, and weather forecasting [20]. These services provide support to terrestrial industries including cell phone and internet, transportation, and banking services with a worldwide impact. These services are generally outside of direct government control. For these reasons it is important for both the US and its Allies to collaborate where interest best coincide.

Strategic communication must address all space activities, not just space defense, it should prioritize activities that benefit the complete space ecosystem of respective nations. In-space sustainment is a way to enhance spacepower with ancillary, dual-use benefits – it develops the space economy while sustaining the principals of free and fair use of all.

4.4 Functional Use Cases

The functional use cases of refueling space vehicles closely mirror space propulsion activities: space launch, rendezvous, and station keeping. For each of these three activities we consider how refueling expands the space vehicle's mission envelop, associated cost savings (if known), and resulting new mission opportunities. An overarching theme is that assured propellant resupply enables space vehicles to consume up to all their propellant on a single

mission or set of missions without "loosing" the asset, that is without incurring a "soft kill." Satellites have traditionally been designed to perform their intended mission until they run out of propellant and are then deorbited or placed in a safe graveyard orbit. Assured propellant resupply in space eliminates the soft kill outcome, maintaining the space vehicle's design life and expanding its mission profile.

4.4.1 Space Launch

Launch vehicle's upper stages can be refueled in a geostationary transfer orbit (GTO), or beyond geostationary orbits (GEO) to extend their reach and reduce the cost of placing a payload into the destination orbit. Refueling upper stages at GTO for delivery of payloads to GEO (instead of utilizing GEO satellites propulsion systems) could save up to 20% for the launch vehicle. Conceivably, this could eliminate GEO satellites' need for an apogee kick motor and associated propellant mass (~2000 kg, or nearly half the satellite's mass). This could free up mass budgets for other functions. For missions beyond GEO potential savings increase. Transportation from Earth to the lunar Gateway would see a 50% reduction in cost; transportation to the lunar surface, 66%; and a nearly equivalent reduction in price for missions to Mars. It requires roughly 12,000 m/s for a round trip from LEO to low lunar orbit (LLO). Without in space refueling well over 300,000 kg of propellant would be needed (for a payload constrained by the assumed *structure* mass fraction of 0.92), sourced from Earth, at the start of the mission *in low Earth orbit* [9]. With one refueling this is reduced by nearly an order of magnitude, to 40,000 kg; a 260,000 kg savings of propellant [8].

Upon mission completion, the upper stage is then either disposed of or in the case of SpaceX's planned Starship, returned to Earth and reused. The upper stage could be refueled in space and repurposed for other missions, including cryogenic propellant storage, or bulk propellant delivery [8]. The upper stage could also be modified to provide in space transportation services, including repositioning space vehicles or maneuvering space vehicles from GEO to other destinations within the cislunar system. This would essentially be a bulked-up version of "final leg" delivery services provided by companies such as Bradford Space or Momentus [21,22].

The Mars Ascent Vehicle (MAV) will be the first launch vehicle to depart an object in the solar system other than the Earth and the Moon (disregarding Osiris Rex's "Touch and Go"

maneuver on the asteroid Bennu). The MAV was originally envisioned to utilize Martian in situ resources to make its own propellant as part of the Martian Sample Return Mission, inclusive of the Perseverance Rover. The MAV team considered utilizing oxygen sourced from Mars' atmosphere combined with liquid methane brought from Earth. This theoretically would have reduced the cost and amount of propellant needed to launch the MAV from Earth. NASA later decided to use solid propellants and awarded the contract to Northrop Grumman, while still successfully demonstrating oxygen extraction from Mars' atmosphere with MOXIE, the Mars Oxygen In-Situ Resource Utilization Experiment, one of the Rover's payloads [23,24,25,26]. The MAV team will still have to contend with ensuring the Northrop Grumman launch vehicle can survive its entire mission profile: Earth launch, storage for eight months in deep space, landing on Mars, and the storage of the propellant on Mars for somewhere between two and six years before it must successfully launch the return mission [27].

Future Mars missions, especially those with Human participants would benefit from local propellant generation and distribution. A round trip from LEO to low Martian orbit cost around 11,000 m/s. This budget compares to the LEO to LLO mission previously discussed but would not have the benefit of in space refueling without a dedicated, assured in space propellant resupply in the vicinity of Mars. A robotic propellant depot and distribution architecture established for cislunar space would need to be modified to account for the different environment of the Martian or other destination body's orbit (including differences in incident sunlight and latency for remotely controlled operations [28]). Again, utilizing Martian in situ resources to refuel a return mission will reduce the order of magnitude of propellant needed when launched from Earth.

4.4.2 Rendezvous

Rendezvous missions are done to 1) insert satellites into a specific point in a constellation; 2) inspect an operational satellite; 3) service an operational satellite; 4) intercept a satellite (as a kinetic anti-satellite weapon); and to 5) avoid collision. A satellite launched into a GTO orbit utilizes its own propulsion system for orbital insertion (utilizing its apogee kick motor). Upon successful insertion, the satellite could be refueled, providing it with an additional 1,700 m/s of delta-V to be used for collision avoidance, repositioning within the GEO belt, or even to fully deorbit rather than enter a graveyard orbit. Space based space surveillance (SBSS)

missions, such as those performed by the Geosynchronous Space Situational Awareness Program (GSSAP), rendezvous with natural motion circumnavigation (NMC) or forced motion circumnavigation (FMC) orbits around satellites in the GEO belt to inspect or observe satellites for intelligence purposes. One estimate suggests the GSSAP program could save nearly the entire cost of a replacement satellite, or $114 million by refueling GSSAP [8]. Finally, servicing satellites, such as the Defense Advanced Research Projects Agency's (DARPA) Robotic Servicing of Geosynchronous Satellite (RSGS) rendezvous with satellites to conduct repairs, such as deployment assistance, to swap out payloads, inspect environmental damage, and retail level refueling of satellites' propellant or cryogenic coolants.

4.4.3 Station keeping

Station Keeping maneuvers are performed to maintain a satellite within its assigned orbital slot. For GEO satellites, this assignment is critical to maintain as the orbital slots are tightly allocated by the International Telecommunications Union to deconflict frequency use and mitigate collisions. The ability to refuel a GEO satellite's station keeping propellent would enable that satellite to either extend its mission beyond what it was originally fueled for or enable it to launch with a minimal amount of propellant. Savings would be mission dependent, but water extracted from the Moon could cost as little as $1100/kg at EML-1 and only slightly more in GEO: this is a tenfold savings over propellant launched from Earth [9,29].

4.5 In-Space Logistics – Modeled after Terrestrial Petroleum Logistics

No single company or government agency, including NASA or the USSF, will be able to dictate standards for a widely adopted in-space logistics infrastructure. For consideration, the Defense Logistics Agency, as the executive agent for bulk petroleum, manages bulk petroleum distribution to the US Department of Defense: they coordinate with Combatant Commands, Industry, and Host Nations. Each branch of service retains its service specific acquisition and employment strategy to support its environment and mission unique operational and tactical needs, see Figure 4-2 [30].

In the petroleum industry, multiple companies are involved in the petroleum value chain: inclusive of prospecting, extracting, product refinement, bulk distribution, retail distribution, and final delivery to the customer. Gas stations are often privately owned franchises, who lease

directly with a retail supplier (delivering truckloads of fuel), who themselves are subcontracted from bulk distributors (via pipeline, or ocean-going vessel), with multiple bulk storage nodes.

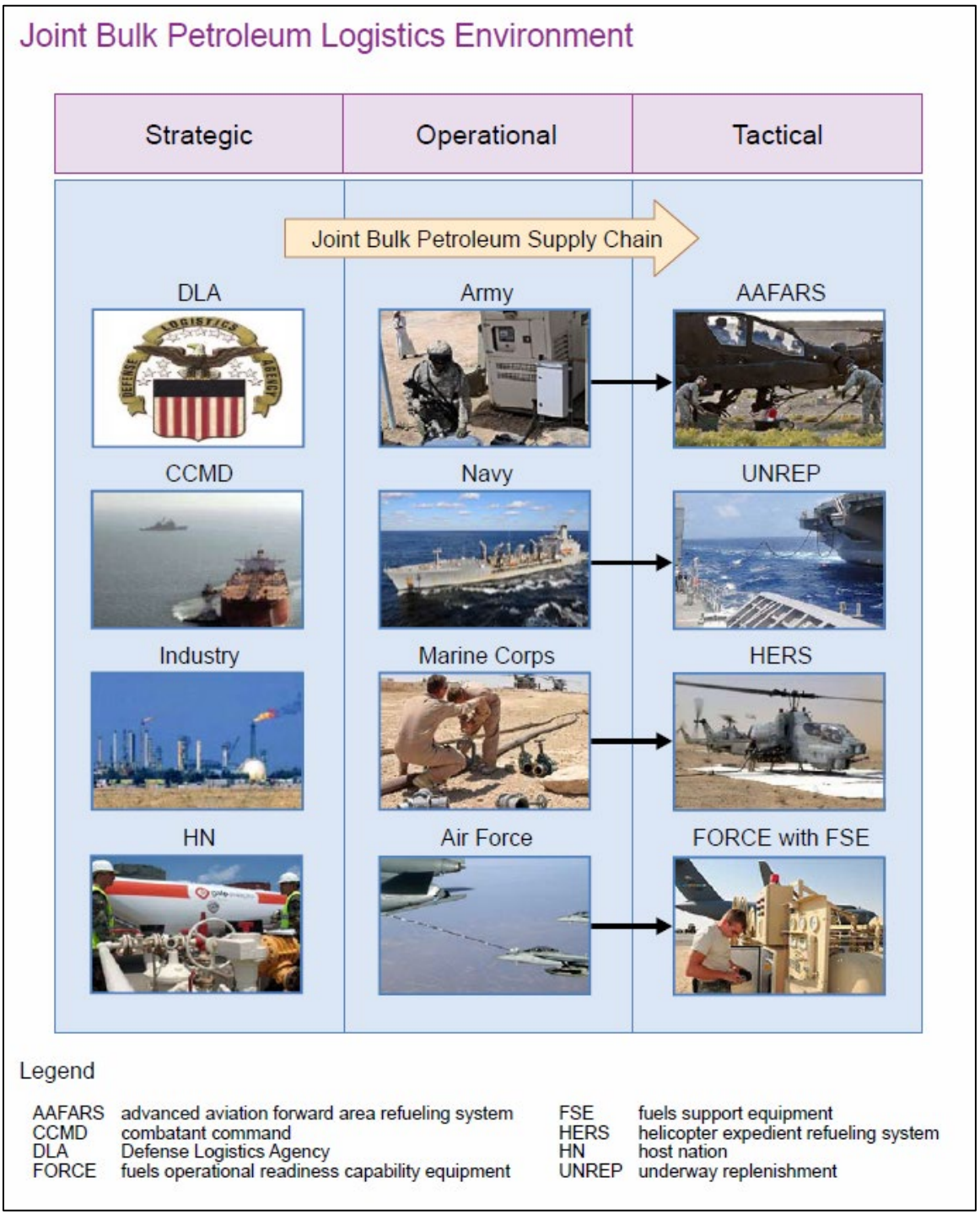

Figure 4-2. Joint Bulk Petroleum Logistics Environment as described in Joint Publication 4-03, Joint Bulk Petroleum and Water Doctrine.

A space resources based propellant value chain will closely mirror that of the terrestrial petroleum industry: it too will include prospecting, extracting, processing, storage, and delivery nodes. Kornuta et al.'s Commercial Lunar Propellant Architecture thoroughly considers the space resources prospecting and extraction portion of the value chain but was intentionally vague about the aggregation, storage, and distribution of propellants [31]. Since that report's release significant work has gone into prospecting, mining, and extracting water from the Moon and asteroids, and transferring cryogenics in space [29,32,33,34]. Retail satellite servicing has expanded from aspirational to now realized with Northrop Grumman's Mission Extension Vehicle series. Additional Space Resources value chain capability gaps still exist but are being identified and are starting to be filled in by researchers and a robust ecosystem [35]. Significant remaining gaps include logistics infrastructure on the lunar surface, such as well-defined launch infrastructure, and In Situ Resource Utilization for other Lunar and Martian resources [36]. NASA has been taking several steps to close these gaps utilizing multiple strategies including public engagement programs like the "Break the Ice Challenge [34,37]."

As a "system of systems" engineering problem, interfaces need to be specifically defined and adopted for the environment(s) and position(s) across the value chain that they connect and serve in. Environmentally, this includes the thermal environment for power generation and thermal management, the radiation environment for radiation hardening or to shield components, day/night cycling for objects orbiting or based on a celestial body, among other considerations. When considering the portion of the value chain the interfaces serve in, considerations include the total volumetric flow rate of the cryogenics being transferred, material selection, mechanical connections considering impact velocities, forces, and vibrations, electrical and data interfaces (both wired and wireless), thermal interfaces, cycling and aging, weathering, and operational practices and protocols [38].

Several companies are already developing and promoting their own interfaces in the hopes of achieving early and wide adoption. Some companies are promoting their interfaces as unrestricted (in the case of NovaWurks, both ITAR and intellectual property-free). Making an interface standard and open does not preclude intellectual property rights. As an example, the computer USB interface is still proprietary, and the owning organization sells licenses for under $10,000 to hardware developers [39].

Eta Space, Lockheed Martin, SpaceX, and ULA were all awarded tipping point contracts by NASA to demonstrate large scale, in-space, cryogenic propellant transfer. These demonstrations and the interfaces developed to support them would be critical to "upstream" propellant transfer, that is propellant transfer from a wholesale manufacturer to a storage depot, or from a storage depot to a bulk transfer vehicle. These transfers are volumetrically high: SpaceX and ULA are specifically planning on demonstrating in-space refueling of launch vehicle upper stages [33].

NovaWurks, Obruta, OrbitFab, SkyCorp, iBOSS (GmbH), AstroScale and Northrop Grumman's Space Logistics have independently developed competing interfaces, visions, and standards for conducting satellite servicing. These concepts range from the now executed Mission Extension Vehicle, which docks to and remains attached to the serviced satellite for the duration of its services, and is relatively "interface agnostic," attaching to a satellite's apogee kick motor, to NovaWurks "Space Lego," or SLEGO concept of utilizing its interface to facilitate in space assembly, including for the exchange of internal propellant tanks between orbits and space systems (in the model of BBQ propane tank exchanges). SLEGO proposes to one up the modularity of docking ports: instead, the SLEGO interface is being promoted as a construction interface at the subsystem, and system levels, allowing for sheering, linear, and rotational motion, rather than just linear docking motion [40,41,42]. Any system that is actively maneuvering and conducting RPOD must be a fully functioning satellite, able to independently maneuver, communicate, and survive in space—the interface is a small but critical part of the solution. These critical interfaces need to be agreed upon by the relevant partners throughout the international value chain in order to realize strategic modularity.

4.6 Strategy Suggestion: A Civilian Led Framework

A propellant distribution system, as outlined above, could be used to support the distribution of raw materials and manufactured goods throughout cislunar space. The full establishment of a complete sustainment system—not just that of propellant—should be the full goal of an in-space logistics commission. Establishing an economy in space gives future US and allied planners increased means to execute national strategy in space. Recognizing the necessity of utilizing space resources to fulfill strategic and functional objectives, the New Space Coalition should position itself in favor of contributing to the creation of a space-resources-based in-space

sustainment architecture. The Artemis Accords present an ideal setup to grow the inevitable military stakeholdership in space resources utilization in adherence to international space law, while partnering with civil and commercial stakeholders.

Three areas of technology emphasis are recommended to facilitate the development of space resources-based sustainment network. These technology areas underpin the establishment of a celestial line of communication connecting the Moon to the Earth and facilitating the inclusion of the Moon into our economic sphere. In all three areas the in-space logistics commission should coordinate among all stakeholders in the sustainment system of systems. Stakeholders will span the space resources value chain: from the companies dedicated to prospecting and extracting resources; through companies providing storage, processing, and distribution services; to the governments, companies, and organizations that are the end in-space consumers of propellants, goods, and services.

First, strategic modularity needs to be achieved across the New Space Coalition. The In-Space Logistics Commission should coordinate stakeholders to adopt common practices, technologies, and procedures to ensure the interoperable sustainment of their civil and military space capabilities. To achieve strategic modularity, the commission should map and functionally partition the components of the logistics system, specify the interfaces, and then freeze those interfaces to establish technical stability for the overall system of systems [43].

Strategic modularity is a systems engineering middle ground management approach between top-down dictates of the interfaces (strangling innovation) and a completely hands off approach leaving individual program managers free to select their own interfaces. If left without system of system level guidance, program managers may adopt the first interface that successfully meets their system's needs, achieving "technical modularity." They will take the easy path of asking their fellow program managers if they know of anything that has previously worked, and they will do this in the absence of a collective interface requirement. This will lead to multiple "standards" which increases the engineering requirements for the sustainment system of systems. The sustainment system of systems would then be required to support each "standards:" this will increase mass and reduce efficiency. Ultimately not adopting a single standard, or well thought out set of standards increases the cost for every system. "Strategic

Modularity" should be designed into any future space logistics system, rather than utilizing back office, "technical modularity" which has been traditionally used by the satellite industry [44].

The second area of emphasis for the in-space logistics commission is to focus on the development of Space resources utilization technologies. Technologies surrounding prospecting, extraction, processing, and distribution need to be matured in the context of civil space exploration programs. Until lunar- and near-Earth-object-sourced propellant can be transported through an in-space sustainment architecture, Earth sourced propellants can be used to test out existing and upcoming alternatives for storing and distributing propellant in space.

Third, investment into orbital servicing assembly and manufacturing (OSAM) technologies, such as "space tugs" (offering space mobility in the form of LEO-GEO orbital lifts), Earth-launched refueling missions, and Robotic Servicing of Geosynchronous Satellites (RSGS) is needed. These missions form the building block to experiment with, maturing the concepts of operations, and refine the technology for international standards adoption [45,46].

4.7 Conclusion

Establishing an in-space propellant sustainment architecture is both legal and necessary. Space resource law is rapidly maturing towards adopting a common framework for managing the use and extraction of resources extracted from celestial objects and the property rights, responsibilities, and limitations of the countries and companies manufacturing products from them. Maneuver in space is inextricably tied to the use of propellant; reliable resupply will enhance national spacepower by reducing the cost of all other space activities. It will enable cheaper space exploration missions and lay the foundation for a material-based (an addition to the existing data-based) space economy. A material-based space economy, inclusive of propellant sourced from space resources, will require spacepower to mirror maritime power. The new space coalition's space forces need to be prepared to leverage these new logistics capabilities, as it will extend their operational reach in cislunar space and enable maneuver without regret in the GEO belt.

An international coalition, under the Artemis Accords, should establish a civilian run "In-Space Logistics Commission," to map out the functional component of space logistics centers and networks, identify the common interfaces and procedures, and freeze those interfaces to create technical stability. An in-space logistics capability requires deliberate but decentralized

coordination among its partner constituents: strategic modularity is a prerequisite. Technical modularity, which emerges through individual program manager coordination, will not suffice, as it will increase complexity and hinder full interoperability.

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CHAPTER 5.

A CONCEPT OF SPACE SUPPORT DERIVED FROM THE GENERAL THEORY OF SPACE POWER

> "In peacetime, nations bolster sea power through 'acquiring strategic geographic features' that will assist in expanding and defending access to the sea's riches, including efforts to reach new markets and increase available existing bases through diplomacy or construction of new ones."
>
> "…the *peaceful strategic offensive* is not only available but is already supported by a significant group of space enthusiasts…"
>
> –Brent Ziarnick [1]

> "We must think about the sustainment fight in decisive action as the synchronization of the distribution loops of materiel. The loops described in sustainment doctrine are from the CSSB to the BSB, the BSB to the FSC and the FSC to the Company Trains."
>
> –Maj. Gen. Patrick Matlock, Commanding General, 1st Armored Division [2]

5.1 Introduction

In 2019, the US Air Force Space Command held a space futures workshop resulting in a publication: "The Futures of Space 2060." This workshop attempted to describe what space would look like 40 years into the future, with a range of possibilities spanning three axes: economic activity (none to expansive), human presence in space (minimal to flourishing), and leadership (from western led through contested/uncontrolled to non-western led [3]). After the US Space Force (USSF) was created in the end of 2019, the USSF Chief Scientist's office held follow on workshops to continue to explore those futures. They anticipate the convergence of capability and Kondratiev infrastructure waves in the 2040s and 2060s. These waves are

hypothesized fast and slow growth economic cycles that last 40 to 60 years, harnessing new technologies and the infrastructure associated with it [4]. This provides the USSF a 20-to-40-year planning horizon to identify and invest in the critical technologies to support appropriate force structure development. These potential timeframes are outside of congressional/appropriation timing windows, providing the USSF Chief Scientist Office the opportunity to positively and timely prioritize research and development to best impact acquisitions and force structure development [5].

The General Theory of Space Power developed by Dr. Brent Ziarnick asserts that production generates wealth from space and is the backbone of economic space power. The USSF Futures workshops implicitly accepted and adopted Ziarnick's description of the General Theory of Space Power: he presented his theory at the first Space Futures Workshop. His theory defines space power as the ability to do something in space. He further argues that developing space capabilities must be deliberate and thoughtful. Fundamentally, the ability to do something in space is constrained by how one has expended their capital. Did a space power invest economically to generate more access (colonies, production, and transportation capabilities), or did they expend their capital on a political message or military operation? The first half of this chapter expands upon space resources and the General Theory of Space Power, addressing both the grammar (production, transportation, and colonies) and logic (economy, military, political) Deltas.

The second half of this chapter is devoted to describing the establishment of a transportation and logistics infrastructure that conceptually spans the source of supply through end military use: an in-space concept of sustainment. Without a strong in-space economy and industrial base the military will not be able to establish an in-space sustainment system that is not Earth resourced. The concept of sustainment envisioned here evolved from Army sustainment, the expectation of rapid reusability of transport vehicles, and the availability of propellant and other supplies sourced from space resources. It is a first attempt at combining military sustainment with space resources and space logistics.

5.2 Space Futures

Workshop 2B, held in November 2021 considered several "images of Future Operations" (IOFOs) which described possible futures in the 2040s. These IOFOs were developed by

prominent minds in the space industry and were chosen to describe meaningful extreme futures impacted by the exponential growth of technology and the coupling of convergence and complexity. Technologies forecasted include the hyperbolic advance toward near-infinite bandwidth, computational power, artificial intelligence and autonomous systems, quantum computing, and femto-scale materiel manufacturing, among other technologies as described by Dr. Gabrielle Rizzo in "Disruptive Technologies in Military Affairs [6]." Rizzo forecasts that human decision making may wind up exiting the Observe Orient Decide Act (OODA) loop because of these technologies, leading to "infinite, distributed Command & Control capacity, concurrency of action and perfect coordination, logistical simplification and instant mission adaptation [6]." In this environment, Rizzo writes:

> "Military superiority is also maintained through a long-term, extensive and systemic strategy for technological advantage, aiming at preserving the Offset, 'a persistent, pervasive, univocal and unbalanced advantage, which shifts the competition from an unfavorable scenario to one that allows the application of forces to an otherwise immovable problem, or surmountable at an unacceptable cost [6].'"

Rizzo does not forecast the end of war, nor fast war, but near instantaneous tactical actions and reallocation of capabilities. Competition will endure through technological change; demonstrating superiority cannot be ambiguous.

The IOFOs described great power competition in space where the US was not necessarily the dominant power in space, and in some cases was a second-tier power. Multi-polar power competition with varied and complex interests and dependencies were presented. Some scenarios had people living and working in space, establishing colonies in mega structures in Earth orbit or cislunar space, and establishing footholds on Mars and in the Venusian atmosphere, while others omitted colonists. All scenarios featured economic interests in space, coupled with the need for space resources. Threats included natural and man-made disasters threatening the economic and political order, sometimes with technological surprise causing imbalances. A common assumption across scenarios was the importance of achieving low-cost maneuver [5]. The question for workshop participants was what should the force structure be? This includes the concept of sustainment. How should the Space Force maintain, sustain, and refuel its assets?

How will Guardians be transported, medically evacuated, or provided with mail or other Morale, Welfare, and Recreational (MWR) activities? Were Guardians and their Families garrisoned in space? Where was food procured from? As the Space Force develops the force structure of the Next Space Force (2040s) and the Force after Next (2060s), they should prioritize budgeting and planning for logistics and sustainment. In WWII fewer than one in ten Soldiers saw combat [7]. Since WWII, logistics and support related functions have steadily account for 60-70% of military manpower, spiking to nearly 80% with the extensive use of contractors by 2005 during the Iraq War [8]. Space travel consumes lots of propellant (mass) and energy, both of which need to be resupplied. Critically, covering the vast distances of space takes time, careful timing, and patience, or the expenditure of even more propellant and energy. Establishing the ability set to provide assured and timely resupply requires significant and deliberate investment in space access. Unfortunately, there is no coordinated national plan to establish space access. The USSF sees its role as following economic interests, while NASA is investing in the foundational science.

NASA's Lunar Surface Innovation Initiative (LSII), part of the Space Technology Mission Directorate, is leading the way in exploring In-Situ Resource Utilization (ISRU) and associated technologies. The LSII is collaborating with John Hopkins Applied Research Laboratory, the host of The Lunar Surface Innovation Consortium (LSIC). The consortium is designed to coordinate and foster industry, government, non-profit, and academic cooperation in the critical technologies needed to support NASA's mission of scientific discovery and exploration. Technologies explored include ISRU, Surface Power generation, Surface Power and Excavation, Extreme Access, Extreme Environments, and Lunar Dust Mitigation [9]. These technologies are the critical path for sustained operations on the Moon and for expansion of American access into space and the government should fund them as such.

Unfortunately, expansion of access to space, and facilitating economic growth, is not inherently baked into NASA's science-oriented mandate [1]. According to NASA's FY 2022 Budget Request, budget dedicated to surface operations on the Moon amounts to 3% of NASA's budget (Tech Maturation, Cislunar Surface Capabilities, and Advanced Exploration Systems). Getting to the Moon and driving around its surface amounts to 23% of NASA's budget (SLS, Orion, HLS, and the Exploration Ground System [10]). The effectiveness of this spending is

questioned by NASA's Inspector General Office [11]. NASA is focused on the political objective of getting to the Moon, not on establishing an economy on the Moon, nor a sustained presence once there. Nor is the task of exploration or the creation of access a part of the military.

Critics of the space program abound. They have pointed out the lack of a clear vision, purpose, and organizational ownership of American expansion into space that has plagued the country since the start of the space program. In 1963, Erik Bergaust, a prolific science writer, founder and first editor of the first American trade journal dedicated to Missiles and Rockets, and official biographer of Wernher Von Braun lamented that

> "The nation cannot yet bring itself to a firm decision whether or not the exploration of space should be military or civilian—or a blend of both. The President and his advisers continue to resist the pleas of many influential authorities to push the program one way or the other. But Kennedy, like Eisenhower before him, seems to prefer a neuter [sic] endeavor, for which none of the vested military or civilian agencies can claim full parenthood [12,13]."

Bergaust covered concepts that the US Air Force and NASA had initially proposed for getting man to the Moon, including an Earth-rendezvous concept promoted by the Air Force and Defense Department. An Air Force "station" would be put into Earth orbit to which astronauts would initially rendezvous before transferring to the vehicle which would take them to the Moon. Other concepts considered by NASA included orbital fueling and orbital assembly along with boarding and connecting [13]. Bergaust thought that rendezvous and docking would ultimately be the key technology that would open the space domain:

> "When we become skilled in rendezvous and docking, we shall be able to employ it for many purposes. We shall be able to approach and inspect any object in space. Through rendezvous we shall be able to assemble and maintain manned and unmanned craft, refuel them, and even rescue astronauts in difficulty. The operational techniques will be available to carry out any task required in the national interest."

What Bergaust described in 1963 is fundamentally a sustainment node.

Establishing sustainment nodes will require deliberate investment in technologies that advance production, storage, and distribution. Those sustainment nodes will need to provide effective services to industry, commerce, space settlements, and eventually to the Space Force. Logistics and sustainment are dual use capabilities (the foundation of economics in peace and necessary for waging war). Establishing effective in-space sustainment industries should be considered part of the "peaceful strategic offensive [1]." The technical expertise that NASA is currently fostering in LSIC and the Artemis program should be prioritized by the government within a broader whole of government logistics and expansion plan. Producing maintenance parts, end items, food, propellants, manufacturing feedstock, and space vehicles in space rather than on Earth was science fiction in the 1960s. We are rapidly approaching maturation of these technologies and should not let them fall into the valley of death between science and acquisition [14]. They are necessary for establishing space power.

5.3 Space Power

The 2020 Defense Space Strategy defines space power as "The sum of a nation's capabilities to leverage space for diplomatic, information, military, and economic activities in peace or war in order to attain national objectives [15]." Dr. Brent Ziarnick takes a more straightforward approach, borrowing from "the simplicity and elusiveness" of Brigadier General William Mitchell's definition of air power. Ziarnick's General Theory of Space Power defines space power as "…the ability to do something in space [1]." Ziarnick divides the concept into two groups, a Grammar Delta, and a Logic Delta. These deltas are graphical concepts and are reproduced in Figure 5-1, with permission from Lt. Col. Ziarnick. The Grammar Delta establishes access, through the trinity of capabilities of production, colonies, and transportation. The application of those capabilities forms the Logic Delta, where the application is used for economic, political, or military purposes. The DIME model fits within the Logic Delta, merging the diplomatic and information aspects of national power into the political spire. The two deltas are connected at their apex, both requiring the capacity to act [1].

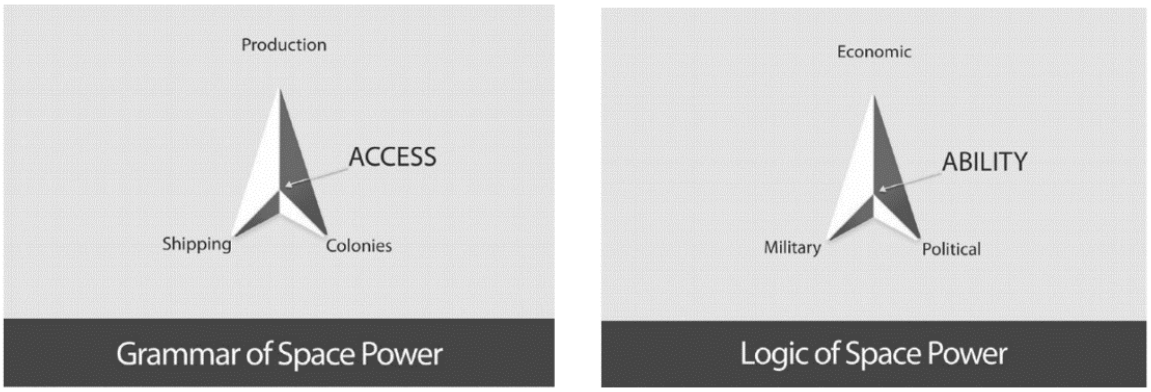

Figure 5-1. The Grammar and Logic Deltas of the General Theory of Space Power (From Developing National Power in Space: A Theoretical Model © 2015 Brent Ziarnick by permission of McFarland & Company, Inc., Box 611, Jefferson NC 28640.)

5.4 The Grammar Delta

The Grammar Delta is built up from three components: transportation capabilities, production capabilities, and colonial capabilities, these three items are combined in unique ways to generate access. Ziarnick illustrates the model by considering a single remote sensing satellite as being composed of all three elements: a sensor, which takes pictures (production), a satellite bus which stores and protects the image and data (colony), and the transceiver which sends the image and associated data through the electromagnetic spectrum to a receiving antenna (transportation [1]).

5.4.1 Production

The space resources field is dedicated to the application of science and technology to survey celestial bodies to identify resources, to create and apply technologies to profitably extract and transport resources to customers, and to clearly identify and advertise the use of the product or service created from the resource (thereby establishing demand throughout the value chain). Production primarily includes the extraction of minerals, volatiles, and energy from space sources, while services include manufacturing, sales, servicing, and assembly. Extracted resources vary by origin (celestial body, including the Sun's energy), state of matter (solid, liquid, gas, plasma), and man-made or natural in origin. Power can be generated by capturing solar energy with solar panels, or through chemical production (combustion or reverse electrolysis), or nuclear fusion or fission. Information products include such things as remote

sensing data, block chain verification of financial transactions and digital designs, secured and unsecured communications, timing and navigation data, and shared positional broadcasts such as used by the aviation and maritime industries. Though extraordinarily important, information products will not be addressed here. The focus here is on the extraction and production of materials and energy, especially those available on the Moon.

In 2016 Paul Spudis told the world that our nearest neighbors, the Moon, is the most convenient and important source of construction materials, of water and gasses for life support and propellants. Spudis and several researchers, famous within the ISRU community, have been publishing earnestly on the topic of ISRU resources on the Moon and asteroids since the 1980s [16,17,18,19]. Spudis identified the Moon as the best first step, over near-Earth asteroids, or any other celestial body further from Earth. The Moon will enable sustainable and expansive exploration and should be the first step in developing and proving ISRU technologies, and technologies for further utilization throughout the Solar System.

> "The Moon is close and easily accessible at any time and is amenable to remote operations controlled from Earth, in near-real time. We should go to the Moon first to learn the techniques difficulties, and technology to conduct planetary resource utilization by manufacturing propellant from lunar water. Nearly every step of this activity, from prospecting and processing to harvesting, will teach us how to mine and process materials from future destinations, on both minor and planetary-sized bodies. Learning how to access and process resources on the Moon is a skill that transfers to any future space destination [20]."

NASA appears to have listened. In 2014 NASA's strategic goals excluded a return to the Moon but remained focused on the asteroid redirect mission [21]. By 2018, NASA's position had shifted to expressly include returning to the Moon "for sustainable long-term exploration and utilization [22]." Strategic goal 2 used similar arguments to Spudis: that the Moon serves as "a training ground… to strengthen our commercial and international partnerships…" and to test "…technologies and techniques to keep humans safe, healthy, and productive… [22]" The Artemis Program and the 2020 Artemis Accords further prioritized a return to the Moon, emphasizing the need to stay and live off the Moon and utilize space resources [23]. Support for this program has remained strong in the second year of the Biden administration as evidenced by

the fiscal year 2022 NASA budget request: $26 Billion, representing an increase of $2.2B over the 2020 budget and a $1.5B increase over the 2021 budget, a nearly 7% year over year increase [10,24].

The portions of NASA's budget that address concerns important to production may include more than $4.3 Billion, representing 16% of the overall budget. $3.2B is dedicated to planetary sciences, which is further allocated to Lunar Discovery and Exploration ($0.5B, inclusive of the VIPER south pole lunar rover that will conduct physical prospecting for water and other volatiles), The Mars Sample Return Mission and Mars Ice Mapper ($0.7B), a NEO Survey ($.1B), and the continuation of discovery and new frontier missions ($1.9B [10,25]). These missions include Lucy which will explore the Trojan asteroids of Jupiter; Psyche, destined for a metal rich asteroid of the same name; and Dragonfly, which will fly in and sample the atmosphere of Saturn's moon Titan [26,27,28]. Additional budgetary items that may be beneficial to developing production include $0.5B dedicated to Tech demonstrations which, among other things include the on-orbit servicing assembly and manufacturing (OSAM) missions, Cryogenic Fluid Management and transfer, Fission Surface Power, and Solar Electric Power. Another half billion is dedicated to furthering Commercial Lunar payload Services (CLPS) missions, which delivers science payloads to the surface of the Moon, payrolling commercial delivery. Only a few of these payloads have prospecting applications, though several feature lunar regolith science sampling, mapping, or roving capabilities. The combined capability may provide insight into the selected landing sites, though the payloads are not uniform from CLPS mission to mission (and one CLPS mission will deliver the VIPER rover [29,30,31]). The final set of funding that can clearly be identified as related to prospecting and production is $0.1B earmarked for Advanced Cislunar and Surface Capabilities. This funding is meant to be used "to conduct risk reduction studies to develop strategies and identify technologies for lunar sustainability and future human missions to the Moon and Mars [10]."

Lunar sourced products include water, volatiles (primarily carbon, hydrogen, helium, and nitrogen), lunar regolith and pure or lightly processed metals. Metals can be extracted from Lunar regolith, through molten regolith electrolysis, carbothermal reduction, solid membrane and molten salt-based electrolysis, hydrogen reduction, and electromagnetic thermal baking [32]. Metal products that can be extracted from Lunar regolith include silicon (at up to 99.999% purity

as claimed by Elliott Carroll, CEO of Lunar Resources for low TRL demonstrations with simulants), iron, aluminum, magnesium, calcium, and titanium [33]. Oxygen is released when the minerals in the regolith are reduced. The relative mass percent and mineral compositions vary between highland and mare soil. As the spatial fidelity of prospecting (both remote sensing and in situ sampling) improves the knowledge of the relative elemental abundance and availability of ores will increase. As experience is gained through extracting these elements, the power requirement knowledge of the power requirements will also increase.

Most of the elements found on Earth can be found on the Moon, with a few exceptions [34,35].

> "…less abundant elements could also be extracted, such as Na, K, Sr and Ba from plagioclase and potassium feldspar, and Mn and Cr from pyroxenes. Chromium might also be recovered from spinel, found in mare basalts. Finally, [Potassium (K), Rare Earth Elements (REE), Phosphorous (P), Moon terrane characterized by incompatible elements] KREEP material and phosphate minerals may be a useful source of incompatible trace elements, such as: alkali and alkali-earth elements, the Rare-Earths, B, Zr, Nb, Sn, Hf, Ta, and radioactive elements such as U and Th [34]."

Utilization of pure elemental metals on the Moon may not be as important as it is to high tech manufacturing on the Earth. Instead, it will be most important for early construction and manufacturing needs on the Moon. Research into lunar manufacturing includes utilizing raw lunar regolith simulants under vacuum conditions. These includes sintering lunar regolith into various structures and shapes (extrusion and more traditional additive manufacturing) and establishing geopolymer cements [36,37,38]. Unrefined sintered lunar regolith is suitable to sustain compressive loads. With the addition of rebar during the sintering process, such as iron, tension loads could be incorporated [39]. Utilization of ISRU for construction is necessary to make a permanent and expansive mission to the Moon affordable [40].

More advanced manufacturing techniques and recycling processes have been explored for the fabrication of tools, sheet metals, rods, and rocket bodies, out of a variety of materials, including metal, ceramic, and plastics, and manufacturing techniques, including additive, subtractive, ink tracing, and pick and place for circuit board manufacturing [41,42,43]. In space

demonstration of these techniques has been largely limited to the ISS. It is presumed that if demonstrations can work in both one-gravity and micro-gravity environments then they may be able to work in lunar gravity [42]. Multiple welding techniques have also been investigated extensively. Their use as a material joiner could be used to assemble larger structures and facilitate repair. This will further reduce the amount of mass needed to be launched and increase the ability of designs to exceed the size and constraints of launch fairings [44].

In-space manufacturing and assembly are predicted to be the future of astronomy. The James Webb Space Telescope (JWST) demonstrated the limits of what can be launched on a single vehicle. Cost overruns and delays were attributed to its system complexity, excessive optimism, and human error among other things. The JWST was not designed to be serviced, and thus had a seven-year ground test program to ensure it performed on orbit [45]. It could be considered an oversight of the JWST program to not have had the servicing ability, however, work and designs for the JWST predated the return to the Moon concepts and the Lunar Gateway, with designs complete in early 2011, with a planned launch in 2018 [46]. NASA's 2019 In-Space Assembled Telescope (iSAT) study found that not only is the assembly of a large high-tech structure feasible with investment in the appropriate technologies, it would also result in savings over a single launch approach [47,48].

The iSAT whitepaper asserted that consideration of in-space assembly (ISA) of telescopes has been reviewed before, but since the 2010 decadal review the ISA paradigm has advanced based on a review of "…the following key capabilities: (i) modularity, (ii) multiple launches, (iii) Rendezvous and Proximity Operations (RPO), (iv) CDVs, (v) robotic assembly, and (vi) in-space verification and validation (V&V [48])." Three of these technology areas were considered to have a high readiness level to support ISA (Launch vehicles, RPO technologies, and Cargo Delivery Vehicles (CDV)), Space Robotics was split into two sub-categories, with hardware being also found to have a high readiness level, while software was found to have a medium readiness level. In-space modularity and V&V processes were found to have a low readiness level. A separate Federally Funded Research and Development Center, the Institute for Defense Analyses (IDA) Science & Technology Institute release a report in 2017 on On-Orbit Manufacturing and Assembly of Spacecraft that reached similar conclusions. They identified several challenges with both manufacturing (at the time of the report only plastic additive

manufacturing had been demonstrated in space), and assembly, but believe fundamentally, the groundwork has been laid for the government to actively invest in related OSAM technologies [49]. Other reports have substantially supported the need for conducting on-orbit servicing and in-space refueling, including a congressionally mandated NASA study to investigate the state of in-space servicing.

> "Its conclusion [was] unequivocal. Viable plans can be put into place to develop a meaningful on-orbit satellite servicing capability, allowing us to achieve our key ambitions in space using today's technology and with current and projected launch systems [50]."

As NASA and its partner companies refine their vision for what is technically and fiscally possible, they will be able to home in more clearly on what they want to do and what they must do. Emerging demand for products and services includes electrical power, metals and regolith for construction, and standardized surface transportation. There is already consensus for the need for production of electrical power across the Moon, including the establishment of global (lunar globe) power transmission infrastructure. There is also consensus on the need for common surface infrastructure, including standardized interfaces facilitating the transport and exchange of goods [51].

5.4.2 Transportation

Transportation is the second spire of Ziarnick's Grammar Delta. Transportation is typically overlooked when considering ISRU, but the transport of goods, products, and services to customers is critical to closing the business case of a space resources plan. Transportation is essential to the establishment of an initial foothold on the Moon: delivery of the excavation, processing, and manufacturing machinery is required before excavation, processing or manufacturing can begin. The transportation of material between points in the excavation, processing, and manufacturing portions of the value chain must also be planned for. Transportation services could be analyzed by form (technology) and function (the specific service they provide). Specific services include space launch from Earth, space tugs for transportation between celestial bodies, space launch and landing to and from the Moon and other celestial bodies, and surface (land, air, and marine) transportation on celestial bodies other than the Earth. Technologies include traditional propulsive rockets (chemical, electric, nuclear

thermal) which travel with their power source and advanced propulsion systems, such as laser propulsion, which relies upon beamed energy sourced remotely: each of these systems utilize energy to heat up and accelerate their propellant, and thus eventually require refueling or refilling [52,53]. Electromagnetic Launch of ice-water as a propellant from the lunar (or Earth's) surface to and from Lagrangian points would be an extremely useful and complimentary technology—though "a secondary means will be required to slow the payload down before intercepting its moving target [54]." As such, the retrograde of the empty container, its propulsion system and other systems, would also be required to enable sustainable reuse.

Rapid reuse coupled with complimentary intermodal transport is as important as the efficiency, thrust, and specific impulse of propulsive technologies. Enabling reusability, inclusive of on-orbit and ground (Earth, Lunar, Martian, etc.) based refueling coupled with propellant production and effective logistical forecasting reduces the overall cost of a system. This, in turn, grants access to more sites within the solar system when coupled with the establishment and emplacement of resupply points co-located at common destinations and sources of propellants or other important products (colonies – in the General Theory). Most importantly, interconnected transportation systems should be developed within the larger context of cooperation surrounding the standardized exchange of cargo and propellant. Parallel to the transport of cargoes and propellants are the transport of humans, as they have significantly different engineering design and en route sustainment needs. While the clear need for the transport and standardized exchange of propellants has already been discussed, the intermodal exchange of goods in the context of space has not.

The modern intermodal container, or shipping container, derives its origins from use in railroad cars as early as the 1830s [55]. It was developed to standardize and increase the efficiency of every aspect of the movement, inspection, and security of goods from point of origin, through international customs, and be usable across roads, rail, and sea. The international logistics system and globalization is intertwined with the history of the intermodal container [56]. The economic benefit of standardizing the shipment of goods was summarized in a 1980s supreme court decision:

> "Because cargo does not have to be handled and repacked as it moves from the warehouse by truck to the dock, into the vessel, then from the vessel to the dock

> and by truck or rail to its destination, the costs of handling are significantly reduced. Expenses of separate export packaging, storage, losses from pilferage and breakage, and costs of insurance and processing cargo documents may also be decreased. Perhaps most significantly, a container ship can be loaded or unloaded in a fraction of the time required for a conventional ship. As a result, the unprofitable in-port time of each ship is reduced, and a smaller number of ships are needed to carry a given volume of cargo. (NLRB v. International Longshoremen 's Association 1980 [57])"

The shipping container impacted maritime traffic so much that cargo ships are measured and procured in twenty-food equivalent capacity (TEU); ships become obsolete when new cargo ships are procured with greater TEU capacity [57]. in 1990, ships were being ordered with 5,000 TEU capacity. In 2021, ships with nearly five times that capacity have already been built [58]. The maritime, rail, and road networks have had the opportunity to mature since the intermodal container was standardized by the International Organization for Standardization (ISO). The aviation industry had not standardized its shipment containers, or rather, has too many competing standards [59]. Meanwhile, the space industry's equivalent to standardized shipping container standards are essentially non-existent. The closest comparison would be launch vehicle adapters for primary satellites, EELV Secondary Payload Adapter (ESPA) rings and canisterized dispensers for secondary payloads. There are a limited number of standards that have been developed, including an Air Force created a standard for the EELV launch program. Several satellite manufactures demand their own adaptor standards, but none of these standards compares to the ubiquity, versatility, and utility of the shipping container.

Supply specific vehicles that visit the ISS demonstrate greater similarity to shipping containers. These supply vehicles include the American made Cygnus, Russian Progress, European Automated Transfer Vehicle, and Japanese H-II Transfer vehicle. All of these are expendable. Astronauts spend at least four hours unloading the transfer vehicles, and then still spend a few hours a day doing stowage operations (including finding lost items, organizing cargo transfer bags, and loading the transfer vehicles with trash [60]). After one use, they are self-disposed of in Earth's atmosphere, along with astronaut's trash, rather than being designed to with other future uses in mind. The Launch adapter should be the same adapter used to connect

these transfer vehicles in space; this could have enabled the ever expansion of the ISS: as modules wear out, they could be disposed of after many years, or they could be recycled or repurposed on orbit. An alternate reuse would be to reutilize them as space tugs, for use in space only. The ISS's docking and interface standards preclude large items from being loaded or unloaded onto the ISS. This not only prevents large items from being transported to the ISS, or from allowing the interfaces to enable structural expansion of the ISS, it requires the astronauts to have to load and unload the ISS. Astronaut time is a precious resource. The ISS interface standards are the most successful interface made, but it is inherently limiting [61,62]. The low total volume of anything shipped into space and the absence of long-term plan for the use of the ISS (beyond just science and political messaging) has allowed this lack of a true standard to develop. Multiple companies offer multiple standards. Loading and prepping launch vehicles is time consuming and limits the capital use of a transport vehicle. In this way, the state of In-space transportation of goods is closer to the days of horse and carriage than the advent of the railroad: lessons learned during that period should not be re-learned.

The first time the railroad was integrated into warfare in Europe, in the Franco-Prussian War of 1870-71, it did not contribute to its fullest potential. Charles Ibry had just developed railroad scheduling two decades before; best practices were not widely shared or adopted [63]. Keep in mind radio communications would not be adopted for another 30 years. Poor coordination between sources of supply and supply terminals resulted in terminals being unable to unload trains before the following train arrived. A shortage of labor prevented rail cars from being unloaded in a timely fashion, compounding a general inability to transfer goods from the train depot for final mile delivery (onto horses and carriages) causing secondary congestion. Further disruptions were caused by local commanders repurposing rail containers for onsite storage [64]. The mismanagement of the railroad, in spite of it featuring prominently in Moltke the Elder's (the Chief of Staff of the Prussian Army) planning, led the Prussians, during their occupation of France to "…live off the country much as Napoleon's soldiers had done seventy years earlier [64]." That is, local commanders lost faith in their supply chain and quartered their soldiers with French farms and families. The Prussian Army repurposed itself to collect food from the countryside. This should illustrate the importance of managing all portions of a transportation system, during every phase of a campaign.

NASA has invested in the first parts of the space railroad, or space superhighway: the Space Launch System (SLS) and Orion, the Lunar Gateway, the Human Landing System (HLS), and a Space Exploration Vehicle (manned lunar rover). These systems represent Earth launch (combined with space tug), Lunar orbital staging (for logistics and communications), lunar landing and ascent vehicles, and surface transportation. The Lunar Gateway, when established, will be discussed in the next section on colonies. Communication assets include the Tracking Data Relay Satellite System (TDRS) communication satellites, from NASA's Space Network, and their ground stations. NASA's first planned human landing, Artemis III, will have astronauts on the Moon for under a week living in and conducting EVAs from the HLS [65]. They will have some science payloads prepositioned for them on the Moon, but are taking all needed supplies and facilities with them, in the HLS.

The competition for the Human Landing system, included SpaceX's Starship, the National Team, and Dynetics. Following competition and subsequent litigation, SpaceX emerged on 7 July 2021 with the only contract for the initial (manned) demonstration following the government accountability office ruling [66]. NASA's justification for selecting SpaceX was based on cost and other features, including Starships' ability to loiter in lunar orbit for 100 days prior to Orion docking with it, its ability to land and launch a significant amount of mass (cargo and crew), the potential ability of Starship to land without disturbing lunar regolith, and its propellant mass margins. SpaceX's Starship so far exceeded NASA's original requirements that NASA's source selection authority, Kathryn Lueders, wrote:

> "SpaceX's capability will support the delivery of a significant amount of additional hardware, including bulky and awkwardly shaped equipment, for emplacement on the lunar surface. This has the potential to greatly improve scientific operations and EVA capabilities [67]."

SpaceX's Starship has the potential to become the de facto standard for shipping supplies. It is limited in its ability to get tonnage of supplies beyond LEO without on-orbit refueling. in the near future due to the cargo capacity (volume and mass), and frequency of travel. Currently, the Starship is at least illustrated to include its own material handling equipment (MHE)-featuring a platform that is lowered to the Lunar surface to off-load cargo and astronauts [68]. Just like the giant containerized cargo ships and ports on earth, it is likely that Starship will invest in lunar

spaceport MHE capabilities to off-load the costs of launching and transporting MHE from Earth [57].

Lueders further praised SpaceX in the areas detailed in the sustainability technical focus area, addressing habitation capability, number of airlocks, the ability to support extra vehicular activities, other surface logistics capabilities, and technical commonality with other systems including common manufacturing capabilities and system reusability.

> "The collective effect of these attributes is that SpaceX's initial lander design will largely obviate the need for additional re-design and development work (and appurtenant Government funding) in order to evolve this initial capability into a more sustainable capability [68]."

Elon Musk appears focused on transportation systems and appears to view them from a system of systems perspective. This is demonstrated by his intent to disrupt transportation and communication systems of all types on Earth, from cars (with Tesla and Tesla's efforts in autonomous driving) and highway systems (with his boring company, and forays into the hyperloop) to the telecommunications and space industry with Starlink coupled with SpaceX's launch capabilities [69,70]. In Elon Musk's most recent Starship update, 10 February 2022, he stated that his goal for Starship is full and rapid reusability. By having the Starship booster return immediately to the landing pad, he sees the potential to refuel it and use it to launch another Starship (that is already on standby) within an hour. Musk continued to explain that each starship then has the potential to be launched every 6 to 8 hours (or used three times per day) and each booster could be reused every hour. Furthermore, by launching multiple Starships near simultaneously and utilizing one Starship to refill the other Starship he claims he will be able to provide enough propellant to enable the first starship to get to the Moon or Mars [71].

NASA's final transportation challenge is to enable surface transportation on the Moon. In the Artemis plan released on September 2020, commentary about surface transportation is limited to the potential of the lunar terrain vehicle being delivered before the Artemis III manned landing, and to future transportation expansion with the habitable mobility platform [65].

> "The three primary mission elements of Artemis Base Camp are: The LTV that can transport crew around the site; the habitable mobility platform for long-duration

> trips away from Artemis Base Camp and the foundation surface habitat will enable short-stays for four crew on the lunar South Pole. Combined with supporting infrastructure added over time such as communications, power, radiation shielding, a landing pad, waste disposal, and storage planning – these elements comprise a sustained capability on the Moon that can be revisited and built upon over the coming decades [72]."

NASA acknowledges the difficulties of transportation on the Lunar surface, comparing the Shackleton Crater to the Washington DC Metro area, but in the publicly released plans, NASA is very vague about how they plan to expand surface capabilities beyond the initial manned landing [72]. NASA has identified the need for both terrain navigation and the establishment of robust lunar wide communications to facilitate surface transportation [72].

Design Reference Missions (DRM) and Cargo Lander-Cargo Design Reference Missions (CL-CDRM) are concepts that have not been finalized or officially announced but have been released through NASA contracting processes. These include six DRMs for crewed missions of lengths of up to 6.5 days, 12.5 days, and 31.8 days, with options to land at the south pole Artemis Base Camp, or at a to be determined alternate location. A contingency option bypasses Gateway to rendezvous with Orion directly. DRM-1 is the 6.5 day stay on the Lunar surface and appears to be analogous to Artemis II. DRM-2 is conceptualized to be 31.8 day stay on the Lunar south pole region. The extended duration mission, DRM-2, specifies that "[t]he HLS, the mission consumables, and the mission equipment will be launched by the HLS partner from Earth to NRHO… Once on the lunar surface, the crew will prepare to perform transfers to other pre-placed habitable elements to live in for the duration of their surface stay [65,72]." During most of DRM-2, the HLS will be in an uncrewed standby mode, serving as a lifeboat, but not providing primary life support functions. Upon mission completion, HLS will return to the Lunar Gateway in NRHO. DRM-3 will be a short duration lunar sortie to a "high-value target sites outside of the South Pole [73]." DRM-4 is a variant of DRM-2 featuring crewed arrival to the Gateway before HLS arrival, with an extended 100-day occupation of HLS at Gateway prior to a 31.8 day south pole Lunar sortie.

The two CL-CDRM missions address the emplacement of the foundation surface habitat and pressurized rover, but do not address specific targets on where to emplace them or how to

organize them. Circular error probable or any specific landing considerations (other than ensuring a near-level surface orientation is achieved) appear to be omitted, at least from the Human Landing System Program System Requirement Document (Draft, 30 Aug 2021 [73]). There is no public long-term vision for how the emplacement of surface capabilities will be organized and eventually cultivated into a space colony.

The first space colony on the Moon may more resemble the beachhead at Normandy or an airport than a village: it will have to have as its primary purpose managing the movement of cargo and people. It will need to facilitate the movement of products, construction material, and machinery to fabricate or set up habitats, laboratories, food production and other life support facilities. It will need to consist of landing and launching facilities with propellant storage, receiving bays, integrated with surface transportation for further distribution onto the Moon. The better planned and scheduled it is, the better the flow and throughput. A space colony should have a master plan that forecasts the expansion of its facilities enabling partnering with local government, industry, and businesses, with a minimum of a twenty-year time horizon, similar to those held by Airports, which are typically commercially owned, for-profit businesses [74].

5.4.3 Colonies

Colonies are the final third of the Grammar Delta and can represent both a sink and source node for products and resources. Colonies store and protect people, equipment, and supplies from the environment and from hostile entities. They should be conceptualized, sized, and placed by the types of function they are designed for according to the General Theory's Logic Delta, to be discussed later. Functions can include human sustainment but could also be purely robotic aggregation and distribution points, or even factories (themselves a fractalized version of the triad aggregating, producing, storing, and then transporting products and data).

Colonies in Mahan's time (the 19th century) were still what we would think of today, dismissively, as banana and rubber plantations. They were sources of resources necessary for feeding the country, necessary to maintain industrial production. They provided a source of cheap labor, and markets for finished products. Ownership of colonies provided secure logistics nodes and ensured access to the goods they produced. According to the American historian Dr. Daniel Immerwahr, it was not until the end of WWII that America decided it no longer needed colonies, in the traditional sense.

America found itself with options and decisions to make in 1945. Should it continue to control the Philippines? Should the US annex or grant statehood to Japan and Iceland, or give them their independence? What about other territories the US captured from Japan [7]? America bypassed the Island of Formosa, but it captured Okinawa, instead choosing to defeat Japanese capabilities, especially logistical ones following MacArthur and Nimitz' philosophy of "… hit 'em where they ain't—let 'em die on the vine [7]." America gave up its colonies for two reasons: one, colonies were unpopular (for both the American Soldiers, who wanted to go home, and the occupied, who had been promised freedom), and two, the means of production had evolved and the means of projecting force had drastically changed. These considerations extended to considerations for colonizing the Moon "Whereas colonizers in the nineteenth century had annexed territory with pride, by the 1960s they understood that forthright imperialism risked infuriating the increasingly powerful Third World. By then, even taking the uninhabited moon seemed as if it might kick up trouble [7]." Immerwahr continues to explain on the demise of colonies:

> "It may help to look at the decline of colonialism from a different angle, focusing not just on supply but on demand as well. The worldwide anti-imperialist revolt drove the cost of colonies up. Yet at the same time, new technologies gave powerful countries ways to enjoy the benefits of empire without claiming populated territories. In doing so, they drove the demand for colonies down [7]."

Rubber was a key ingredient in industrial life, and in the American way of war. When Japan attacked Pearl Harbor and then proceeded to take much of Southeast Asia it cut off 97% of the US's supply—threatening Americans' way of life and the American Way of War, and the Country's collapse [7]. This problem prompted the government to invest in chemical engineering solutions, Manhattan Project style, to replace colonial rubber with synthetic rubber. This feat happened for nearly all colonial products that America was dependent upon, and also resulted in the tremendous expansion in the use of plastics [7]. "Together with innovations in chemistry and industrial engineering, the U.S. mastery of logistics would diminish the value of colonies and inaugurate a new pattern of global power, based less on claiming large swaths of land and more on controlling small points [7]."

The difference between sea transportation and space transportation is cost. Sea transportation is the lowest cost transportation available, cheaper than transportation on road, rail, or air travel, and most certainly still cheaper than point-to-point suborbital flight [75]. This means that the production of goods at foreign ports—at distant spaceports—becomes necessary and likely more cost effective. Dr. Sowers established that a kilogram of water extracted from and then purchased on the Moon is significantly cheaper than a kilogram of water delivered from Earth [76]. He set a price point at which United Launch Alliance would pay for water while he was Chief Scientist, but that same cost tradeoff between local production and transportation cost will play out for nearly any demand item required on the Moon.

Demand for products launched from Earth and consideration for what industry can produce on the Moon for use on the Moon and in space, should be aligned in a "Lunar Spaceport Master Plan." The spaceport master plan would be developed by the commercial owner of the business in coordination with national and international law, tenant launch providers (customers), local industry (products and services seeking transportation services), and the local government (NASA, or the Office of Insular Affairs [77,78]). If an American business, they would need to secure terrain use rights and corresponding safety zones based on the Artemis Accords, international treaties the US is subject to, via coordination through the FAA's Office of Space Commerce (which manages space ports on Earth [79]). It well might not be possible for a lunar spaceport to secure a tenant "spaceline," like airports secure airlines. NASA, the ESA, China, and Russia have all announced plans to establish lunar colonies, but they are all planning to do it as sovereign entities, rather than foster their own commercial space industry in the image of aviation. To fully foster the commercial industry, the government must allow and encourage industry to lead, run, and develop spaceports on the Moon, while advertising how they plan on spending and purchasing capabilities. The airport industry depends upon government forecasts, from the international level to the regional level.

Aviation and airport transportation systems are coordinated internationally through the International Civil Aviation Organization (ICAO) which was established in 1944 by the Chicago Convention to: promote orderly and peaceful growth of civil aviation, aircraft design and operations, the development of airways, airports and air navigation aids for international travel; promote safe, regular efficient, and economical air transportation; and prevent economic waste,

unfair competition, and discrimination between states [80]. At the national level, the FAA produces a National Plan of Integrated Airport Systems, which is a 10-year capital investment plan that advises but does not direct commercial entities [74]. Regional level planning is conducted by port authorities, such as the Port Authority of New York and New Jersey. Port authorities can plan at the airport hub level and coordinate traffic among multiple airlines for the distribution of traffic and capital planning. These authorities often have planning authority over other modes of transportation that can be planned in coordination with, such as rail, highway, and seaports [74]. Each US State issues a state aviation system plan as well under the guidance of the FAA. These plans have a 20–30-year time horizon forecasting such things as land acquisition, planned runway improvements, the construction of new terminals, navigation aids, and building construction. Collectively, these civil government partnership planning documents inform the economic situation of an airport master plan [74]. Additional information informing the airport master plan includes information about regional and local feeder airports, the airport's historic usage statistics, airport related land use and local aeronautic activity, as well as socioeconomic factors. The airport layout plan is the graphical overlay of the runway and other important structures including aprons, taxiways, blast pads, safety areas, buildings, navigation aids, and other manmade structures. It includes important natural terrain features and identifies land reserved for future expansion, both for the airport itself and for the surrounding industry and government use. Other plans support the airport master plan, including the environmental management plan and the financial plan [74].

When translated to the Lunar environment a spaceport master plan will need these same inputs: feeder spaceport traffic estimates, clear national and local governance and support, and integration with, in this case, space traffic management plans, communication plans, and space tourism and colonization plans. Differences between airport or even Earth based spaceport operations and management is going to be both operational (such as the sourcing of ISRU based propellants, and critical life support volatiles such as oxygen, nitrogen, and water, as well as cryogenic management), and structural (addressing the lunar space environment: solar and thermal cycling, the radiation environment, and lunar dust mitigation).

NASA, with the Artemis program so far is only expressing interest in a temporary human presence on the Moon, up to 31.8 days [73]. In the Artemis plan, NASA indicates that it may be

interested in stays of up to 60 days in the near term, with only stated aspirations for longer missions [65]. For short term missions temporary inflatable shelters, potentially reinforced with regolith will suffice, but may need to be replaced if they are unable to survive the Lunar environment between missions while unoccupied [81]. The Foundation Surface Habitat is envisioned as a prepositioned shelter landed at the base camp ahead of astronaut arrival, for use of up to 60 days, and will be emplaced in the early 2030s [82]. These temporary shelters should be used as part of an expansion program to establish more permanent infrastructure.

NASA only forecasts a budget five years out, and as a government agency is constrained by Congress passing a budget [10]. A longer term forecast on what the Artemis base camp will expand into is unrealistic until around the time that the base camp is established. Any expectation of a master plan detailing the physical layout of the base camp, plans for expansion, plans for allocating land to industry to meet their own needs is premature, but should be considered as soon as feasible. The planning considerations that NASA has detailed for the base camp are limited to science objectives, found in the Artemis III Science Definition Plan, a 6.5 day stay on the Lunar surface.

In the Artemis III Science Definition Plan NASA identified four critical, enabling capabilities. The first capability is long lived power and communications that can survive the lunar night and operate in permanently shadowed region, with lasting utility for leave behind science experiments. The second capability is the pre-deployment of science assets, for use by astronauts after landing or for independent or supporting science. Third, the science team recommended the astronauts get a mobility asset, and fourth the establishment of cryogenic storage capabilities to preserve near lunar conditions during sample return. Cartographic considerations included improved resolution of digital terrain and elevation data as well as establishing a time and location coordination system across science elements and astronaut monitoring activities. Enhanced geological mapping data was also requested by the science team [83].Landing site selection, the Science team determined, was outside their scope:

> “The final Artemis III landing site will ultimately be selected on the basis of a variety of factors, some of which are presently unknown, including the capabilities of the HLS vehicles, the final launch window of the Artemis III mission, the availability of orbital data sufficient to inform site selection and landing site safety

determinations, landing sites of surface exploration precursor missions, and architectural decisions relating to location of the Artemis Base Camp [83]."

The Artemis Base Camp and its expansion into a formal human outpost on the Moon is not the only potential version of a space colony. Entirely unmanned industrial outposts connecting lunar mining, surface transportation, and storage to launch facilities is another option. Colonies fundamentally represent nodes in a transportation system. Takuto Ishimatsu, in his dissertation, "Generalized Multi-Commodity Network Flows: Case Studies in Space Logistics and Complex Infrastructure Systems" described space logistics from a network perspective. Each node, in his model represented either a mass-origin node, a mass-transit node, or a destination node, while edges represented transportation modes, and thus represented a cost [84]. Ishimatsu's work focused on optimizing multi-commodity flow to sustain a NASA mission to Mars, incorporating Lunar ISRU and Martian ISRU for sustainment, proposing the establishment of propellant depots in GTO and Deimos Transfer Orbits (DTO [84]).

Orbital depots were recommended by the original 1969 space task group for the purpose of refueling space vehicles and facilitating onward transport from low Earth orbit [85]. Aircraft and spacecraft design are centered around minimizing mass. For spacecraft it is based on the rocket equation. For aircraft, the fuel mass fraction dominates preliminary sizing estimates [86]. The insistence of making aircraft non-mission specific decreases their ability to perform each mission. This results in penalties that must be carried over in every other stage of the mission. Flying boats captivated the imagination of early aviation enthusiasts, but these designs impact everything from lift to drag ratio to overall mass, making them useful only in niche markets where it is uneconomical to build airports [87]. The Kennedy administration elected to bypass the concept of an orbital refueling depot in the early sixties due to political exigency. Orbital refueling coupled with Earth rendezvous was considered and promoted by the Air Force and NASA at the time [13]. A space launch vehicle should not also be a deep space transport vehicle and a reentry vehicle: vehicles should be designed with specific missions in mind to minimize mass, increase reusability and lower the long-term system cost.

From this perspective, the ISS or its commercial successor should be repurposed as a LEO gateway: humans and items that can only be manufactured on Earth can be launched to the ISS. From there they are transported from there to other destinations, such as the envisioned

Lunar Gateway in the Artemis program, or to rendezvous with a Mars cycler [88]. Once outside of Earth's gravity well, transportation in the cislunar system dramatically falls off—it is waste to continually return mass launched to the bottom of the gravity well.

> "A Lunar Gateway Station in the vicinity of the lunar L_1 libration point (between the Earth and the Moon) was proposed as a way station for transfers into the solar system and into the Earth-Sun halo orbits. This is enabled by a historical accident: the energy levels of the Sun-Earth L_1 and L_2 points differ from those of the Earth-Moon system by only 50 m/s (as measured by maneuver velocity [89])."

5.5 The Logic Delta

The Logic Delta focuses on how and why space capabilities are used. Production, transportation, and colonies enable access. They build up and combine to create abilities that are ultimately used to generate political, military, or economic power. Admiral Mahan asserted that "military considerations are accessory and subordinate to the other great interests, economic and commercial, which they assure and so subserve [1]." He should also have asserted that political considerations also subserve economic and commercial interests. Only economic power is self-sustaining. Utilizing access for political or military ends consumes abilities, unless they are used as part of a strategy that promotes and protects space commerce, and the businesses generating wealth and value.

5.6 Space Power Development

The allocation of NASA funding provides insight into how NASA prioritizes advancement of science as an end unto itself, rather than to advance the interests of the commercial industry. In the Regolith to Rebar workshop, hosted by the dedicated excavation and construction topic group of the Lunar Surface Innovation Initiative and held February 23, 2022, NASA attempted to link up aspiring providers of metals to aspiring providers of construction and manufacturing services. There was a lack of understanding of how to close business cases. NASA is seen as the ultimate customer at the end of the value chain purchasing the final services and products (whether the purchase of constructed facilities, tools, or other products). The service and construction providers were then unable to give metal providers a clear idea of what they wanted, though one of the CEOs present at the workshop claimed to be able to close several business cases with companies other than NASA, without providing additional examples or

specifics to the community at large. NASA did ask what the various commercial entities needed to be successful. Responses varied, but ultimately, they were interested in securing the ultimate customer at the end of the value chain: NASA.

Ziarnick details five methods for developing the space economy, based on economist Joseph Schumpeter's theory of economic development. The five methods are: 1) the introduction of a new good, 2) the introduction of new methods of production, 3) the opening of a new market, 4) the conquest of a new source of supply, and 5) the reorganization of an existing industry. Production of construction materials, maintenance materials, and consumables from space resources requires all five steps [1]. The impediment appears to be investment funding, space investments are considered high risk, and they generally have too long of an investment maturation period: investors want to see a return on investment in a meaningful time period to them. If the US government wishes to be serious about establishing a new market it will need to be the primary investor. Until a healthy economy is established, the venture will be the burden of the state.

The space economy, in terms of the space-for-space economy has not taken off-yet. As of 2021 95% of the space economy was still dedicated to the space-for-Earth economy, in spite of NASA and the Department of Commerce's Office of Space Commerce and other governmental organizations efforts at getting people to live and work in space [90]. Expanding the space economy for the purpose of increasing national power has only become the subject of the Nation's focus within the last few administrations.

The 2020 National Space Policy, created by the Trump administration, and so far, maintained by the current administration, lists two goals for the space economy. It states: "The Unites States shall:

> "Promote and incentivize private industry to facilitate the creation of new global and domestic markets for United States space goods and services, and strengthen and preserve the position of the United States as the global partner of choice for international space commerce…"
>
> "Extend human economic activity into deep space by establishing a permanent human presence on the Moon, and, in cooperation with private industry and

> international partners, develop infrastructure and services that will enable science driven exploration, space resource utilization, and human missions to Mars [91]."

The National Space Policy does not go so far as to call out which agency is tasked with doing these activities, however, by making it national policy (indicating it is part of the Nation's grand strategy), they become goals for subsequent department and agency planning, within the power of their legal and fiscal scope [92]. Actual activities are determined by funding, planning, and appropriation, and subject to congressional approval, not speech [93,94]. Space power will not grow itself, it must be actively fostered, without falling to a "heresy of space power [1]."

Ziarnick defined a heresy of space power as the substitution of grammar for logic. That is, grammar is the building up of capability, logic is the expenditure of capability. If a program is being sold as "developing or building political power" then they are trying to develop a political grammar—which is wrong. Past American space activities have fallen into this category of heresy of space power, including the Apollo program and the International Space Station (ISS). "Both [DoD and NASA] have neglected developing the common ability to operate in space that the General Theory suggests is the true fount of space power [1]." For instance, Ziarnick argues that the ISS was developed with an end goal of international cooperation rather than to increase access to space. The 1969 Space Task Group originally envisioned the space transportation system would include a space shuttle, orbital fuel depots, space tugs, and nuclear-powered deep space vehicles, and be utilized by both NASA and the DoD [1,85]. The Artemis mission may fall into this category too, if it is mismanaged.

NASA is arguably underfunded, and its founding charter makes pursuit of space commerce and space access for the purpose of developing an economy in space unnecessarily difficult. The philosophy of living off the land is forefront: NASA along with its partners are beginning to explore how to extract water and oxygen for human sustainment from Lunar regolith; how to build facilities on the Moon for Humans to live and work in from the materials present on the Moon; and determining how best to get astronauts to and from the Moon [65]. All of these concepts are still at an early, low-level, low technology readiness state, with limited research and development funding. Inclusion of the use of ISRU materials is omitted from the Artemis Base Camp plan [72].

What NASA lacks is a clear tie-in to the economics of space. It is not NASA's fault – they are bound by the Congressional legislation forming NASA: NASA's purpose is to pursue peaceful scientific inquiry and exploration [95]. They, like all government agencies, are not allowed to advertise or lobby on their own behalf [96]. At the time of NASA's formal creation America lacked a clear theory of space power—but its importance was not lost on the 1969 Task Group: they believed that one of the key returns from the space program was a "…non-provocative enhancement of our national security [85]." Space power as a theory languished in low Earth orbit since the end of the Apollo program—was it more like sea power, or air power, or something else entirely [92,97]? With the inclusion of the Moon and the rest of the Solar System, the application of Mahanian concepts of sea power to space power was able to flourish—you could have lines of communication connecting the Earth to the Moon, or to Mars. Brent Ziarnick points out that space power, just like sea power, is based on economics: trade centered around production, colonies, and shipping [1]. The purpose of space power is to generate more space power, more access to space: one must actively invest in the manufacturing of goods and services made from space resources (production); in the delivery of those products to where they are needed (shipping); and in the ability to store and distribute those products and services (colonies).

Space resources fits nicely within the grammar of Ziarnick's theory of space power and can be used to build upon that framework. It requires the effective application of logistics: forecasting the sustainment needs for "beans, bullets and bandages" across time, space, and purpose [98]. It is however, the space enthusiasts and their business plans that show the greatest potential for developing access to space.

5.7 The Space Enthusiasts

Dr. Ziarnick affectionately refers to non-state actors in space as space enthusiasts. They should not be taken lightly. These enthusiasts include power players: billionaires, investors, hedge fund managers, and entrepreneurs. They also include academics and science fiction authors as well as the consumers of science fiction and space news—that is, voters. Elon Musk has already expanded access to space at an unprecedented rate through his efforts (completed and planned) with SpaceX and Starlink. Other entrepreneurs include Rick Tumlinson and Daniel Faber who have shaped the scene on the Hill and in Silicon Valley by promoting asteroid mining

and spacecraft servicing. Jeff Bezos popularized the idea of off-worlding industrial production. Burt Rutan and Richard Branson believe in reusable commercial space travel. Bigelow and other have promoted space hotels and space tourism. Before them Gerard O'Neill created an inspiring vision of space colonies. The founders of Made in Space, and other early applications of advanced manufacturing for space should be included in this group. Science fiction authors have inspired the world, from writing about asteroid mining and ice shipping to space elevators and naval shipyards in space. These enthusiasts see that space has something to offer people. Space has a function; it has utility; it has value. This is the basis of a business plan: the value proposition. It is the basis of a space economy. The space enthusiasts will lead the way with their business plans.

5.8 Strategy and Logistics

When Mahan published his now famous 1890 book, The Influence of Sea Power Upon History, he saw that America was unprepared to defend its sea commerce, as "…its merchant service had disappeared, [and] the dwindling of the armed fleet and general lack of interest in it are strictly logical consequences [99]." He believed that commerce was going to compel the US to develop a Navy. The world interpreted his book as a need to secure sea commerce. His analysis of the history of sea trade and naval conflict and its ability to impact nations' relative power was read by powerful people who claimed to be inspired by the book. This list included Queen Victoria of England, Kaiser Wilhelm II (both of whom met with him after reading his book… both nations then built up their navies in preparation for World War I), the Japanese Naval Academy, and the future president Theodor Roosevelt, who, at the time was the Deputy Secretary of the Navy [1,7]. Roosevelt was so inspired by the book that he created the conditions for war with the Spanish Empire (undermining the Secretary of the Navy when he went took an afternoon off, and the President [7]). Less than a year later Spain recognized the independence of Cuba, sold the Philippines to the US for $20 million, and gave the US Guam and Puerto Rico [100]. Mahanian thought was blamed for this violence. However, close inspection of Mahan's writing reveals that he believed in the supremacy of economic power; its precondition for successful war, and the necessity of enhancing a government's capability to defend and manage commerce within the domain (sea commerce or in our context, space commerce). Use of force happened only after legislative and diplomatic failure; however, a strong military enables diplomatic success. The strength of a military is not only in its force structure but in its

endurance – defined by its logistics capabilities backed up by the country's economy. The economy represents a nation's ability to wage war, the military logistics is the application of those economic strengths. Both are needed before a war; both are required to deter an adversary.

The Russian invasion of Ukraine in February 2022 can be seen in the terms of conventional deterrence as a failure and, so far, in the terms of nuclear deterrence, as a success (as no nuclear weapons have been used). Modern deterrence theory establishes the rationale for building up forces and having arms races: to convince an adversary that the cost of taking an action will lead to unbearable consequences.

> "Deterrence theories allowed policymakers to organize strategic knowledge into a clear conceptual framework that was easier to ''sell,'' providing them with strategic language and jargon that included concepts such as massive retaliation, invulnerability, assured destruction, counterforce, pre-emptive strike, first strike, second strike, and flexible response [101]."

Logistics posturing and economics are part of deterrence, they are quiet "tells" about the sincerity of an actor. NATO and the US advertised economic consequences and supplied Ukraine with small arms to defend themselves but did not demonstrate or initiate a logistics build up until after Russia invaded. According to a Times of India interview with two senior Indian generals, Ata Hasnain and Shokin Chauhan, NATO was economically unprepared for conflict [102]. The US and NATO regularly asserted that they were a defensive alliance, and only minimally increased the presence of conventional forces along NATOs Eastern borders. Further, they announced that since Ukraine was not a part of NATO, they would not become involved directly, or station their troops there, nor deploy them there if Russia invaded. Meanwhile, Russia indicated that if NATO intervened in Ukraine, it would follow its escalate-to-win doctrine and employ nuclear weapons if NATO did intervene. Russia steadily and rapidly built up their logistics capabilities in preparation for the invasion [103,104]. Russia called the US and NATO sanctions a bluff and believed the consequences for invading Ukraine would be worth it. After the fact, Germany and other NATO partners are now increasing their national military budget, to include considering supplying Ukraine with major weapon systems (and presumably corresponding sustainment support) including aircraft and is cutting off Russia from its access to

the aviation industry [105,106,107]. The establishment and disruption of critical supply lines such as these would have been a greater deterrent had they been publicly considered in advance.

The operational management of a military is critical to its success. Logistics by themselves do not win wars, but it can cause one to lose. Ukraine's use of unmanned aerial vehicles to target logistic capabilities has contributed to logistics difficulties already complicating Russia's ability to invade [108,109]. Russian logistical preparations were monitored over the course of the buildup of Russian forces. The staging of medical facilities, bulk ammunition, and fuel outside what would be considered necessary for a training exercise, in part, signaled a buildup for an invasion [104,109]. The establishment of sustainment activities prior to the onset of hostilities is a part of operational shaping. The establishment and maintenance of railways, highway systems, and production facilities could be considered part of theater shaping activities for Russia. Global and theater shaping activities are long term activities that set the conditions for military success. They are conducted in partnership with other government organizations (than just the Department of Defense) and with partner nations.

> "The joint community, in concert with multinational and interagency partners, must maintain and exercise strong regional partnerships as essential shaping activities in peacetime to ensure operational access during plan execution. For example, obtaining and maintaining rights of navigation and overflight help ensure global reach and rapid projection of military power [110]."

Mahan did not use the term shaping operations, but his foresight was similarly aligned: A nation must establish coaling stations and secure its lines of communications to the home base [99]. His writings promoted the peaceful strategic offensive: the government should foster and monitor commerce to set the conditions for a successful war.

> "The government by its policy can favor the natural growth of a people's industries and its tendencies to seek adventure and gain by way of the sea; or it can try to develop such industries and such sea-going bent, when they do not naturally exist; or, on the other hand, the government may by mistaken action check and fetter the progress which the people left to themselves would make. In any one of these ways the influence of the government will be felt, making or marring the sea power of

the country in the matter of peaceful commerce; upon which alone, it cannot be too often insisted a thoroughly strong navy can be based [99]."

5.9 Force Sustainment

This section builds on concepts and scenarios designed by the Space Force Chief Scientist's office for the Space Futures Workshop 2B. "Images of Future Operations" (IOFOs) were developed to explore potential boundary conditions of possible futures, incorporating imaginative and exponential development of the sciences, technologies, and economies of space in the future. The IOFOs specifically incorporated the adoption of the real possibility that we will see "maneuver without regret" (low-cost space travel) and a large number of people from many nations starting to not only live and work in space by the 2040s, but potentially flourish in space megastructures inspired by O'Neil and 1970's NASA investigations into space colonies [111]. The workshop asked such questions as "what will the force structure look like?" and "what future mission sets and capabilities will need to be addressed [5]?" The advent of the space resources industry is being taken seriously by the USSF, but the USSF lacks a concept for an in-space sustainment force structure needed to guide its peaceful strategic offensive and cislunar shaping activities. The remainder of this paper will describe a potential space concept of support by taking a close look at the elements of Army sustainment.

Army sustainment is organized into four broad elements: logistics, financial management, personnel services, and health care services. If the nation is to truly expand and extend its operations into space it must be prepared to continue to provide sustainment support to the Space Force, its Guardians, their equipment and vehicles, contractors, and eventually their families, wherever they are, on Earth or in the space domain. These elements will be discussed in this section: how they are applicable and translatable into the space environment, both as we currently understand or perform these functions, and a vision for how they can be enabled in the next force (2040s) or the force after next (2060s [5])."

5.9.1 Logistics

Army logistics is broken into seven elements: maintenance, transportation, supply, field services, distribution, operational contract support, and general engineering support. Maintenance is divided into field maintenance and sustainment maintenance [98]. Field maintenance is maintenance performed by the operator and company level support unit (forward

support company). Field maintenance includes remove and replace, adjustment, alignment, and fault/failure diagnosis, as well as battle damage assessment, repair, and recovery. The purpose of field maintenance is to return a system to a fully operational state as soon as possible, as far forward in the battlefield as possible. National-level maintenance providers, primarily civilian contractors, perform sustainment maintenance. Repair is conducted to off-system components with end items being returned into the supply system. Sustainment maintenance consists of overhauling and remanufacturing activities that return components, modules, assemblies, and end items to the supply system at the national standard. DoD civilians and contractors perform these maintenance activities. If an entire system is sent for sustainment maintenance the operational unit removes the item from its property books and reports a shortage for backfill. "The intent of sustainment-level maintenance is to perform commodity-oriented repairs to return items to a national standard, providing a consistent and measurable level of reliability [98]." Implementing modularity and storing maintenance replacement parts as far forward in the battlefield as possible reduces repair recycle times and maximizes the use of supply parts distribution and maintenance reporting [112].

Transportation units facilitate combat endurance. They move sustainment from ports, throughout the Army sustainment system to the point of employment, and then retrograde materiel. Transportation functions include movement control, intermodal operations, mode operations, and theater distribution. Movement control is the process of allocating and regulating movement, synchronizing assets and distribution flow over lines of communication according to command priorities. Movement control provides the commander with situational awareness of the disposition of his or her sustainment assets and ensures lines of communication are open to enable freedom of access for combat units. Intermodal operations are the movement of troops and supplies "using multimodal capabilities (air, highway, rail, sea) and conveyances (truck, barge, containers, pallets [98])." It requires the use of facilities, transportation assets, material handling equipment, and often operates in expeditionary theater entry points "across a network of specialized transportation nodes." Mode operations are the execution of and administration of movement along a variety of conveyances. Theater distribution, distinct from distribution, allocates assets across a broad geographical area in support of a geographic combatant commander (GCC) for further transport and distribution to the end user [98].

Table 5-1. Army classes of supply, derived from ADP 4-0, and Potential Space Resources Derived Products.

Class	Description	Potential Space Resource Derived Products
CL I	Subsistence and Drinking Water	In-space food production & potable water handling/purification systems (plant, animal, & 3D-printed meat cultures, etc.)
CL II	Clothing and Individual Equipment	In-space small item production (clothing items, spacesuits, hand tools, other small sized items)
CL III	Petroleum, Oils, and Lubricants	Propellants, to include non-potable & purified water
CL IV	Construction Materials, including fortification materials	Regolith, purified metals, powders, ISRU derived feedstocks
CL V	Ammunition, explosives, and rockets	Beamed energy, energy storage, batteries, receiving and transmitting antennas, traditional explosives, solid rocket propellants
CL VI	Personal demand items (health, hygiene, snacks, and beverages)	Mail, alcohol, other consumer goods produced in space and/or on Earth for in-space consumption
CL VII	Major end items (Complete combat and non-combat systems)	Large structures and arrays (solar panels, radar systems, engines, guidance navigation and control subsystems etc.), robotic arms, complete spacecraft subsystems
CL VIII	Medical Supplies	Medical supplies, to include vaccines, antibiotics, 3d printed organs, surgical supplies, splints, gauze, surgery and hospital specific robotic systems, etc.
CL IX	Repair parts and components	Advanced manufacturing of repair parts (on-demand, trusted, additive and subtractive manufacturing from feedstock) – low mass consumption/waste
CL X	Other non-military items, including agriculture and economic development aids	Support to space settlement/industry: provision of “starter kits” and relief packets (humanitarian assistance activities)

Supply is the receipt, storage, and organization of all classes of supply for military operations. Classes of supply are included in Table 5-1, above.

Field services provide critical functions for Soldier health and readiness, it includes aerial delivery, field feeding, shower and laundry, mortuary affairs, and water purification services. Aerial delivery provides a unique mode of delivery of supplies critical to supporting forces that are otherwise unable to be resupplied or resupplied in a timely manner. Mortuary affairs units conduct search and recovery, identification, and preparation and disposition of human remains. Mortuary affairs unit coordinate the retrograde of human remains and personnel effects to their families. The GCC can authorize temporary internment [98].

Operational contract support covers the spectrum of planning, procuring, and obtaining supplies, services, and construction via commercial sources for the support of the GCC. Acquisition and non-acquisition personnel perform this role [98].

General engineering support includes engineering capabilities that are not performed in combat engineering. These capabilities modify, maintain, or protect the physical environment. They maintain and build infrastructure such as buildings, roads, bridges, airfields, facilities, utility infrastructure for ports of debarkation, main supply routes, and base camps. Combat engineering, general engineering, and geospatial engineering are combined to enable logistics and force protection [98].

5.9.2 Theater Setting and the Concept of Support

The operational level of war sustainment planning method, “the concept of support,” is straightforward. It is the application of the operational art of assessing risk and allocating limited assets (personnel, and equipment) across the battlefield in time, space (physical location), and purpose. It also requires the planner to know the science of their equipment. What are the supported units’ equipment capabilities? What are their consumption rates? It also requires an understanding of procuring sustainment support via contracts with industry and the host nation [98]. On a two-dimensional battlespace, like the surface of the Earth, this requires minimal math. Time-distance charts are needed. Understanding of congestion, flow, distribution, consumption rate, an understanding of the supported unit’s mission, and the commander’s intent are needed. In the absence of sustainment assets in space, and in the absence of a sustainment philosophy across the Space Force, the application of this method is both inappropriate and impossible. Yet,

it provides a model to establish both what the Space Force's sustainment philosophy could or should be and creates constraints for imagining what the force structure should be—that is what can the Space Force not do without the appropriate logistics infrastructure. Lt. Col. Pryor and Maj. Bost have an excellent article articulating the importance of a Brigade Combat Team (BCT) having a shared concept of support and standard operating procedures established [2]. This experience cannot be directly translated to space, but it must be conceptually explored, and then a force structure can be developed around it.

Fundamentally, the concept of support is the plan that sustainment professionals create to coordinate with the maneuver force. It established times and locations to facilitate the exchange of supplies, the disposal of waste, and the retrograde of such items as aerial delivery materials and systems that cannot be repaired at the field maintenance level. This plan is coordinated across all classes of supply for all phases of a planned operation.

The US Army's method for developing a concept of support is to first work closely with the intelligence and maneuver planners. Intelligence drives maneuver and maneuver drives sustainment. That is, ultimately maneuver is still constrained by the logistics capabilities of its own units (or else it may outrun its own sustainment capabilities—a tank without fuel, tracks, or ammo quickly becomes useless). Similarly, a satellite without propellant, or whose solar panels degrade becomes useless without on-orbit servicing.

A space concept of support is distinct from space lines of communication (SLOC)—a SLOC is merely the route (physical or digital) upon which communication and supplies flow. The Concept of support details what is being supplied by whom on what route to which operational assets or units. It is the operational art that bridges the strategic concept of SLOC to the tactical action of conducting resupply missions.

An example space concept of support is informed by the space operating environment, including information about the adversary: these two data sets combined with intelligence analysis to create the information preparation of the battlefield (IPB).

> "Intelligence preparation of the battlefield is the systematic process of analyzing the mission variables of enemy, terrain, weather, and civil considerations in an area of interest to determine their effect on operations. IPB allows commanders and

> staffs to take a holistic approach to analyzing the operational environment (OE [113]).”

The IPB provides the commander with an understanding of potential opportunities and threats, including enemy courses of action. In cislunar space key terrain includes the Earth-Moon Lagrange points and the first two Sun-Earth Lagrange points, due to the relative ease of travel to those points. The Moon, in 2040 and certainly by 2060, should be considered an industrial base where production of systems, maintenance parts, and consumables can take place.

The IPB is the first portion of the mission analysis step of the military decision-making process. Other information is needed to provide course of action recommendations to the commander, this includes understanding the arrangement of friendly forces, and the breakdown of command authorities and areas of responsibility. The joint force differentiates between theaters, command authorities and mission sets. Mission sets are separated by combatant commands, established by the President’s Unified Command Plan (UCP).

> “The UCP is a classified executive branch document prepared by the Chairman of the Joint Chiefs of Staff (CJCS) and reviewed and updated every two years that assigns missions; planning, training, and operational responsibilities; and geographic areas of responsibilities to [combatant commands [114]].”

For instance, the Contiguous United States of America, Canada, and Alaska is the NORAD/NORTHCOM geographical combatant command. Its combatant commander (CCDR) is generally assigned the supporting command role in sustaining fights. The CCDR coordinates the movement of the joint force’s operational units out of its area of responsibility (AOR) with the support of US Transportation Command (USTRANSCOM) into the supported CCDR’s AOR. USTRANSCOM is one of the non-geographic combatant commands, which provide global services, and until recently were exclusively supporting commands. Cyber Command, Space Command, and Strategic Command area also non-geographic commands.

USTRANSCOM, along with its subordinate commands, notably the US Army Surface Deployment and Distribution command, coordinate theater setting activities, such as port opening [98]. Theater setting is an ongoing global shaping activity that includes whole-of-government initiatives to establish “bilateral or multilateral diplomatic agreements to allow U.S.

forces to have access to ports, terminals, airfields, and bases within the AOR to support future military contingency operations." Theater setting is coordinated by multiple commands and agencies, including USTRANCOM, US Army Materiel Command, the Defense Logistics Agency, Air Mobility Command, and the Military Sealift Command. These organizations work together to provide support to the Geographic CCDR. Within the combatant command (CCMD) the Army Service Component Command (the senior Army organization in charge of all other Army organizations within the theater) is designated the Theater Army (TA). The TA establishes the Theater Sustainment Command (TSC) which executes Intra-theatre sustainment tasks to ensure the needs of the theater are met and executes the sustainment plan within theater, but the CCDR is ultimately responsible for setting the theater [98]. "The TA serves as an enabling headquarters and conducts set the theater tasks that include: theater opening; port and terminal operations; joint reception, staging, onward movement, and integration (JRSOI); logistics-over-the-shore operations; force modernization; theater-specific training; administrative control; and, redeployment tasks that support reverse JRSOI and the return of the force to home station [115]." Other shaping activity roles include ensuring interoperability with partner nations, establishing or updating sustainment agreements with host nations, reassessing logistic estimates, conducting environmental assessments, and securing or upgrading critical logistics nodes including ports, airports, and air terminals [98].

The Army has executive agency (EA) specific functions that it performs for the other services—these are functions that would have been overlooked by Space Force and former Air Force planners considering how to sustain the Space Force, or conduct in-space sustainment operations, as these actions are not done or are only partially considered by them. The Army has 42 of these EA functions, including "the Military Postal Service; the Official Mail Program; production, coordination, and distribution of land-based water resources to the CCMDs; Single Manager for Conventional Ammunition; the Department of Defense Detainee Program; Armed Services Blood Program; and the Defense Mortuary Affairs Program [115]." These tasks inform the Army's planning of its force structure (80% of its sustainment capabilities are provided by reservists), budget, and how it plans execution of set the theater tasks. The Army provides additional support to other services as the primary for overland distribution of petroleum in wartime, common user land transportation and intra-theater patient evacuation [115].

These setting the theater tasks, especially those requiring infrastructure development take years to conduct. Setting the theater in space may take even longer. It will require a whole of government effort to determine who has what responsibility and may be a task for the Vice President and the National Space Council to delineate responsibilities and then request funding or propose laws for Congress to consider. The next section proposes one way to set the cislunar theater and establish a concept of space support.

> "An Army cannot be globally responsive when it takes weeks or months to deploy forces because of restrictive transportation nodes, poorly positioned equipment, nonexistent access agreements, [financial management] systems that are not in order, or its failure to understand and employ all the sustainment assets at its disposal. Accordingly, these areas must be addressed and resolved before it has to deploy with no notice to a theater."
>
> -Lt. Gen. Gustave "Gus" Perna [116]

5.9.3 A Conceptualized Space Theater Setting and Concept of Space Support

As stated previously, intelligence drives maneuver and maneuver drives sustainment planning. Building off of the USSF Chief Scientist Office's Space Futures workshop's Visions of the Futures, the author imagined a scenario set in the 2040s upon which one could plan to set the theater and then establish a concept of support. This is not the only solution, nor does this future represent a future imagined by the USSF—it is of the authors own imagination. Figure 5-2 depicts a notional information preparation of the battlefield, from which combatant command "volumes of responsibility" are defined, on which a high-level sustainment overlay can be placed. Instead of Geographic AORs, volumes of responsibility are defined: a combatant command for Earth's gravitational sphere of influence (SOI), another for the Moon's SOI, and a third combatant command, nominally USSTRANSCOM, coordinates transportation between the two and from the rest of the Solar System into the cislunar system's SOI, and coordinates and manages the Space Force's interests in civilian and military space ports.

The notional scenario imagined in Figure *5-2* is the defense of colonists and space-based capabilities from an Earth and Geostationary orbit-based threat. Hostile forces are threatening to take over or destroy industrial capabilities on the Moon, and are willing to threaten space-based infrastructure, such as space based solar power (SBSP). In this scenario, an imagined limit of

capabilities of the threat is up to 2xGEO (a combination of on-orbit delta-V maneuver availability for kinetic threats, and the effective range of their directed energy threats). The boundary of the 2xGEO sphere delineates the current extent of the adversary's reach and is named the forward line of operations (FLOO)—although it is truly a surface area it is based on the concept of the forward line of troops. Adversary capabilities also hold Earth-based launch assets at risk, both from space and ground. Unpredictable orbital maneuvering and disaggregated mega-constellations in LEO and MEO provide some defense against targeting solutions. More maneuver and technical defenses are discussed in Appendix B. Maneuver's Contribution to Defense. The graceful degradation inherent to disaggregated systems mitigates some of the damage done to system-of-system level performance [117].

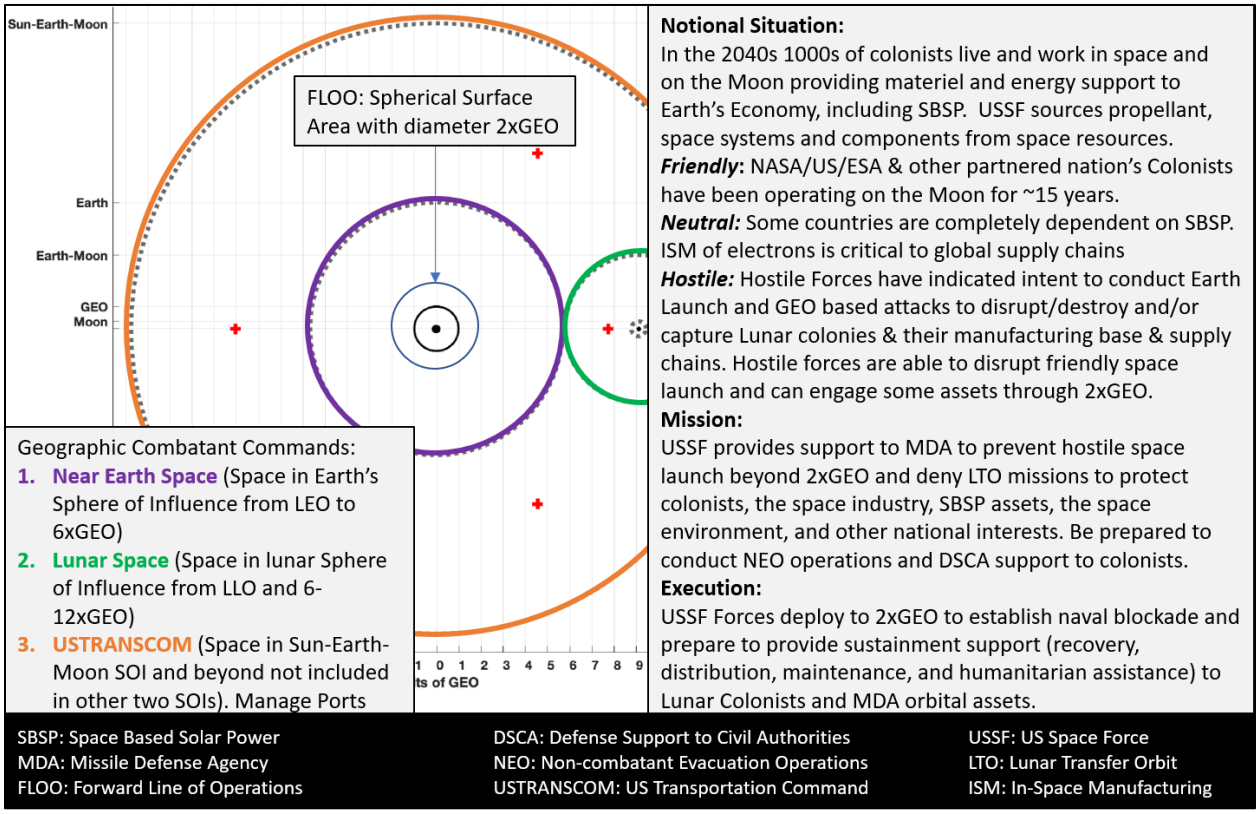

Figure 5-2. Notional Information Preparation of the Battlefield for a 2040-2060 contingency operation. Notional "Geographic" Combatant Commands are overlaid on a two-dimensional representation of the Earth-Moon Circular Restricted Three Body Problem (CR3BP), with the Earth at the Center, the Moon to the right, and Lagrangian points annotated with red crosses. CR3BP graphic used from AFRL Publication: "A Primer on Cislunar Space."

In this scenario, the USSF is tasked to establish a naval blockade to prevent any vehicles entering a trans-lunar injection orbit (TLO) in coordination with the Missile Defense Agency's prevention of hostile space launch or kinetic ASAT launch. The USSF is also tasked to be prepared to provide non-combatant evacuations (NEO) and defense support to civil authorities (DSCA) in the colonies.

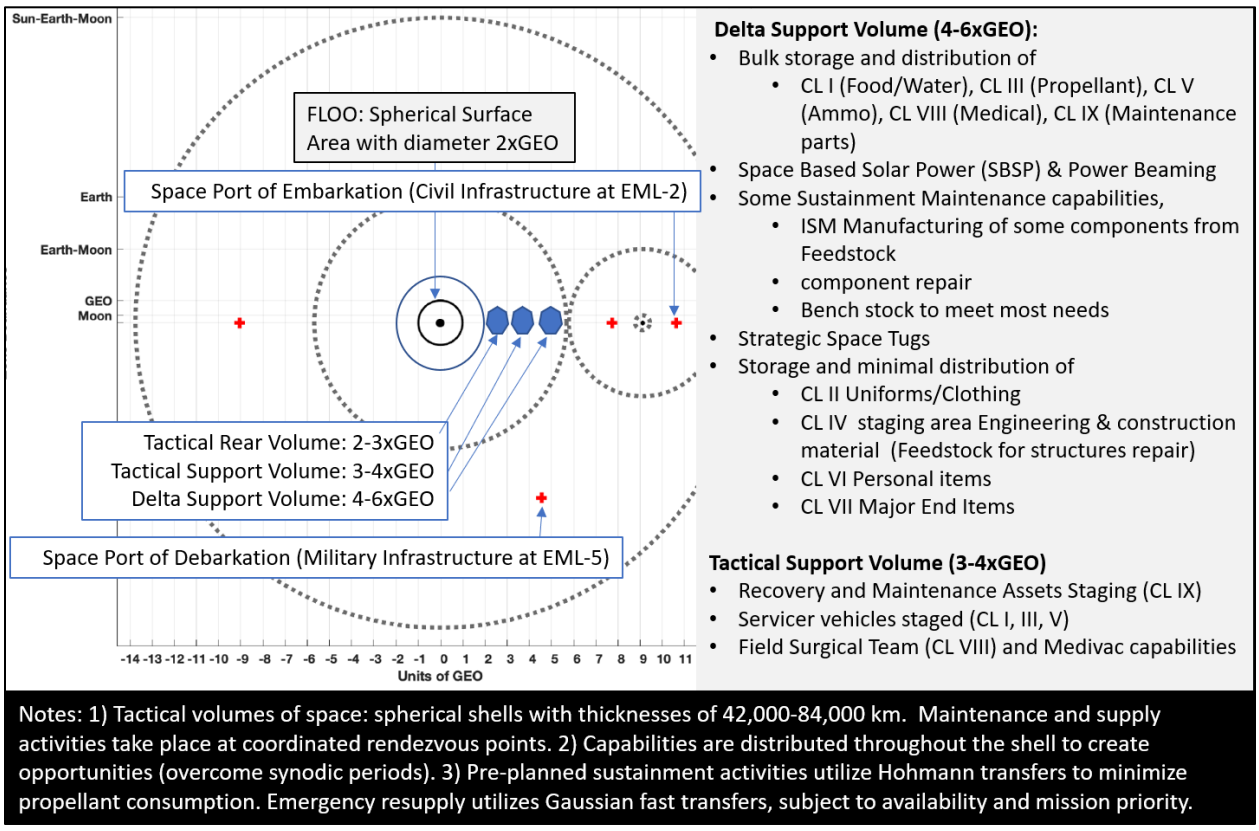

Figure 5-3. Example Space Sustainment Overlay. CR3BP Graphic credit "A Primer on Cislunar Space."

Figure 5-3 depicts an example space sustainment overlay. A Space Port of Embarkation (SpPOE) is established in a Lissajous orbit about Earth-Moon Lagrange point two to aggregate supplies launched from the Moon. The SpPOE leverages preexisting civilian infrastructure used to colonize the Moon and facilitate delivery of supplies to and from the Moon. It is run by industry with military interests directed by the supporting geographic CCDR & USTRANSCOM equivalent. It aggregates and organizes supplies launched from the surface of a celestial body for onward movement. An SpPOE should be located in the immediate vicinity of an industrialized

celestial object with significant gravity (i.e., Moon vs. Asteroid). Other Lagrange points could be utilized, including Sun-Earth, or Sun-Mars depending upon the situation and need.

A military Space Port of Debarkation is established at EML-5 to facilitate the tactical and operational reorganization of space vehicles and supplies for staging and onward movement. It is run by a Theater Sustainment Delta (a command specific to providing and coordinating sustainment within a theater, the delta is the USSF's largest tactical formation, and is equivalent to an Army brigade). The Theater Sustainment Delta would be directed by the supported combatant commander and would be located within theater but outside the range of an adversary's engagement zone. The SpPOD serves as an intermediate staging base [118].

Delta, Tactical, and Tactical rear areas serve as further intermediate conceptual nodes for the exchange of supplies, services, and retrograde of vehicles. These nodes represent volumes of control represented by the spherical shell from radius 4xGEO to 6xGEO for the Delta Support Area, the shell from 3-4xGEO for a tactical support area, and 2-3xGEO for the tactical rear area. The forward line of operations is a notional boundary of the spherical area defined by the radius of 2xGEO.

Sustainment loops travel from the industrial source of supply all the way to the tactical end user, and from the tactical end user are retrograded to the rear for recycling or repair and reentry into the supply system. Figure 5-4 depicts the conceptual flow of material on the Lunar surface from mining and extraction points to raw material storage and processing centers, and from there to manufacturing centers and/or to launch facilities for prep for launch off world.

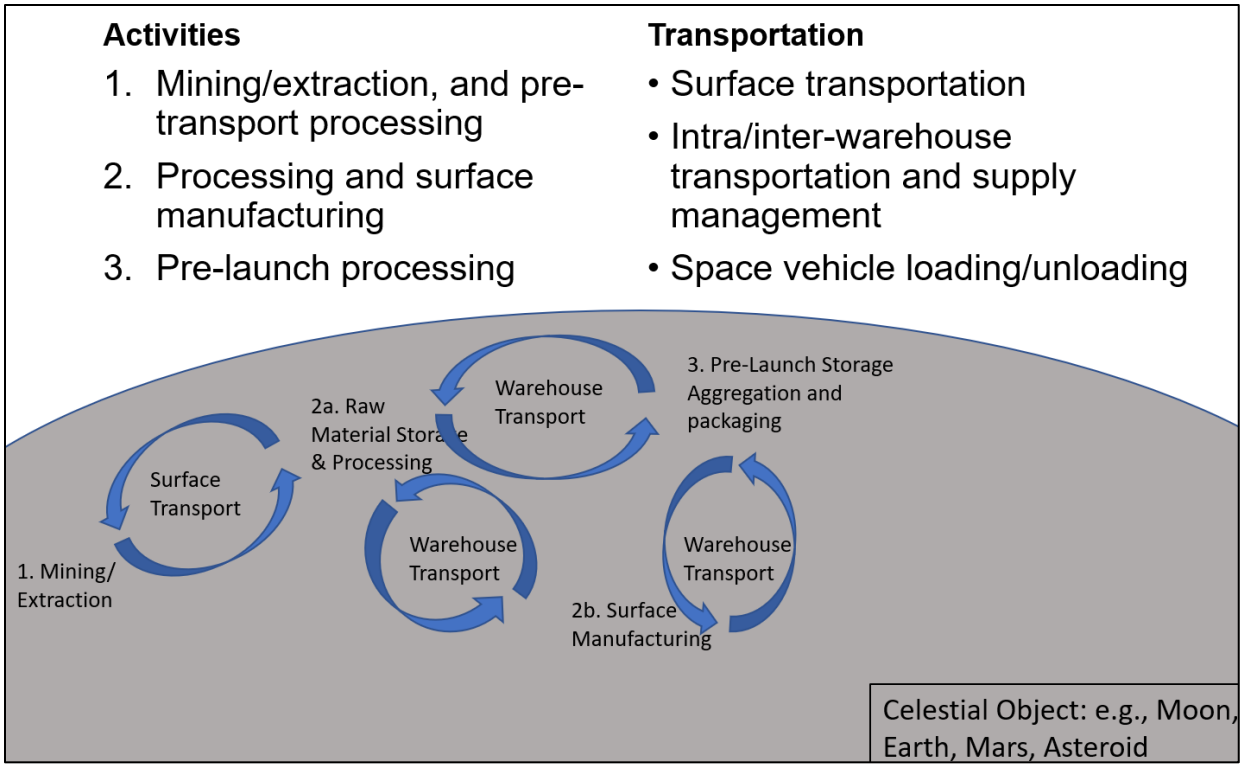

Figure 5-4. Surface Sustainment Loops

Figure 5-5 depicts sustainment loops traveling from a lunar launch facility to the SpPOD and onward to various in-space industrial activity areas, such as spaceship yards. Supplies and resources can then be cycled to and from the SpPOD or Industry activity areas to the SpPOE. Military specific space sustainment loops are depicted in Figure 5-6. From the SpPOE supplies, space vehicles, consumables and repair parts are moved forward to conduct repair and refueling as close to FLOO as possible. Conducting repair and resupply missions forward minimizes the amount of time combat systems are removed from the fight. Any systems that are damaged and irreparable will need to evacuate themselves, be evacuated by another combat vehicle, or specialized recovery vehicle for repair in the rear.

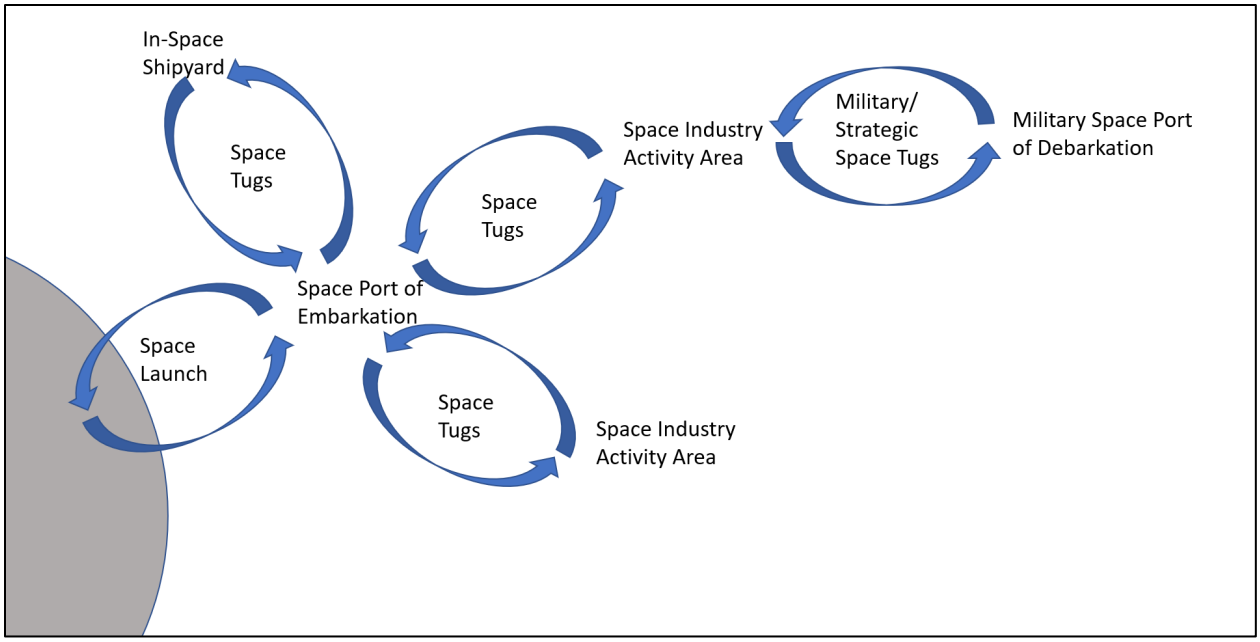

Figure 5-5. Civil Space Sustainment Loops

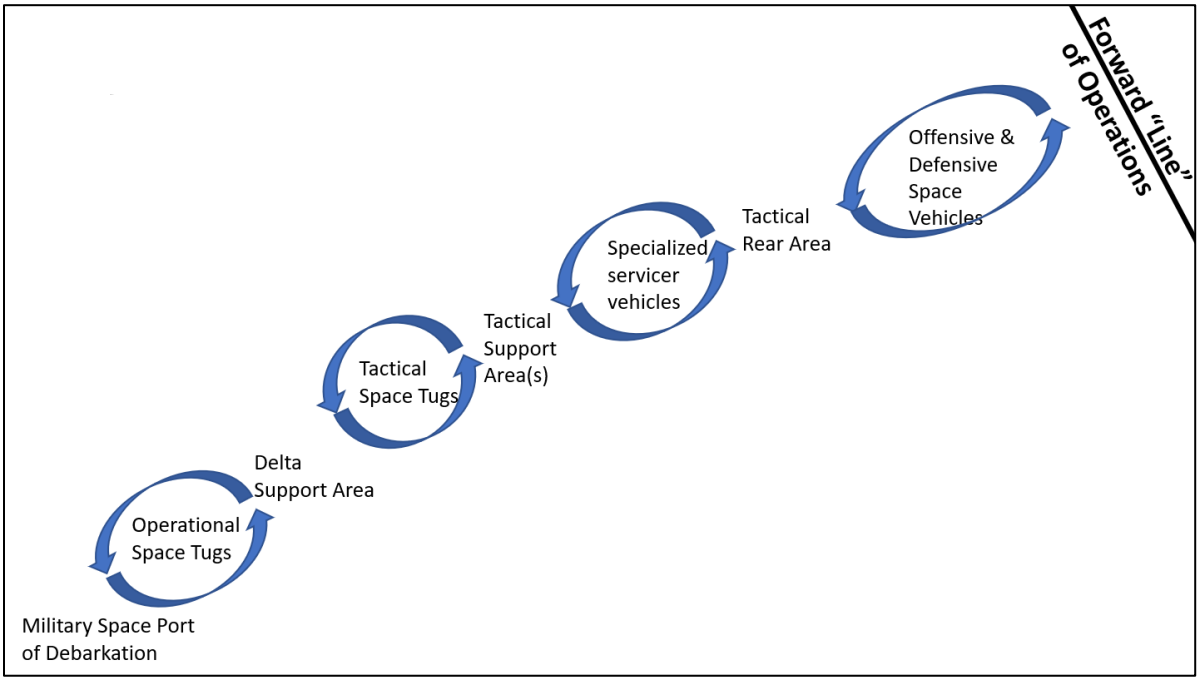

Figure 5-6. Military Space Sustainment Loops

5.10 Conclusion

The long-term planning for the sustainment of forces during peacetime is a critical part of cislunar shaping operations. Establishing the ability to rapidly realign forces in space and use

sustainment capabilities to project force establishes an innate deterrent ability. Sustainment activities are inherently peaceful and provide benefits to civil and commercial space activities. It is in the Department of Defense's mission set to establish theater distribution and to utilize general engineering support to build, repair, and maintain critical transportation infrastructure, such as ports of debarkation and airports. It is not a stretch of the imagination that the Army—or rather Space Force Corps of Engineers would have some responsibility along with their commercial partners for the planning, construction, and management of spaceports to the benefit of civil programs in the near term and the benefit of future military needs that may never and hopefully will never materialize.

Space resources are critical to establishing a second space line of communication to forces in space and are especially needed if an adversary can hold your space assets and launch vehicles through GEO at risk with ground based anti-satellite weapons systems. Space Resources enable access: they are emerging sources of production of not just propellant but also of all the raw materials, energy, and food needed for the construction of modern satellites and space vehicles, and the ability to sustain both humans and space vehicles. Prospecting, extracting, processing, and manufacturing value chains are foundational parts of the value chain and need to be invested in now.

Human presence may or may not eventually be required, but the formation of an economic ecosystem in space is required: raw and lightly processed materials will be aggregated where industry can best manufacture and further distribute products. These nodes represent colonies. The transportation occurs between nodes: resource extraction and aggregation points; manufacturing and storage or point of sale; and point of sale and point of consumption.

Space launch vehicles are the first and often only vehicle considered when one first considers space transportation, but it should also include space launch from the Moon and Mars (etc.) and transportation within space, both in the traditional sense of station keeping, but also in the new concept of space tugs or tankers. Transportation services coupled with in-space production and staging of space services will lead to effective sustainment in space. Establishing the ability to provide meaningful sustainment nodes throughout the solar system will enable space vehicles to operate more effectively.

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CHAPTER 6.

CONCLUSION AND FUTURE WORK

6.1 Conclusion

The purpose of this thesis was to explore the uses of space resources to sustain space activities. Chapter 2 established that space resources are integral to national power, and that we are competing with China in a new space race, despite their denials [1,2]. China is the US's pacing threat. The threat of invasion of Taiwan is the pacing scenario [3]. War extends into space; it is not limited to any domain. War extends across all domains [4]. China's activities in space, especially its recent efforts to explore and utilize the Moon should be taken seriously [5,6]. At the same time, the greatest obstacle to operate in space is not an adversary—it is the space environment itself. "The overwhelming amount of access denied in space is due to the limits of technology to reach it and the lack of infrastructure to support operations there, not from the actions of an active adversary [7]." Military planners must seek out new ways to gain access to, operate within, and be prepared to dominate in this domain. For this reason, securing a propellant distribution architecture derived from space resources is the principal way of overcoming this obstacle. Chapter 3 established that propellant architecture could be established by utilizing water extracted from the Moon. Distribution of propellant cannot be done in isolation. A force structure must be developed around it that promotes interoperability across the entire value chain, from source of supply through end user. Chapter 4 investigated modularity and the use of standardized interfaces. It concluded that technical modularity and technical standards alone are not enough, nor is a top-down dictation of standards appropriate. An emergent modular system can only be created through loose collaboration with a strategic modularity mindset: encouraging agile technical modularity while mindful of the place a system acts within the overall system-of-systems. Finally, Chapter 5 described the first concept of space support. A concept of support requires the development of—and the artful emplacement of—fundamental space logistics capabilities: transportation, supply storage and management, and production capabilities. This trinity of sustainment capabilities enables the peaceful development and use of space and provides a future foundation from which the US Space Force may defend

the modern rules based liberal world order and the interests of the United States and its Allies: conducting set the theater tasks must be done in space.

6.2 Future Work

Future work must fill in the gray and underdefined areas in a future space logistics system. There are many areas here that are underdefined; greater imagination is needed to consider all the potential options for the placement of sustainment nodes and the automation required to enable the complexity that is understated but assumed throughout. Significant obstacles remain to be overcome by future researchers.

Orbital mechanics-based distribution models could be used to demonstrate and substantiate the significant benefits of these described distribution networks, as compared to the continued distribution from Earth. Design work on interfaces specifically designed for the automatic exchange of multiple classes of supplies, as well as cryogenic fluids, power, and structural and dynamic forces are needed. Beyond the design work, significant diplomatic efforts are needed to establish, adopt, and disseminate an international strategically modular system of systems design. Significantly more work is needed in the field of space logistics. Much of it is currently unknown or theoretical at best. Future areas of exploration include spaceport management, design, and planning; lunar surface transportation and intermodal networks; lunar surface to space transportation management; and the development and optimization of in-space specific transportation, and associated sustainment functions. Further efforts at establishing space governance are also needed, as commercial partners should take the lead on space activities. I have done the easy work of imagining and describing a conceptual logistics system in space, the hard part will be designing one that works. This thesis was just the first step in describing one possible sustainment solution to one imagined conflict. The next step requires collaboration between military planners, elected leaders, and the space resources industry and academia to work together to coordinate and overcome legal, fiscal, and technical hurdles necessary to achieve this national capability.

> "The more I see of war, the more I realize how it all depends on administration to see *where* you would like your army to be and *when*; it takes much knowledge and hard work to know where you can place your forces and whether you can maintain them there. A real knowledge of supply and movement factors must be the basis of

every leader's plan; only then can he know how and when to take risks with those factors, and battles are won only by taking risks."

-Field Marshall A.C.P. Wavell [8]

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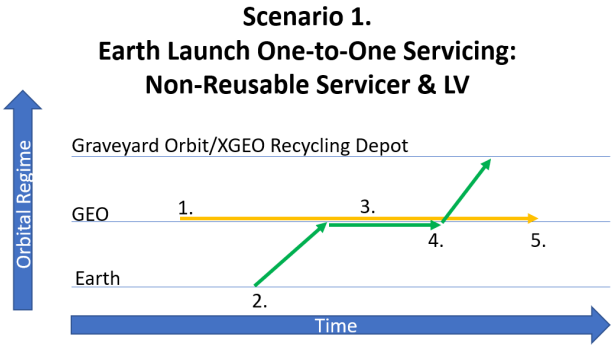
APPENDIX A.

SUSTAINMENT MODELS

This section contains sustainment models that did not fit into any chapter but were considered necessary for the development of this thesis. These scenarios explored how one would sustain and distribute consumables (especially propellant) from Earth or from the first Earth-Moon-Lagrange point to various orbits around Earth, including GEO and LEO.



1. Customer Satellite makes service request in GEO.
2. Servicing Satellite Launches to GEO
3. Cooperative RPOD and refueling.
4. Undocking and departure of servicing satellite to graveyard orbit or to XGEO recycling Depot.
5. Customer Satellite continues mission until new servicing request or end of life.

Hardware
-Expendable Servicer
-Launch Vehicle

Operations
-Propellant Sales
-Inspection Services

Risk
-High-cost low volume servicing

Opportunities
-Service low volume propellant types
-Service unique customers/design to launch

Note: Space Logistics MEV-1 and -2 is an example of non-reusable one to many servicing

Figure A-1. Scenario 1: Earth Launch One-to-One Servicing: Non-Reusable Servicer and Launch Vehicle

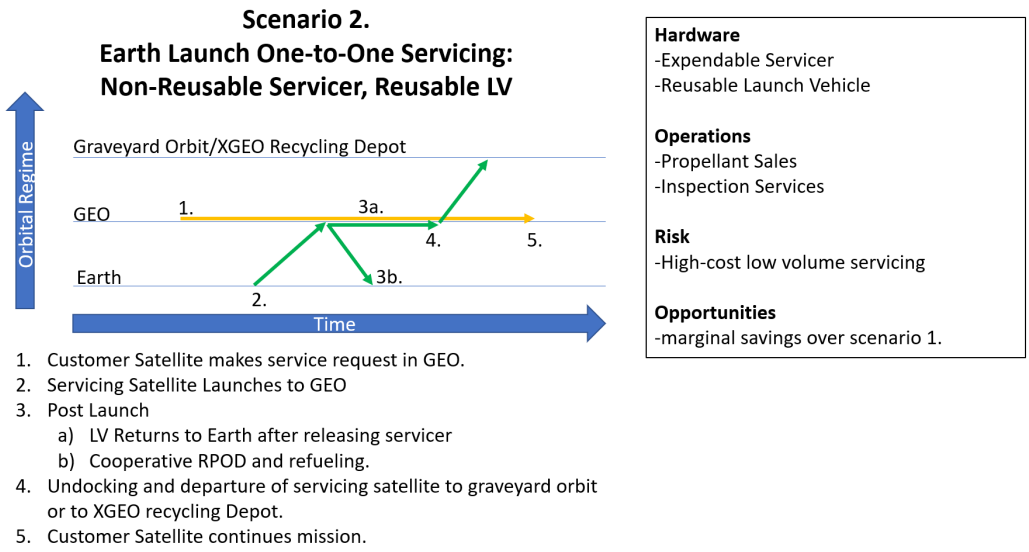


Figure A-2. Scenario 2: Earth Launch One-to-One Servicing: Non-Reusable Servicer, Reusable Launch Vehicle

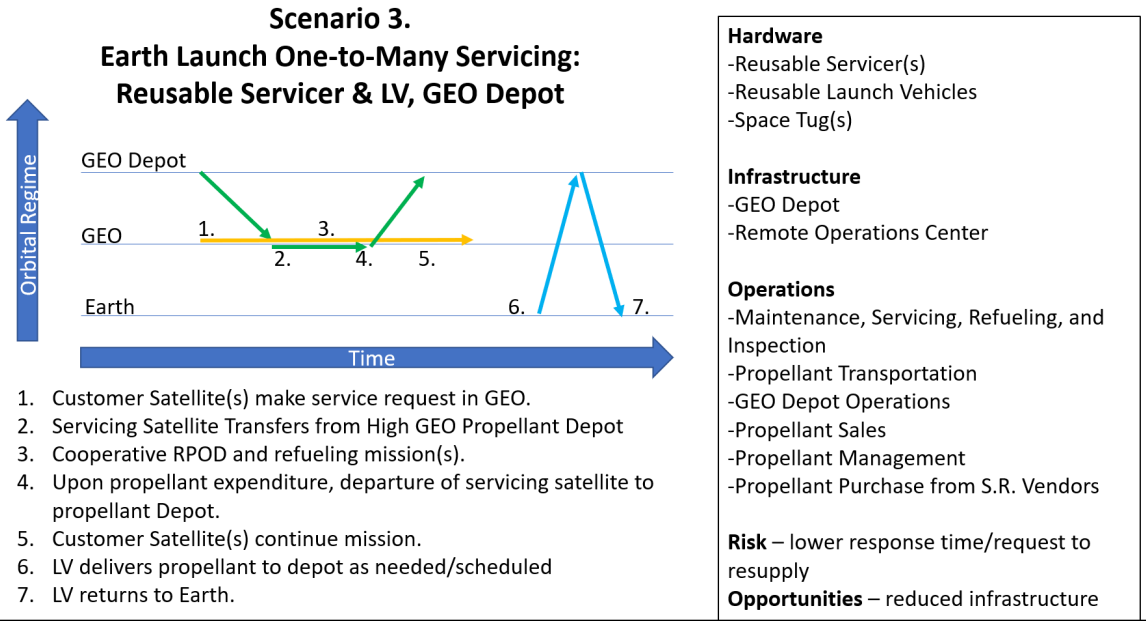
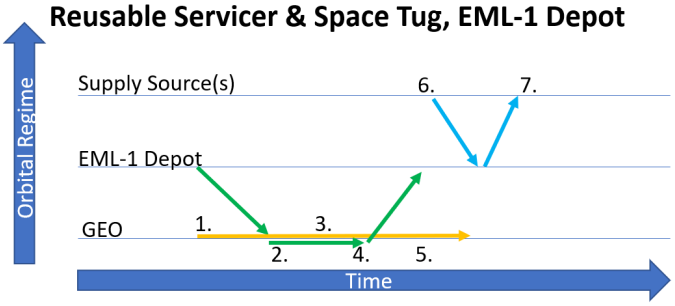


Figure A-3. Scenario 3: Earth Launch One-to-Many Servicing: Reusable Servicer and Launch Vehicle, with a Geostationary Depot



1. Customer satellite(s) make service request in GEO.
2. Servicing satellite transfers from EML-1 propellant depot.
3. Cooperative RPOD and refueling mission(s).
4. Return of servicing satellite to EML-1 propellant depot.
5. Customer satellite(s) continue mission.
6. Space tug delivers propellant to depot as needed/scheduled.
7. Space tug returns to source of supply (e.g. Lunar surface, asteroid mining operation).

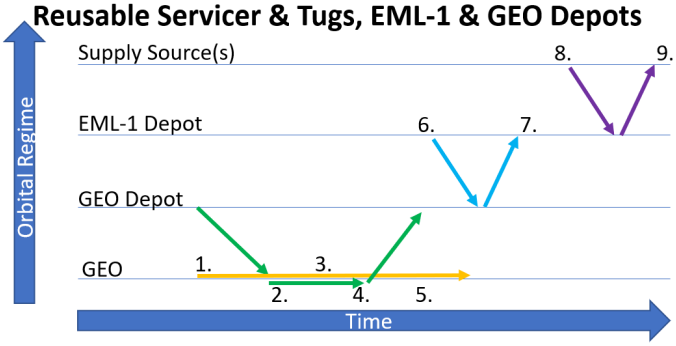
Hardware
-Reusable Servicer(s)
-Reusable Launch Vehicles
-Space Tug(s)

Infrastructure
-EML-1 Depot
-Remote Operations Center

Operations
-Maintenance, Servicing, Refueling, and Inspection
-Propellant Transportation
-GEO Depot Operations
-Propellant Sales
-Propellant Management
-Propellant Purchase from S.R. Vendors

Risk – lower response time/request to resupply
Opportunities – Space Resource Derived Propellants

Figure A-4. Scenario 4: Space Resources One-to-Many Servicing: Reusable Servicer and Space Tug, EML-1 Depot



1. Customer satellite(s) make service request in GEO.
2. Servicing satellite transfers from EML-1 propellant depot.
3. Cooperative RPOD and refueling mission(s).
4. Return of servicing satellite to propellant depot.
5. Customer satellite(s) continue mission.
6. Space tug delivers propellant to GEO depot as needed/scheduled.
7. Space tug returns to EML-1 Depot.
8. Space tug delivers propellant to EML-1 depot as needed/scheduled.
9. Space tug returns to source of supply.

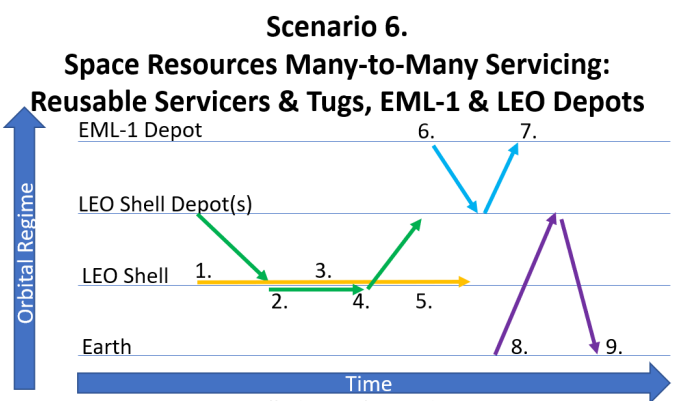
Hardware
-GEO Servicers
-Reusable Launch Vehicles
-Space Tugs

Infrastructure
-GEO Depot
-EML-1 Depot
-Remote Operations Center

Operations
-Maintenance, Servicing, Refueling, and Inspection
-Propellant Transportation
-GEO Depot Operations
-EML-1 Depot Operations
-Propellant Sales
-Propellant Management
-Propellant Purchase from S.R. Vendors

Risk – Increased complexity and capital requirement
Opportunities – Increased resiliency, diverse sources of supply (can include Earth resources)

Figure A-5. Scenario 5: Space Resources One-to-Many Servicing: Reusable Servicer and Tugs, EML-1, and GEO Depots



1. Customer mega-constellation make service contract.
2. Servicing satellite(s) transfers from LEO propellant depot to first orbital plane.
3. Cooperative RPOD and refueling missions for each satellite in plane.
4. Return of servicing satellite to next propellant depot.
5. Customer satellite(s) continue mission.
   Repeat steps 2-5 for each orbital plane in shell.
6. Space tug delivers propellant to LEO depots as needed/scheduled.
7. Space tug returns to EML-1 Depot.

8/9. Reusable launch vehicle delivers additional propellant to LEO depot as needed.

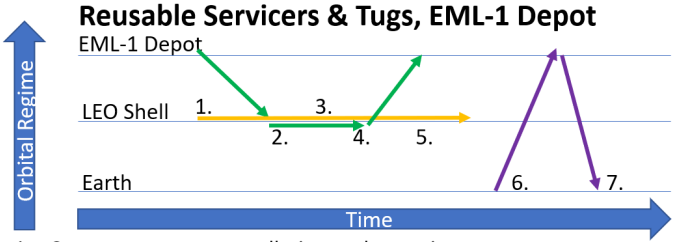
Hardware
-LEO Servicers
-Reusable Launch Vehicles
-Space Tugs

Infrastructure
-LEO Depot(s)
-EML-1 Depot
-Remote Operations Center

Operations
-Maintenance, Servicing, Refueling, and Inspection, deorbiting
-Propellant Transportation
-LEO Depot Operations
-EML-1 Depot Operations
-Propellant Sales
-Propellant Management
-Propellant Purchase from S.R. Vendors

Risk – Increased complexity and capital requirement
Opportunities – Increased resiliency, diverse sources of supply (can include Earth resources)

Figure A-6. Scenario: Space Resources Many-to-Many Servicing: Reusable Servicers and Tugs, EML-1, and Low Earth Orbit Depots



1. Customer mega-constellation make service contract.
2. Servicing satellite(s) transfers from EML-1 propellant depot to each orbital plane.
3. Cooperative RPOD and refueling missions for each satellite in plane.
4. Return of servicing satellite to EML-1 propellant depot.
5. Customer satellite(s) continue mission.
   Repeat steps 2-5 for each orbital plane in shell.

6/7. Reusable launch vehicle delivers additional propellant to LEO depot as needed.

Hardware
-LEO-EML-1 Servicers
-Reusable Launch Vehicles

Infrastructure
-EML-1 Depot
-Remote Operations Center

Operations
-Maintenance, Servicing, Refueling, and Inspection, deorbiting
-Propellant Transportation
-EML-1 Depot Operations
-Propellant Sales
-Propellant Management
-Propellant Purchase from S.R. Vendors

Risk – Increased congestion at EML-1, more propellant required per plane to conduct multiple EML-1 to LEO transits

Opportunities – Reduced Capital requirements for Depot

Figure A-7. Scenario 7: Space Resources Many-to-Many Servicing: Reusable Servicers and Tugs, EML-1 Depot

APPENDIX B.

MANEUVER'S CONTRIBUTION TO DEFENSE

This section references satellite defenses described in the Center for Strategic Studies publication "Defense Against the Dark Arts in Space. The author condensed the work into tables. Particular attention was made to consider how satellite constellations utilize maneuver as a part of their integrated defense against attack on orbit. Maneuver is also integrated into satellite systems as a fundamental portion of their design for station keeping, but once "maneuver without regret" become available, that is low-cost or ultra-low-cost maneuver, maneuver can be designed into satellite systems and into constellation design to enhance their ability to dodge attacks, evade threat inspection systems, or increase the difficulty of tracking and predicting their position.

Table B-1. Passive, Architectural Defenses as Defined in "Defense Against the Dark Arts in Space."[3]

Passive, Architectural Defenses

Disaggregated Constellations	*"Disaggregation is the separation of distinct missions onto different platforms or payloads, effectively breaking up multi-mission satellites into separate mission-specific satellites that operate in parallel."* This forces an attacker to identify specific missions (i.e., strategic communications vs. tactical communications) - an attack then communicates intent.
Distributed Constellations	*"A distributed system uses "a number of nodes, working together, to perform the same mission or functions as a single node." In a distributed constellation, the end user is not dependent on any single satellite but rather uses multiple satellites to derive a capability."* This forces an attacker to take out multiple targets to degrade capability. This "graceful degradation" increases complexity for the attacker and decreases individual satellite reliability requirements and cost.
Proliferated Constellations	*"Proliferated satellite constellations deploy a larger number of the same types of satellites to similar orbits to perform the same missions."* Proliferated constellations simply provide more capability to establish economies of scale. This increases the number of satellites an attacker must target and defeat.
Diversified Architectures	*"In a Diversified Architecture, multiple systems contribute to the same mission using platforms and payloads that may be operating in different orbits or in different domains."* Establishing a mission architecture that is supported by systems in other orbital regimes or domains increases targeting complexity and cost to the attacker.

[3] Todd Harrison, Kaitlyn Johnson, and Young Makena, "Defense Against the Dark Arts in Space: Protecting Space Systems from Counterspace Weapons" (Center For Strategic and International Studies, February 25, 2021), 10–12, https://www.csis.org/analysis/defense-against-dark-arts-space-protecting-space-systems-counterspace-weapons.

Table B-2. Passive, Technical Defenses as Defined in "Defense Against the Dark Arts in Space."[4]

Passive, Technical Defenses	
Exquisite SDA	*"Space domain awareness (SDA) includes identifying and tracking space objects, predicting where objects will be in the future, monitoring the space environment and space weather, and characterizing the capabilities of space objects and how they are being used."* Quickly detecting, characterizing, and attributing attacks increases the time for a defender to respond or plan a response.
Space Based RF Mapping	*"Space-based RF mapping is the ability to monitor and analyze the RF environment that affects space systems both in space and on Earth."* Improved situational awareness of the space environment enables the defender to distinguish between natural objects, naturally occurring phenomena, man-made activity, and anomalous activity. This extends to detecting, geolocating, and attributing sources of jamming, spoofing, and other electronic attacks.
Electromagnetic Shielding	*"Surrounding the electronics and cables within a satellite with shielding and adding surge protection devices throughout the RF and electrical system can protect against the effects of radiation, high-powered microwave attacks, and electromagnetic pulse weapons."* Protection from environmental radiation, HPM, and EMP weapons adds weight, design complexity, and additional testing requirements.
Filtering and Shuttering	*"Filters and shutters can be used on remote sensing satellites to protect sensors from laser dazzling and blinding."* Protecting sensors from dazzling and blinding adds weight and complexity and requires an understanding of the threat: an operational response can prevent acquisition of images.
Jam-resistant Waveforms	*"The way data is encoded for transmission on a radio wave (i.e., the waveform) is a key factor in how difficult that transmission is to jam or spoof. Different types of waveforms can be used to improve the resistance of communications systems to jamming and spoofing, such as using frequency hopping spread spectrum (FHSS) and interleaving."* Use of jam-resistant waveforms prevents corruption and reduces the probability that a jamming attack is successful. It may add latency and remains vulnerable to a high-powered wideband jammer with knowledge of the defended system.
Antenna Nulling & Adaptive Filtering	*"Satellites can be designed with antennas that "null" or minimize signals from a particular geographic region on the surface of the Earth or locations in space where jamming is detected. Adaptive filtering, in contrast, is used to block specific frequency bands regardless of where these transmissions originate."* A defender can protect against direction or frequency specific jamming but may also blocks valid users and signals. Some vulnerabilities to jamming remain.

[4] Harrison, Johnson, and Makena, 13–16.

Table B-3. Passive, Operational Defenses as Defined in "Defense Against the Dark Arts in Space."[5]

Passive, Operational Defenses	
Rapid Deployment	*"Rapid deployment is a form of protection that involves the speedy launch of a new or expanded space capability when needed. Keeping a capability on the ground until needed can protect the system from pre-emptive attack and limit an adversary's knowledge of the system and ability to factor it into strategic planning."* Severe limitations dull the potential benefit and impact of rapid deployment, including training and simulation requirements, storage and obsolescence, and launch constraints.
Reconstitution	*"Reconstitution can be used to quickly replace existing space capabilities by launching more satellites or bringing online more ground stations to restore functionality to an acceptable level for a particular mission, operation, or contingency after severe degradation."* The limitations of reconstitution are like rapid deployment however, the satellite constellation would retain some or most of the original vulnerability to an attacker's capability. The risk of obsolescence is increased but can be managed.
Maneuver	*"Satellite maneuver is an operational tactic that can be used by satellites fitted with chemical thrusters to avoid kinetic and some directed energy ASAT weapons."* Maneuver is subject to the realities of orbital mechanics (consider the mass ratios of the satellite, the corresponding delta-v imbalance of the attacker and defender, real time and accurate PNT and SDA). Maneuver is best employed in combination with active defenses. When employed, maneuver may disrupt current operations and require a return maneuver to its original orbital slot.
Stealth	*"Space systems can be operated and designed in ways that make them difficult to detect and track. Similar to platforms in other domains, stealthy satellites can use a smaller size, radar-absorbing coatings, radar-deflecting shapes, radar jamming and spoofing, unexpected or optimized maneuvers, and careful control of reflected radar, optical, and infrared energy to make themselves more difficult to detect and track."* Measuring the effectiveness of stealth, and the disruption to an attacker's kill chain is difficult. Engineering and adding additional features to a satellite will increase weight, complexity, and cost.
Deception and Decoys	*"Deception can be used to conceal or mislead others on the "location, capability, operational status, mission type, and/or robustness" of a satellite... Another form of deception could be changing the capabilities or payloads on satellites while in orbit."* Swapping payloads between satellites and constellations through plug-and-play on-orbit servicing requires further investment in on-orbit servicing--effective obfuscation would require regular resupply and servicing missions between multiple constellations with similar plug-and-play interfaces. Decoys can be physical objects or emitters.

[5] Harrison, Johnson, and Makena, 16–18.

Table B-4. Active, Space-Based Defenses as Defined in "Defense Against the Dark Arts in Space."[6]

Active, Space-Based Defenses	
Jamming and Spoofing	*"A jammer or spoofer can be used to disrupt sensors on an incoming kinetic ASAT weapon so that it cannot steer itself effectively in the terminal phase of flight. When used in conjunction with maneuver, this could allow a satellite to effectively "dodge" a kinetic attack."* Jamming and Spoofing can also be used against an attacker's space domain awareness sensors or to disrupt their communications with the ASAT. On-board systems would compete for weight and complexity with primary mission. Off-Board systems may be outside the field of view of the ASAT or would need to maneuver into the ASAT's predicted sensor field of view.
Laser Dazzling or Blinding	*"Laser systems can be used to dazzle or blind the optical or infrared sensors on an incoming ASAT weapon in the terminal phase of flight… Blinding an ASAT weapon's guidance system and then maneuvering to a new position (if necessary) could allow a satellite to effectively "dodge" a kinetic attack."* Use of directed energy weapon systems could also be used to ward off unwanted co-orbital inspection or space domain awareness satellites from performing their mission.
Shoot-Back	*"Satellites can be equipped with systems that either fire a physical projectile at an incoming ASAT weapon or use a high-powered laser or microwave system to have physically destructive effects, such as overheating or causing short circuits, on an incoming ASAT weapon."* The drawbacks of shooting back include the potential increase in orbital debris and added weight and complexity to the defensed satellite. Off-boarding defenses would require the establishment of a "Zone Defense," requiring additional maneuver capabilities. This capability has potential utility for both missile defense and space defense.
Physical Seizure	*"A space vehicle capable of docking with, manipulating, or maneuvering other satellites or pieces of debris can be used to thwart space-based attacks or mitigate the effects after an attack has occurred. Such a system could be used to physically seize a threatening satellite that is being used to attack or endanger other satellites or to capture a satellite that has been disabled or hijacked for nefarious purposes."* Major constraints include time, propellant, and the seizing satellite's original orbit.

[6] Harrison, Johnson, and Makena, 18–20.

APPENDIX C.

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[External] Re: Copywrite Permission

Alexander Genzel <alexander.genzel@outlook.de>
Fri 4/8/2022 12:18 AM
To: Alexander Jehle <ajehle@mines.edu>

Alex,

first of all, congratulations for your successful thesis! I'm sure it feels great to be the first Space Resources PhD and wish you all the best in a very promising career with lots of opportunities to bring in this very unique expertise.

I agree with using our paper as a chapter within your thesis.

Thanks for keeping in touch with the editors.

I'm also letting you know that I have left active service in the military and switched to the reserve. I will continue working on Responsive Space Operations and Dual Use small satellites at my own company which is being supported by the Armed Forces Entrepreneurship center. And we are also establishing our first US office by fall or winter this year.

Also, I will be stopping by at CSM for my graduation and will be around the area from the 02nd to 16th of May. I'm not sure anymore if you are based around there, but just in case...

Maybe we could do a call sometime soon again? I'd be curious to catch up with you and see how things have evolved on the US side.

Best

Alexander

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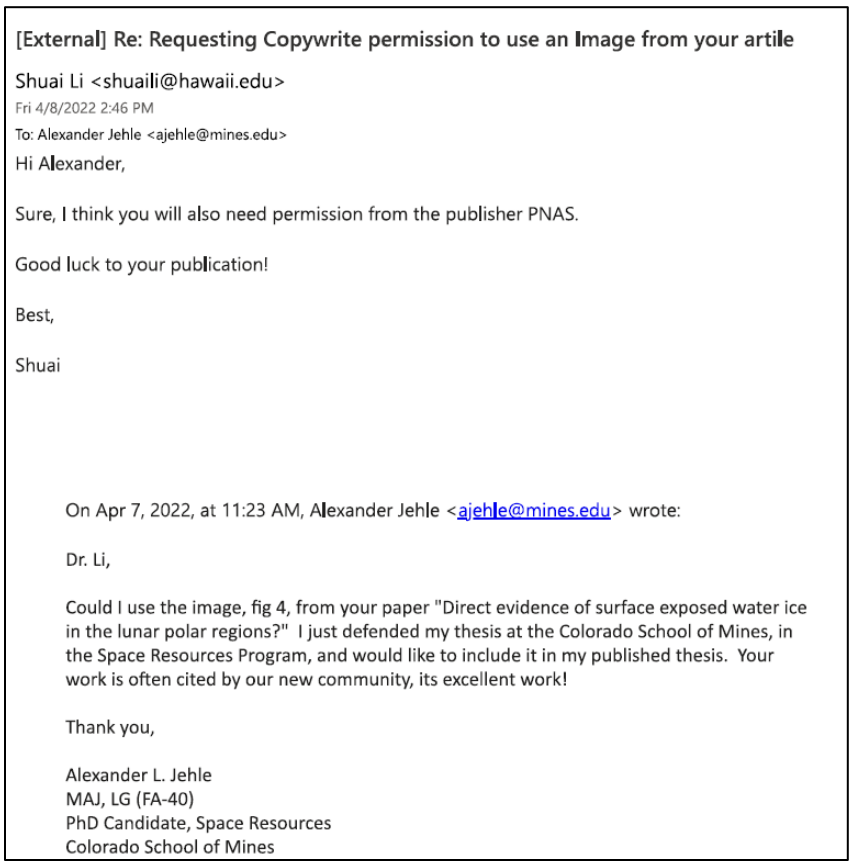

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Shuai Li <shuaili@hawaii.edu>
Fri 4/8/2022 2:46 PM
To: Alexander Jehle <ajehle@mines.edu>

Hi Alexander,

Sure, I think you will also need permission from the publisher PNAS.

Good luck to your publication!

Best,

Shuai

On Apr 7, 2022, at 11:23 AM, Alexander Jehle <ajehle@mines.edu> wrote:

Dr. Li,

Could I use the image, fig 4, from your paper "Direct evidence of surface exposed water ice in the lunar polar regions?" I just defended my thesis at the Colorado School of Mines, in the Space Resources Program, and would like to include it in my published thesis. Your work is often cited by our new community, its excellent work!

Thank you,

Alexander L. Jehle
MAJ, LG (FA-40)
PhD Candidate, Space Resources
Colorado School of Mines

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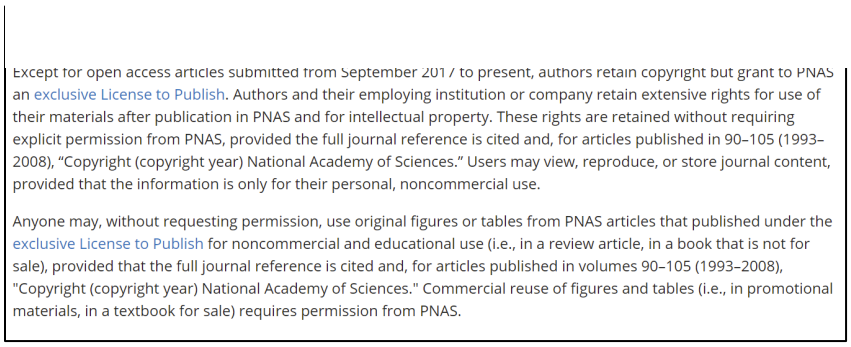

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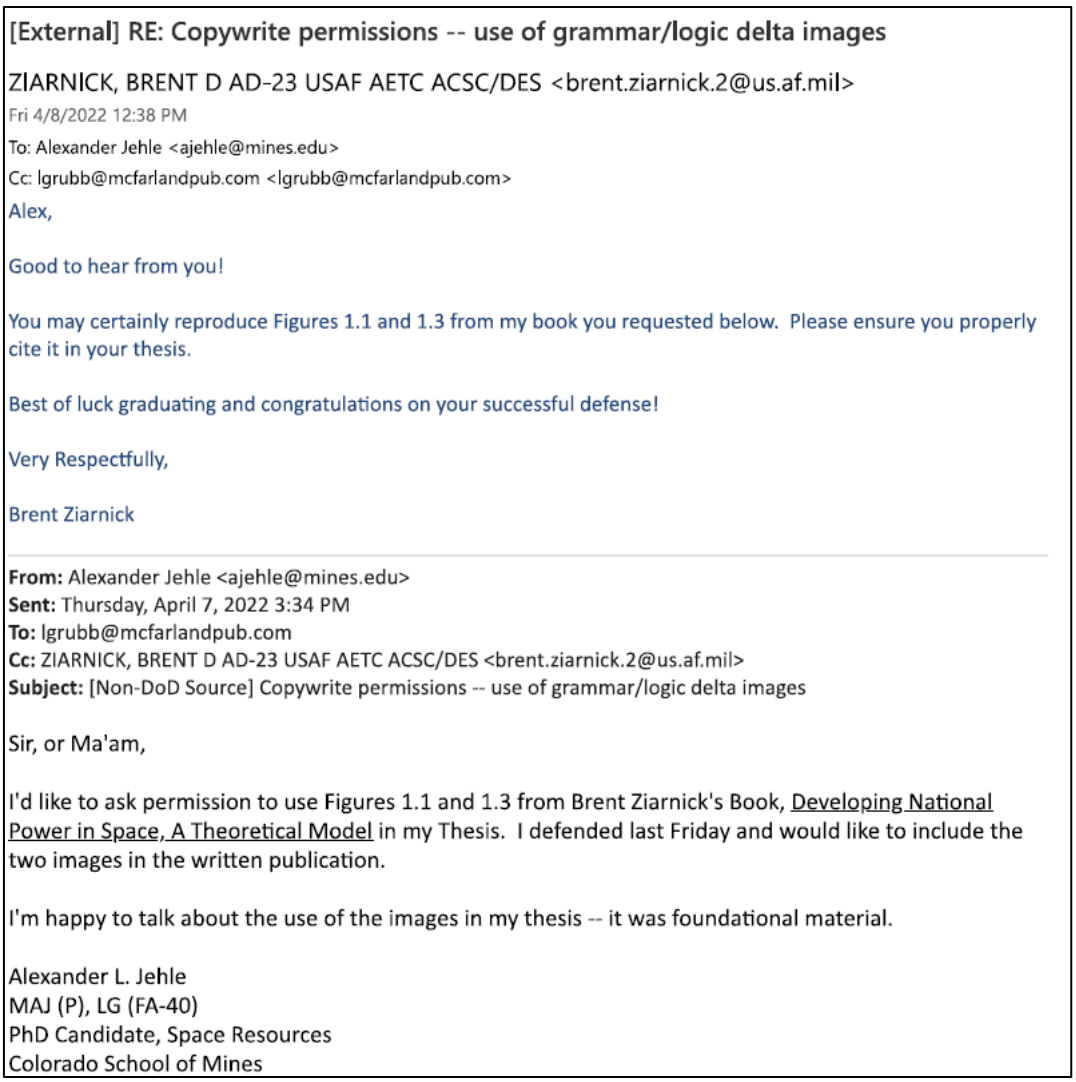

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ZIARNICK, BRENT D AD-23 USAF AETC ACSC/DES <brent.ziarnick.2@us.af.mil>
Fri 4/8/2022 12:38 PM
To: Alexander Jehle <ajehle@mines.edu>
Cc: lgrubb@mcfarlandpub.com <lgrubb@mcfarlandpub.com>

Alex,

Good to hear from you!

You may certainly reproduce Figures 1.1 and 1.3 from my book you requested below. Please ensure you properly cite it in your thesis.

Best of luck graduating and congratulations on your successful defense!

Very Respectfully,

Brent Ziarnick

From: Alexander Jehle <ajehle@mines.edu>
Sent: Thursday, April 7, 2022 3:34 PM
To: lgrubb@mcfarlandpub.com
Cc: ZIARNICK, BRENT D AD-23 USAF AETC ACSC/DES <brent.ziarnick.2@us.af.mil>
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I'm happy to talk about the use of the images in my thesis -- it was foundational material.

Alexander L. Jehle
MAJ (P), LG (FA-40)
PhD Candidate, Space Resources
Colorado School of Mines

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