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COMPARATIVE CISLUNAR STRATEGIES

by

Matthew J. Serio

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Thesis Advisor:
Second Reader:

James C. Moltz
Matthew R. Crook

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COMPARATIVE CISLUNAR STRATEGIES

Matthew J. Serio
Lieutenant, United States Navy
BSE, Miami University, 2016

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September 2023**

Approved by: James C. Moltz
Advisor

Matthew R. Crook
Second Reader

Afshon P. Ostovar
Associate Chair for Research
Department of National Security Affairs

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ABSTRACT

As interest in cislunar space rapidly increases around the globe, a new, 21st-century space race has begun for cislunar advantage. While this race continues, time is fleeting for nations to establish a clear cislunar space strategy. The question is, what kind of cislunar space strategy will effectively establish cislunar space power? Near-Earth space strategies cannot simply be copied due to the starkly different nature of cislunar space. This thesis identifies four possible strategies, varying in degrees of cooperation, and juxtaposes them across three case studies of specific, operational cislunar challenges: space situational awareness, infrastructure, and energy. Ultimately, a strategy of commercial internationalism is recommended. Supported by international coalitions and coordination with private companies, this strategy presents the most promising and most sustainable means of achieving cislunar space power and overcoming the complex challenges presented in the cases of space situational awareness, infrastructure, and energy.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	Three-Dimensional
AMF	Additive Manufacturing Facility
ASI	Italian Space Agency
CSA	Canadian Space Agency
DSAC	Deep Space Atomic Clock
ESA	European Space Agency
GEO	Geostationary Orbit
GMT	Greenwich Mean Time
GPS	Global Positioning System
He-3	Helium-3
HEO	Highly Elliptical Orbit
HST	Hubble Space Telescope
ISECG	International Space Exploration Coordination Group
ISON	International Scientific Optical Network
ISS	International Space Station
JAXA	Japanese Aerospace Exploration Agency
JHU APL	John Hopkins University Applied Physics Laboratory
JWST	James Webb Space Telescope
LCROSS	Lunar CRater Observation and Sensing Satellite
LCT	Lunar Cold Trap
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
NASA	National Aeronautics and Space Administration
NEO	Near Earth Objects
ODPO	Orbital Debris Program Office

OST	Outer Space Treaty
PNT	Position Navigation and Timing
PSR	Permanently Shadowed Region
RF	Radio Frequency
RTG	Radioisotope Thermoelectric Generator
SSA	Space Situational Awareness
SSN	Space Surveillance Network
SST	Space Surveillance and Tracking
SWE	Space Weather
UN	United Nations
US	United States
USSR	Union of Soviet Socialist Republics
UT	Universal Time

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I. INTRODUCTION

What kind of strategy is needed to establish and develop cislunar space power? With the coming expansion of human activities on the Moon, to include a possible permanent human presence, and the desire of many nations to conduct research on and mine the Moon, a new 21st century space race is emerging. Until now, much of outer space strategy has been within the confines of Earth orbital space and has been led by individual countries. But cislunar space strategy is likely to require different tools and perhaps different political coalitions. Endeavours such as the United States (US)-led Artemis Program seek to lay the foundation for a cislunar space power strategy. China and Russia are leading a rival approach. But the different environment of cislunar space may call for vastly different approaches than the strategies that worked in Earth orbital space during the Cold War. In the past, goods and services developed in Earth orbital space have primarily served the Earth economy, but now consideration must be given to how space-derived or space-built goods and services might help develop a “large-scale, largely self-sufficient, developed space economy.”¹ The U.S. and its partners aim to address these challenges both through national space program efforts like those of the National Aeronautics and Space Administration (NASA) and through private companies.

In addition to the various tools, possible political coalitions, and the different environments that must be examined, the goals of this cislunar space strategy must be identified in order to ensure that other efforts are ultimately contributing to those goals. Where the 20th century space race sought prestige and potential global space supremacy, this thesis will identify how this 21st century space race will focus on creating a sustainable presence that will enable continued operations, industrialization, and future exploration beyond that of cislunar space. In addition to clearly identifying the goals of a cislunar space power strategy, this thesis will analyse the two most critical aspects required to achieve those goals: space-based infrastructure and lunar-based infrastructure. Capabilities such as space situational awareness (SSA), infrastructure, and energy will be addressed with

¹ Matthew Weinzierl, “Space, the Final Economic Frontier,” *Journal of Economic Perspectives* 32, no. 2 (Spring 2018): 174, <https://doi.org/10.1257/jep.32.2.173>.

respect to how they contribute to the greater objectives of the strategy as a whole. Lastly, this thesis will review how the U.S. compares to global competitors in this 21st century space race.

A. SIGNIFICANCE OF THE RESEARCH QUESTION

On January 14th, 2004, President Bush gave a speech at NASA in which he advocated for the return of humans to the Moon, and one day beyond.² For the first time since the end of the Apollo Program, a call to return to the lunar surface emerged. Dubbed the Constellation Program, the effort struggled through five years of cost, schedule, communication, and organizational difficulty until it was canceled in 2010.³ President Obama initiated the Asteroid Redirect Mission where a robotic effort would redirect a small asteroid into a more stable orbit and then manned missions would explore the asteroid.⁴ President Obama canceled President Bush's program, and President Trump canceled President Obamas' mission, returning focus back to the Moon. Despite this repetition of cancellation, a more important consistency emerged: each presidential administration maintained an effort to return manned missions to space, one that was outlined in their National Space Policies.⁵ While President Biden, has not yet released a National Space Policy, his administration wasted no time publishing the *United States Space Priorities Framework*, an accomplishment of his first year in office, where he too asserted the intention of returning man to space, and more specifically, to the Moon.⁶ Despite the

² James Clay Moltz, *The Politics of Space Security: Strategic Restraint and the Pursuit of National Interests*, 3rd ed. (Stanford, CA: Stanford University Press, 2019), 277.

³ L. Dale Thomas et al., "NASA's Constellation Program: The Final Word," *Systems Engineering* 16, no. 1 (2013): 71, 77, <https://doi.org/10.1002/sys.21219>.

⁴ Michele Gates et al., "NASA's Asteroid Redirect Mission Concept Development Summary," in *2015 IEEE Aerospace Conference* (2015 IEEE Aerospace Conference, IEEE, 2015), 1–13, <https://doi.org/10.1109/AERO.2015.7119163>.

⁵ White House, *National Space Policy of the United States of America* (Washington, DC: White House, 2010), 11, <https://www.hsdl.org/c/abstract/?docid=22716>; White House, *National Space Policy of the United States of America* (Washington, DC: White House, 2020), 1, <https://www.hsdl.org/c/abstract/?docid=847883>.

⁶ White House, *United States Space Priorities Framework* (Washington, DC: White House, 2021), 5, <https://www.whitehouse.gov/wp-content/uploads/2021/12/United-States-Space-Priorities-Framework--December-1-2021.pdf>.

ideological and political differences spanning these four presidential administrations, the call to return to space—and ultimately the Moon—has remained a constant since that January 14th when President Bush gave his speech.

While going to the Moon is no longer a new feat, the possibilities of permanent settlement, coordinated multi-national research and experimentation, and the mining of the Moon and other celestial bodies have never been done before. Andrew Brearley expresses this sentiment similarly stating, “that the moment of the Moon becoming a useful resource is imminent.”⁷ The Moon and greater cislunar space continues to attract attention from all areas of the globe, the timing could not be more appropriate. This is precisely why a strategy is necessary.

B. BRIEF TECHNICAL AND LEGAL CONTEXT FOR CISLUNAR SPACE

1. Physical Dimensions

The definition of cislunar space that will be considered for the remainder of this thesis comes from the Cislunar Technology Strategy Interagency Working Group: a body designed to “coordinate science and technology policy, strategy, and Federal research and development pertaining to Cislunar space.”⁸ The working group was derived from the subcommittee on Cislunar Science & Technology as part of the National Science and Technology Council within the Office of Science and Technology Policy.⁹ The working group defines cislunar space as “the three-dimensional volume of space beyond the Earth’s geosynchronous orbit that is mainly under the gravitational influence of Earth and/or the Moon. Cislunar space includes the Earth-Moon Lagrange Point regions, trajectories utilizing those regions, and the lunar surface.”¹⁰ This effectively reduces cislunar space to all space beyond Earth orbit out to, and including, the Moon. Possibilities for this space are

⁷ Andrew Brearley, “Mining the Moon: Owning the Night Sky?,” *Astropolitics* 4, no. 1 (2006): 48, <https://doi.org/10.1080/14777620600762790>.

⁸ National Science & Technology Council, *2022 National Cislunar Science and Technology Strategy* (Washington, DC: White House, 2022), ii, <https://www.whitehouse.gov/wp-content/uploads/2022/11/11-2022-NSTC-National-Cislunar-ST-Strategy.pdf>.

⁹ National Science & Technology Council, ii.

¹⁰ National Science & Technology Council, 3.

broad and largely untested as of now. However, as alluded to in previous sections, the intentions and aspirations for this space are as vast as space itself.

The area of cislunar space most generally known is that of the lunar surface. While the Apollo missions are best known for the historic human landing on the surface achieved by *Apollo 11*, successful robotic missions by *Surveyor 1*, 3, 5, 6, and 7 provided invaluable information to NASA regarding the lunar soil, called regolith, prior to a manned attempt. As a result of these robotic missions, many questions about the lunar surface were answered before Neil Armstrong took his “small step.”¹¹ The Apollo missions enabled extraordinary scientific research to be conducted about the lunar surface. *Apollo 11*, 12, 14, 15, 16, and 17 returned 21.6, 34, 42, 77, 96, and 110 kilograms of samples, respectively.¹² The Moon has been the object of man’s desire in space since President Kennedy’s famous 1961 speech, and it is no surprise that it maintains that same status to this day, considering that it is the closest celestial body to the Earth.¹³

Following the lunar surface, the aspect of cislunar space most discussed are the Lagrange point regions, also referred to as the Lagrange Libration Points or L-points. Attributed to French scientist Joseph Lagrange in the 18th century, these five points of equilibrium—named L1 through L5—exist whenever an astronomical body orbits another. In the case of cislunar space, those two bodies are the Earth and the Moon or the Sun and the Earth. Two notable examples of current applicability for the Lagrange points in the Sun-Earth system are the Solar and Heliospheric Observatory positioned at L1, and the more well-known James Webb Space Telescope currently positioned at L2.¹⁴ It has yet to

¹¹ Arlin Crotts, *The New Moon: Water, Exploration, and Future Habitation* (New York: Cambridge University Press, 2014), 23, 26.

¹² Crotts, 33, 34, 38, 39.

¹³ John F. Kennedy, “Address to Joint Session of Congress May 25, 1961,” Historic Speeches, May 25, 1961, <https://www.jfklibrary.org/learn/about-jfk/historic-speeches/address-to-joint-session-of-congress-may-25-1961>.

¹⁴ Elizabeth Howell, “SOHO: Spying on the Sun,” *Space*, April 15, 2016, <https://www.space.com/18501-soho-solar-heliospheric-observatory.html>; Michelle Thaller and Rob Gutro, “NASA - ‘L2’ Will Be the James Webb Space Telescope’s Home in Space,” *NASA Mission News*, June 23, 2010, <https://www.nasa.gov/topics/universe/features/webb-l2.html>.

be clearly codified whether the Lagrange points in the Earth-Moon system will provide a similar utility as those in the Sun-Earth system.

Also within cislunar space is the consideration of lunar orbits. Like the Earth, the Moon exerts a gravitational force and can hold objects within a mathematically predictable pattern, or orbit, around itself. Up to this point in man's exploration of space, there has been little effort to exploit this possibility. However, as will be discussed later in this thesis, the Artemis Program seeks to station a *Lunar Gateway* in orbit around the Moon to leverage the untapped potential of this facet of cislunar space.¹⁵

Given the aforementioned definition of cislunar space and the manner in which these three areas of cislunar space—lunar surface, Lagrange points, and lunar orbit—are intimately involved with one another, consideration for each aspect ought to be weighed heavily when developing any cislunar strategy. Now that the physical boundaries of cislunar space have been outlined, the legal boundaries must next be understood.

2. Legal Concerns

Healthy doses of fear and proactive foresight drove the governments of the U.S. and the Union of Soviet Socialist Republics (USSR) to lead the way in developing the legal structure that is still observed in space today. Ultimately adopted by the United Nations (UN) General Assembly, the cornerstone of this structure is the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies; this treaty is often referred by its abbreviated nickname as the “Outer Space Treaty” (OST).¹⁶ Four additional treaties followed the OST to further bolster the ideals that it brought forward: the Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space (known as the Rescue Agreement of 1968); the Convention on International Liability for Damage Caused by Space Objects (known as the Liability Convention of 1972); the

¹⁵ Kelli Mars, “Gateway Overview,” Gateway, August 17, 2016, <http://www.nasa.gov/gateway/overview>.

¹⁶ United Nations Office for Outer Space Affairs, “Treaties,” History, accessed January 28, 2023, <https://www.unoosa.org/oosa/en/aboutus/history/treaties.html>.

Convention on Registration of Objects Launched into Outer Space (known as the Registration Convention of 1975); and the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (known as the Moon Agreement of 1979).¹⁷ While this robust collection of governing documents exists and is largely accepted, the unfolding attention that cislunar space draws may find that this regime is no longer sufficient to properly maintain the stability that has been taken for granted since the U.S. and USSR first sought it in the peaks of the Cold War.

Of the five treaties mentioned above that currently comprise the legal parameters of space, the Moon Agreement of 1979 stands as an outlier. Only ratified by seven, non-spacefaring countries, Brearley speculates that this treaty will never be accepted by major space powers.¹⁸ This is most immediately problematic because the Moon Agreement, according to Brearley, is “the only treaty that attempts to find a means for managing lunar resources.”¹⁹ Seeing as how lunar resources may quickly be a driving force behind global powers returning to the Moon, this treaty’s validity—or lack thereof—may rapidly become a key concern much sooner than many anticipated.

C. LITERATURE REVIEW

Various scholars categorize schools of thought on space strategy differently. Described as alternative space “doctrines” by Lupton and as “schools of thought” by Klein, four predominate options emerge for the military role in space.²⁰ Lupton succinctly characterizes each strategy as follows: space should be a domain absent of military forces (sanctuary); the military can use space assets, but should not rely on them in wartime because they are not likely to survive (survivability); space-based weapons can dictate a defensive stalemate in exchange of a mutually assured destruction deterrent (high-ground);

¹⁷ United Nations Office for Outer Space Affairs; United Nations General Assembly, *United Nations Treaties and Principles on Outer Space* (New York: United Nations, 2002), iii, <https://digitalcommons.unl.edu/spacelawdocs/10/>.

¹⁸ Brearley, “Mining the Moon,” 48.

¹⁹ Brearley, 48.

²⁰ David E. Lupton, *On Space Warfare: A Space Power Doctrine* (Maxwell Air Force Base, AL: Air University Press, 1988), 39–42; John J. Klein, *Space Warfare: Strategy, Principles, and Policy* (London: Routledge, 2006), 130–34.

and, that the ability to dissuade hostile action is increased if you control space (control).²¹ Using the same terminology, Klein argues that none of these perspectives proves sufficient for an all-encompassing space strategy, but states that they are worth comparing for the perspective they provide concerning space weaponization.²² Each of these options provides militaries the opportunity to use space in a peaceful manner if that is the desire. Karl Mueller highlights that while there can be many or only a few different options, they are not necessarily mutually exclusive; he generalizes his six classifications, three under a “pro-sanctuary” school (idealist, internationalist, and nationalist) and three under a “pro-weaponization” school (space racers, space controllers, and space hegemonists).²³ However, in addition to his characterization under these schools of thought, he further emphasizes that it is likely the case that certain approaches overlap between various schools of thought.²⁴ This thesis will identify four main space strategies as extrapolations of pre-existing schools of thought in the professional academic community. These four strategies exist on a spectrum of cooperation. Ranging from least cooperative to most cooperative, these strategies are: *space dominance*, *technological nationalism*, *commercial internationalism*, and *global space consortium*.

1. Space Dominance

Certainly, the most antagonistic strategy that emerges from existing literature is that of *space dominance*: a strategy developed by Dolman. Paying homage to the classic principle, *Realpolitik*, Dolman acknowledges that “political realism is a central theme of this work” and ascribes his perspective as *Astropolitik*.²⁵ Reenforcing this choice in nomenclature, Dolman identifies that a severe realist perspective is not necessarily a guarantee when considering space strategy, rather it has presented itself as a predictable

²¹ Lupton, *On Space Warfare*, 35–37.

²² Klein, *Space Warfare*, 130–31.

²³ Karl P. Mueller, “Totem and Taboo: Depolarizing the Space Weaponization Debate,” *Astropolitics* 1, no. 1 (January 2003): 9, <https://doi.org/10.1080/1477-760391832499>.

²⁴ Mueller, 9.

²⁵ Everett C. Dolman, *Astropolitik: Classical Geopolitics in the Space Age* (London: Frank Cass, 2002), 1.

pattern that leaders should prepare themselves for, and as a reminder “of the horrible depths to which other . . . strategies of dominance ultimately degenerated.”²⁶ In a similar vein, *space dominance* can be perceived as a strategy in which drastic regression in existing international treaties and means of cooperation, would occur, and all of the apparent progress that has been made toward stability in space to this point would be undone for the purpose of unilateral advantage and hegemonic dominance.

The themes of *space dominance* and *Astropolitik* align in the steps a nation would take in order to embrace this strategy. A nation would need to remove itself from the restrictions of the “flawed” legal structure currently in place.²⁷ Once the limitations of the Outer Space Treaty are removed, a nation would be free to act however it has the capability. Therefore, it would logically seek to establish control over key areas that influence space—on Earth, in near-Earth space, and in cislunar space. Dolman emphasizes that “control of Earth space not only guarantees long-term control of the outer reaches of space, but it also provides a near-term advantage on the terrestrial battlefield.”²⁸ The ability to control key launch positions on Earth, low-Earth orbits, geostationary orbits, and even the Lagrange points would provide a dominant nation a significant advantage over all others. Lambeth, along with other scholars in this school, describes space as the ultimate “high ground,” and it is in this same light that Dolman suggests a nation sit above the Earth and deny any other nation the ability to enter its domain.²⁹

Channeling the powerful words of Thucydides that “the strong do what they can and the weak suffer what they must,”³⁰ *space dominance* embraces a belief in the strategic necessity of a nation to exploit and expand any disparity between itself and any perceived current, or future, competitor. Disregarding all opportunities for mutual support to any

²⁶ Dolman, 2–3.

²⁷ Dolman, 141.

²⁸ Dolman, 70.

²⁹ Benjamin S. Lambeth, *Mastering the Ultimate High Ground: Next Steps in the Military Uses of Space* (Santa Monica, CA: RAND Corporation, 2003), 14, https://www.rand.org/pubs/monograph_reports/MR1649.html; Dolman, *Astropolitik*, 157.

³⁰ Richard K. Betts, ed., *Conflict after the Cold War: Arguments on Causes of War and Peace*, 4th ed. (Boston: Pearson, 2013), 70.

other nation—even if it in turn benefits one’s own nation—the mantra of self-serving action above all else reigns in this strategy.

2. Technological Nationalism

A second strategy to consider is what we might call *technological nationalism*. Embraced by some scholars in the frame of a technocracy, McDougall’s definition of this term most appropriately aligns with the theme of *technological nationalism*: “the institutionalization of technological change for state purposes.”³¹ The space race of the 20th century saw the USSR and U.S. embrace the spirit of *technological nationalism* as they sought prestige and space supremacy over each other through the means of military and state sponsored space efforts. *Technological nationalism*, as well as the remaining strategies that will be discussed, maintains that the current international legal structure affecting space should remain intact, and possibly bolstered with additions.

Identifying space as a “subset of foreign policy,” Johnson-Freese suggests that a technologically driven space strategy should “refocus efforts back to space support and force enhancement in the near term, and away from active forms of space control.”³² This intent clearly separates *technological nationalism* from *space dominance*. Lupton reminds us, though, that there are always visible and invisible “aggressive military space activities . . . behind a veil of secrecy” taking place for the advancement of a nations interests in addition to the civil services provided from space.³³ The question that remains is how this military action should complement those non-military services being provided. Johnson-Freese asserts that “linking ‘peaceful purposes’ to national interests more closely connects space to defense and the military than ever before.”³⁴ It is not a secret that a nation’s military acts as it does in order to advance its nation’s interests; *technological nationalism*

³¹ Walter A. McDougall, *The Heavens and the Earth: A Political History of the Space Age* (New York: Basic Books, 1988), 5.

³² Joan Johnson-Freese, *Space as a Strategic Asset* (New York: Columbia University Press, 2007), 257, 244.

³³ Lupton, *On Space Warfare*, 1, 39–40.

³⁴ Johnson-Freese, *Space as a Strategic Asset*, 235.

is the embodiment of the relationship between state driven technological advance and the military.

3. Commercial Internationalism

A third strategy that emerges from the literature might be called *commercial internationalism*. This strategy takes into account the importance of activities undertaken by non-state actors. *Commercial internationalism* leverages the contributions allied nations and the commercial sector can provide. Moltz characterizes this shift from the 20th century into the 21st century under the term netocracy as “a new form of organization based on public-private partnerships, distributed architectures, rapid innovation, and the use of multiple commercial and allied partners.”³⁵ Moltz also uses adjectives such as resilient, networked, flexible, and disaggregated to emphasize the utility of a strategy that aligns with *commercial internationalism*.³⁶ Separating itself from *technological nationalism*, *commercial internationalism* accentuates how the whole is greater than the sum of its parts.

Gentoku Toyoma focuses on the benefits of multilateral cooperation and alliances in support of such a strategy. He groups mutual benefit opportunities between allied nations into defensive operations, reconstitution, and resilience. In extending the category of resilience, he identifies disaggregation, distribution, and diversification as prospects for international cooperation in space strategy.³⁷ Not only does the ability to share information among allies enhance the effectiveness of their military capabilities, but every additional nation that contributes to burden sharing lightens the load to the other nations—whether financially, materially, or innovatively. The synergistic impact of this effect can be substantial. This aspect of *commercial internationalism* also links the allied effort with that of the private sector; Toyoma highlights that if allied commercial industry is properly distributed and diversified, it can create a positive feeding cycle where the private sector

³⁵ James Clay Moltz, “The Changing Dynamics of Twenty-First-Century Space Power,” *Journal of Strategic Security* 12, no. 1 (April 2019): 78, <https://doi.org/10.5038/1944-0472.12.1.1729>.

³⁶ Moltz, 69, 78.

³⁷ Gentoku Toyoma, “Countering Threats in Space through International Cooperation,” *Space Policy* 55 (February 2021): 2–3, <https://doi.org/10.1016/j.spacepol.2020.101387>.

gains more business and support while enhancing the allied effort as a whole—a win-win situation.³⁸

Vedda further advocates that public and private sectors should be partners, and summarizes the important relationship between the two by saying:

The public sector has an important role to play in performing basic research, buying down risk, and otherwise creating an environment that will encourage private-sector entry. History demonstrates that big undertakings in modern American society are collaborations between the public and private sectors. It is counterproductive—and unsupported by historical evidence—to argue that either sector should go it alone. History disproves notions that only governments can or will develop space, that only the private sector is capable of creating solutions to problems, or that regulations always harm industry.³⁹

Through examples in maritime, rail, highway, and aviation transportation, Vedda demonstrates how innovation through emerging technologies thrives when public and private efforts work together.⁴⁰ Nations can enable an environment where *commercial internationalism* can succeed by “creating and improving technologies, giving out land grants, formulating safety regulations, and improving the stability and predictability of the business environment.”⁴¹ This kind of relationship is not one that blossoms overnight; it is one that must be nurtured over time with the intent of employing a strategy like *commercial internationalism*.

4. Global Space Consortium

A fourth strategy to consider is what we might call a *global space consortium*. Many scholars advocate for the creation of an entity that governs over the domain of space on behalf of the whole of Earth outside of any individual nation or coalition.

³⁸ Toyoma, 3.

³⁹ James A. Vedda, *Becoming Spacefarers: Rescuing America’s Space Program* (Bloomington, IN: Xlibris Corp, 2012), 193.

⁴⁰ Vedda, 103–30.

⁴¹ Vedda, 130.

Brearley asserts that the OST framed the Moon under the legal conception of *res communis*, or a global commons, a significant change in status from the previous view where the Moon was considered *res nullius*.⁴² McDougall differentiates *res nullius* as “space as belonging to no one,” *res communis omnium* as “space as ‘the heritage of all mankind,’” and *res extra commercium* as space “with sovereignty and jurisdiction vested in the UN.”⁴³ Robinson and White highlight that McDougall’s *res communis omnium* can be seen as a derivative of the more generic *res communis* which they define as simply “common heritage;” it is this definition that Brearley uses.⁴⁴ The relationship that *res communis* expounds from McDougall’s is slight but significant due to the omission of the word *omnium*. Moltz is one of many scholars to draw comparisons between the Moon and other commons such as the polar ice caps—specifically Antarctica—the deep seabed, and the New World as it was initially discovered.⁴⁵ These scholars highlight that while there are similarities between many of these commons, none provide a complete enough analogy to yield a one-to-one solution. Dolman nods to the well-known Hardin piece when concluding that the tragedy of the commons, as applicable to the Moon, is that mankind is unable to properly regulate itself without a bureaucratic organization overseeing it.⁴⁶ Nancy Gallagher identifies the necessity of such an entity in order to avoid this tragedy.⁴⁷ Gallagher describes the common objectives of nations who employ a *global space consortium* need to pursue by saying:

Space cooperation should have the positive objective of organizing space users to *work together and accomplish more for less than they could on their*

⁴² Brearley, “Mining the Moon,” 46–47.

⁴³ McDougall, *The Heavens and the Earth*, 187.

⁴⁴ George S. Robinson and Harold M. White, *Envoys of Mankind: A Declaration of First Principles for the Governance of Space Societies* (Washington, DC: Smithsonian Institution Press, 1986), 185.

⁴⁵ Moltz, *The Politics of Space Security*, 14; James Clay Moltz, “Toward Cooperation or Conflict on the Moon?: Considering Lunar Governance in Historical Perspective,” *Strategic Studies Quarterly* 3, no. 3 (2009): 83, <https://www.jstor.org/stable/26268666>.

⁴⁶ Dolman, *Astropolitik*, 103.

⁴⁷ Nancy Gallagher, “Space Governance and International Cooperation,” *Astropolitik* 8, no. 2–3 (2010): 259, <https://doi.org/10.1080/14777622.2010.524131>.

own, not just the negative objectives of minimizing inadvertent interference, environmental degradation of deliberate attack [emphasis added].⁴⁸

Manifested in the creation of a global institution, *global space consortium* would allow nations a body in which the behavior of all would be shaped for the benefit of all.⁴⁹

Wolter traces support for the creation of such an entity back to 1952⁵⁰ He further cites Nicolas Matte in describing the inertia to be overcome in order to make this manifestation of *global space consortium* a reality, saying:

Enormous political efforts will be required to overcome the existing tendencies of states to put their national security above international security. This will depend in particular on the common understanding that in the area of common security an antagonistic juxtaposition of national and international security is wrong, and that an institutional structure is needed to give all states the feeling that their national security is best served by an institutional safeguard of cooperative security in outer space.⁵¹

Beyond the establishment of this entity, the matter of authority would remain an obstacle to overcome. Wolter quotes Horsford calling for “full executive powers” to be granted.⁵² To better gauge this level of authority, Brearley draws parallels between the authority of the International Seabed Authority—as it governs the global common of the deep seabed—and his proposed Lunar Resource Authority.⁵³

Regardless of the name of such an entity, the *global space consortium* strategy is rooted in logic provided by Gallagher: specifically, that all users of space should engage in the shared objectives of maintaining the use of space for peaceful purposes, shielding

⁴⁸ Gallagher, 271.

⁴⁹ Nancy Gallagher, *Towards a Reconsideration of the Rules for Space Security* (College Park, MD: University of Maryland, 2005), 35, https://publicpolicy.umd.edu/sites/default/files/2019-08/space_rules2006.pdf.

⁵⁰ Detlev Wolter, *Common Security in Outer Space and International Law* (Geneva: UNIDIR, 2006), 171.

⁵¹ Wolter, 186.

⁵² Wolter, 175.

⁵³ Brearley, “Mining the Moon,” 56.

capabilities in space from danger, and using those capabilities for the greatest common value.⁵⁴

D. POTENTIAL EXPLANATIONS AND HYPOTHESES

As satisfying as it would be to conclude that any one of these strategies to cislunar space is superior to the others, that may not be the case due to the different advantages of each strategy. Also, as Mueller notes, these strategies are not necessarily mutually exclusive.⁵⁵ It is quite possible that a nation employing *technological nationalism* or *commercial internationalism* might shift toward *space dominance* if it deems a more hostile strategy necessary, or toward *global space consortium* if it deems a more cooperative strategy as necessary. As this thesis continues to explore each of these strategies in the areas of SSA, infrastructure, and energy, it can be anticipated that one strategy may be more advantageous in one or two of these areas while another strategy might provide better opportunities in the third area.

In examining these three cases, it can be expected that the areas of SSA and infrastructure will be best supported by a *commercial internationalism* strategy due to the magnitude of planning, work, and cooperation that each of these areas requires. With a coalition of allies and appropriate relationships with the private sector, a nation's individual requirements will be drastically reduced with the addition of every contributing nation or company while the benefit to the whole becomes even greater due to synergies from cooperation. It can similarly be deduced that the area of energy will be better supported by a *technological nationalist* strategy; while all three areas will be new to cislunar space, SSA and infrastructure have been developed to an extent in Earth orbital space, but energy least of all. In this way, *technological nationalism* might be expected to produce the quickest development in the area of energy.

⁵⁴ Gallagher, "Space Governance and International Cooperation," 273.

⁵⁵ Mueller, "Totem and Taboo," 9.

E. RESEARCH DESIGN

The research method supporting this thesis is equal parts analytical and comparative. The research method is analytical in the way that the thesis will identify necessary operational requirements, challenges and capability gaps, and possible opportunities within the critical areas of SSA, infrastructure, and energy of cislunar space. The research method is comparative in the way that the thesis will juxtapose *space dominance*, *technological nationalism*, *commercial internationalism*, and *global space consortium* with respect to each of these three aspects of cislunar space.

Each case study will identify objective requirements and then an analysis of each strategy will discuss how they might be expected to meet or fail to meet these operational imperative requirements. There are inherently aspects of overlap between these four strategies, but qualities at the core of each can stand alone, and those qualities may offer an implementing nation benefits in some areas of cislunar strategy, while they may also hinder in other areas. The dependance of any future operations in, or beyond, cislunar space on the areas of SSA, infrastructure, and energy justifies the substantial attention to these areas; without substantial capabilities in each of these areas it would be difficult to imagine a situation where a sustainable lunar base or settlement could develop. Lastly, shortcomings and potential pitfalls of each strategy will be identified in order that they be actively avoided. This thesis will be supported by open-source literature relevant to the subject of each case.

F. THESIS OVERVIEW

This thesis is structured into five chapters, with the first and last being the introduction and conclusion respectively. The second chapter will examine the first of three case studies: SSA and how its foundational nature effectively enables all operations in cislunar space. The third chapter discusses the second case study: lunar infrastructure, including space-based as well as Moon-based infrastructure. The fourth chapter will explore: energy and how collection and distribution of these resources will support manned efforts, industry, and propulsion in cislunar space. The fifth chapter will provide a robust comparison of *space dominance*, *technological nationalism*, *commercial internationalism*,

and *global space consortium*, and how each strategy might provide solutions in cislunar space to the challenges uncovered in the three case studies while also identify the strategy that best supports future success in cislunar space. The fifth chapter will additionally make policy recommendations for the future of cislunar space strategy.

II. CASE STUDY 1: SPACE SITUATIONAL AWARENESS

Space situational awareness can be used interchangeably with space domain awareness; this thesis will maintain the consistent use in terminology of space situational awareness (SSA) even when applied to the cislunar domain where it could be considered cislunar situational awareness or cislunar domain awareness. SSA is a fundamental capability necessary to operate safely in any area of space whether it be near Earth space or cislunar space; however, there are different aspects of SSA to consider in the ways they may apply to cislunar space. As Kennewell and Vo observe:

The European Space Agency (ESA), however, uses the fuller definition, and specifically lists three segments of knowledge in SSA: ‘SST – Space surveillance and tracking of objects in Earth orbit (Watching for active and inactive satellites, discarded launch states and fragmentation debris that orbit the earth). SWE – Space weather (Monitoring conditions at the Sun and in the solar wind, and in Earth’s magnetosphere, ionosphere and thermosphere, that can affect space-borne and ground-based infrastructure or endanger human life or health). NEO – Near-Earth objects (detecting natural objects that can potentially impact Earth and cause damage).’⁵⁶

The perspective in which most SSA literature frames these three categories (SST, SWE, and NEO) is one where only Earth-orbital space, and SSA for Earth purposes, are considered. A stark lack of cislunar, or lunar, SSA is apparent.

This need for cislunar SSA was emphasized as recently as 2022 when astronomers calculated that a used rocket body would impact the Moon in March; however, this rocket body was improperly evaluated to be residual debris from a more recent SpaceX launch when it turned out to be from China’s 2014 mission *Chang’e T1*, what Foust calls a case of “celestial mistaken identity.”⁵⁷ More than simply an evaluation mistake, Schingler, Samson, and Raju note that the confirmation was unable to be made until June—a shocking

⁵⁶ John A Kennewell and Ba-Ngu Vo, “An Overview of Space Situational Awareness,” in *Proceedings of the 16th International Conference on Information Fusion* (Perth, Western Australia: IEEE, 2013), 1029, <https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6641108>.

⁵⁷ Jeff Foust, “Chinese Rocket, Not Falcon 9, Linked to Upper Stage on Lunar Impact Trajectory,” *SpaceNews*, February 13, 2022, <https://spacenews.com/chinese-rocket-not-falcon-9-linked-to-upper-stage-on-lunar-impact-trajectory/>.

three months after the rocket body supposedly crashed onto the Moon.⁵⁸ In a 21st century of immediate feedback and prompt answers to questions, three months was an unacceptable amount of time to wait for confirmation. In addition to this delay, the lack of awareness on the status of the rocket body raises a number of more concerning questions. What if the rocket body had damaged a future lunar base or mining facility and was therefore subject to the Liability Convention? Or worse, what if it had killed astronauts on the lunar surface? Fortunately, none of these was present, but as the 21st century space race fuels desires to make them all commonplace, the additional capability of cislunar and lunar SSA is not only desirable but absolutely necessary. All things considered, the three-month delay was the best-case scenario when reflecting on how this situation may have ended much worse. The collective authors summarize what this unfortunate situation underscores, asserting, “the series of events shows the difficulty in tracking objects in cislunar space, given the lack of telescopes, radars or other tools to identify them,” and “we lack situational awareness and effective frameworks for reasoning about this domain [cislunar space]. We need new tools to help us understand emerging landscape, lest perceptions become distorted, increasing the risk of conflict.”⁵⁹ Also, Schingler, Samson, and Raju draw attention to a challenge of cislunar SSA saying, “existing space situational awareness assets are designed and operated to watch what’s happening in orbit around the Earth, not the Moon.”⁶⁰ It will be essential that assets are able to be employed in a new way where the focus is no longer the Earth and is instead the Moon. The question of how cislunar SSA assets, capabilities, and tools will be developed is rooted in a greater cislunar strategy.

This chapter has already highlighted the need for cislunar SSA capabilities. It will continue by briefly describing the method of Earth orbit SSA for comparison’s sake, and to set a baseline of potentially expected capabilities. Finally, it will distinguish specific unique technical and operational challenges and requirements regarding cislunar SSA in

⁵⁸ Jessie Kate Schingler, Victoria Samson, and Nivedita Raju, “Don’t Delay Getting Serious about Cislunar Security,” War on the Rocks, July 6, 2022, <https://warontherocks.com/2022/07/dont-delay-getting-serious-about-cislunar-security/>.

⁵⁹ Foust, “Chinese Rocket, Not Falcon 9.”

⁶⁰ Schingler, Samson, and Raju, “Don’t Delay Getting Serious about Cislunar Security.”

order to more fully facilitate the comparative strategic discussion that will follow in Chapter V.

A. EARTH ORBIT SSA

When considering Earth orbit SSA, the questions of *why* and *how* come to the forefront. The *why* is a more succinct answer, and one generally understood by the space community: manmade and naturally occurring objects (the SST and NEO categories of ESA's earlier definition) are monitored to inform necessary entities so that proactive measures can be taken to prevent collisions.⁶¹ Concern over debris and the Kessler Syndrome is well appreciated, which allows the *how* to be more fully explored.

In 1961, the Space Surveillance Network (SSN) came into existence when the Air Force Space Surveillance System reaching initial operational capability; this lone sensor—called The Fence—is now one of twelve sensors that contribute to this greater network.⁶² Named for the “detection fence” that is created as a byproduct of its combined three transmit antennas and six receive antennas placed geographically around the Earth, The Fence serves as an example of a traditional radar system.⁶³ The twelve sensors are now comprised of a combination of powerful telescopes, traditional radar systems (like The Fence), and more modern phased array systems.⁶⁴ Under the authority of the United States (US) military, this system exists for the purpose of enhancing SSA needs in near-Earth space.⁶⁵ Another example of Earth-orbital SSA is the International Scientific Optical Network (ISON); 30 optical sensors (telescopes) stretching across eight nations make up “one of the largest observation systems” and target observation of geostationary orbits

⁶¹ Kennewell and Vo, “An Overview of Space Situational Awareness,” 1031.

⁶² Edward P. Chatters and Brian J. Crothers, “Space Surveillance Network,” in *AU-18 Space Primer* (Maxwell Air Force Base, AL: Air University Press, 2009), 251–56, <https://www.jstor.org/stable/resrep13939.26>.

⁶³ Chatters and Crothers, 252.

⁶⁴ Chatters and Crothers, 251–56.

⁶⁵ Chatters and Crothers, 249.

(GEO).⁶⁶ ISON is a non-government “project” that is internationally open, while being primarily sponsored by the Russian Academy of Sciences.⁶⁷

More recently, as interest in space has continued to grow and opportunities for profit have emerged, the number of parties capable of providing SSA services expanded from military and civil origins to commercial ones and themes of *commercial internationalism* have begun to emerge. A paradigm shift of sorts can be seen when comparing the different generalized perspectives of the 1960s and *technological nationalism* to the 2020s and *commercial internationalism*. Companies such as LeoLabs and ExoAnalytic Solutions use networks of remotely operated sensors positioned globally on the Earth’s surface to monitor near-Earth space from various locations.⁶⁸ These sensor networks—specifically, LeoLabs’ Vertex and ExoAnalytic Solutions’ ExoMonitoring—detect and track object in space; the detections are stored in databases prior to being analyzed, classified, and identified to then contribute to a “living map of low Earth orbit,” and “high-quality, real-time space object monitoring.”⁶⁹ Many of these commercial companies remain based in the U.S., however NorthStar Earth and Space is a Canadian company that contends in this budding industry.⁷⁰ While this trend from *technological nationalism* to *commercial internationalism* demonstrates an eagerness to adapt and embrace new ways of pursuing the same goal. This trend, however, is something to consider when applying the same SSA strategies and technologies to cislunar space—a feat not so easily done.

⁶⁶ Molotov et al., *Faint High Orbit Debris Observations with ISON Optical Network* (Moscow, Russia: Keldysh Institute of Applied Mathematics, 2009), 1, https://amostech.com/TechnicalPapers/2009/Orbital_Debris/Molotov.pdf.

⁶⁷ Molotov et al., 1–2.

⁶⁸ “Welcome to LeoLabs,” Leolabs, accessed April 2, 2023, <https://leolabs.space/about-us/>; ExoAnalytic Solutions, “Space Domain Awareness,” Solutions, accessed April 2, 2023, <https://exoanalytic.com/space-domain-awareness/>.

⁶⁹ “Our Vertex,” Leolabs, accessed April 17, 2023, <https://leolabs.space/vertex/>; ExoAnalytic Solutions, “Space Domain Awareness.”

⁷⁰ NorthStar Earth & Space, “NorthStar: Empowering Humanity to Preserve Our Planet,” NorthStar Earth & Space Inc., accessed April 14, 2023, <https://northstar-data.com/space/>.

The iterative process of going from large, complex, and exquisite SSA assets under the authority of national governments, militaries, and civil space organizations to more simple, resilient systems of assets under the authority of private companies occurred over a period of decades. When comparing potential cislunar SSA technologies and strategies to what has been seen on the Earth it is likely that after a period of time, the same pattern will repeat itself. While private companies are benefiting and profiting from interest in space, their services are primarily for people on the Earth—the same situation may not exist for some time on the Moon due to the fact that there does not yet exist a human presence on the Moon that would pay for similar services. Many SSA requirements will immediately exist on the Moon in the same way that they do on Earth, however, it can be anticipated that the efforts will stem from more centralized government programs prior to expanding into private companies. These government programs may very well use the technological application that private companies have found success within Earth-orbital space though, unless an emerging technology makes an unexpected impact that changes this application. Employing many small, relatively cheap, and replaceable sensors that can be controlled and monitored remotely is very appealing for an environment like the lunar surface—especially where occupied ground stations are not yet an option.

Further expanding beyond the *why* and *how* of Earth orbit SSA, more is learned and known about Earth-orbital space every day. The principal aspect of this to benefit SSA is the appreciation of orbital mechanics and the physics of Earth-orbital space. The predictable, stable, and understood near-Earth orbits provide a significantly more compliant situation than those in cislunar space, where these features are not understood, or non-existent. Knowledge of these orbits and the exploitable benefits that could be derived from them has heavily contributed to the development and expansion of sensors used in, and the understanding of, Earth orbit SSA whereas this is not yet the case for the Moon or potential lunar orbits.

B. TECHNICAL CHALLENGES

Recalling the definition of cislunar space outlined in the previous chapter, the sphere of influence that cislunar SSA capabilities are required to maintain persistent

evaluation of is significant. Current Earth-based capabilities are generally designed to observe, at furthest, GEO at 22,300 miles in altitude, but the Moon is at a range ten times greater than GEO and the L2 Lagrange point region is even further at approximately 35,680 miles, or 1.6 GEO, from the Moon—therefore, current Earth-based capabilities will require a twelve-fold increase in scale in order to properly evaluate the volume of space necessary.⁷¹ The tyranny of distance is a challenge that has been imposed on all who have sought to venture into space, but it is only more exacerbated when expanding from Earth-orbital space to cislunar space. Greater and enhanced capabilities are required to properly maintain recognition of this vast volume of space; doubling a capability is difficult enough, but going from a scale of one to twelve is nothing to scoff at. While recognizing the desire to be most aware of the space immediately surrounding the Moon more than the entire volume of cislunar space, the point of highlighting the sheer volume of space is primarily present in order to emphasize the challenge in the greater complete context of all of cislunar space.

Various technical parameters drive the ability to properly detect, classify, and identify objects at such distances from Earth. Whether considering optical sensors or radar sensors that leverage the radio frequency (RF) spectrum, aperture size becomes the limiting factor with respect to range. Optical sensors are designed based on geometric optics and physical optics. Concerning geometric optics, Olsen states that “the light gathering ability of a lens is defined by its diameter,” and that the “effectiveness” of an aperture is determined based on the ratio of the focal length to the primary optic diameter.⁷² Similarly, for physical optics, the wave characteristics of light must be taken into account; Olsen explains that the Rayleigh criterion determines highest possible angular resolution of a sensor based on the ratio of the wavelength of light to the aperture diameter.⁷³ In each aspect of optical sensing, geometric and physical, the size of the aperture directly

⁷¹ Schingler, Samson, and Raju, “Don’t Delay Getting Serious about Cislunar Security”; Moltz, *The Politics of Space Security*, 344.

⁷² Richard C. Olsen, *Remote Sensing from Air and Space*, 2nd ed. (Bellingham, WA: SPIE Press, 2016), 63–64.

⁷³ Olsen, 65–69.

contributes to an ability to see further and with higher resolution. The same principles can be applied to radar systems in determining range and resolution. Olsen asserts that the same Rayleigh criterion applies for radar antennas, where a “long antenna or a short operating wavelength will improve azimuth resolution.”⁷⁴ It would be fair to conclude then that if large enough apertures and antennas exist in space, design can optimize the systems in such a way that detection over significant range and volume is possible. The problem, however, is that apertures and antenna sizes required to accomplish this cannot be collapsed small enough to enable their launch into space. A well-known example of this can be seen in the Hubble Space Telescope (HST) in comparison to the James Webb Space Telescope (JWST). At the time of its launch, in 1990, HST consisted of the largest aperture at the time measuring 2.4 meters in diameter; fast forward to 2021 where JWST was equipped with a folding aperture measuring 6.5 meters in diameter.⁷⁵ With 6.25 times more collection area and an approximate field of view 15 times larger than HST, JWST has significantly more capability and potential utility. An additional detail worth noting in the comparison of HST and JWST is the position of each asset: HST is positioned in low-Earth orbit (LEO) whereas JWST is positioned at the L2 Lagrange Point region beyond the Moon. While this position was chosen for the purpose of keeping the sensor cool, the scheme allows JWST to not only see further than HST can, but its starting point is further away from Earth adding even more to its utility.

The Catch-22 of this, however, is that with the capability to see further, there is more data to process after collection and a further need to optimize range and resolution. Between human involvement and software developed to assist operators, there is still a considerable challenge in accurately associating and fusing data.⁷⁶ An additional design factor that must be considered is the inversely proportional relationship that exists between aperture size and field of view; while resolution can still be optimized, the limited field of

⁷⁴ Olsen, 208–10.

⁷⁵ “Comparison: Webb vs Hubble Telescope,” NASA, accessed March 18, 2023, <https://jwst.nasa.gov/content/about/comparisonWebbVsHubble.html>.

⁷⁶ Kennewell and Vo, “An Overview of Space Situational Awareness,” 1035.

view may require tipping and cueing from other sensors.⁷⁷ Also, just being able to see far enough does not naturally equate to the ability to refine that sight to a level needed to prevent collisions. Resolution challenges continue to exist even in Earth-orbital space, so it begs the question of how there can be sufficient SSA in cislunar space if it is not even possible in Earth-orbital space.

In addition to the vast volume that is encompassed within cislunar space, a study from John Hopkins University Applied Physics Laboratory (JHU APL) described the orbits in cislunar space as “chaotic” (while others use words such as “unstable”), making it even more difficult to establish any kind of fixed system—whether SSA or future life-support for settlement.⁷⁸ Where LEO, medium-Earth orbits (MEO), highly-elliptical orbits (HEO), and GEO are utilized and optimized based on desired effect and purpose, there are no such established low-lunar orbits. Moreover, there is no equivalent to GEO around the Moon because at the same relative distance an object would already be under Earth’s gravity more than the Moon’s.⁷⁹ These parallels that are so significantly leveraged in Earth-orbital space will have to be reconstructed around the Moon and throughout cislunar space; the simple fact exists that more is known and understood about Earth orbits than cislunar orbits, and the former are closer, smaller, and more predictable. While the growing interest in cislunar space is advancing knowledge of cislunar orbits, there is a substantial amount of ground to make up before sufficient understanding of cislunar orbits can be considered comparable to that of Earth orbits and similarly used for SSA.

There is also growing interest in the Earth-Moon Lagrange point regions; however, a key difference between these areas and Earth orbits—or future lunar orbits—is that these regions are all under the influence of two gravitational forces, that of the Earth and that of the Moon. There is much still unknown about these regions, and they remain largely

⁷⁷ Mallory DeCoster et al., “On-Orbit Assembly and Manufacturing of Large Structures to Enable Space Situational Awareness,” in *AIAA SCITECH 2023 Forum* (AIAA SCITECH 2023 Forum, National Harbor, MD & Online: American Institute of Aeronautics and Astronautics, 2023), 7, <https://doi.org/10.2514/6.2023-1118>.

⁷⁸ DeCoster et al., 2; Schingler, Samson, and Raju, “Don’t Delay Getting Serious about Cislunar Security.”

⁷⁹ Schingler, Samson, and Raju, “Don’t Delay Getting Serious about Cislunar Security.”

untested despite a few notable uses presented in the previous chapter. The aforementioned study produced by JHU APL asserts that if many of the challenges discussed in this section were able to be overcome, a system of three satellites could be developed for the L2, L4, and L5 Lagrange point regions with apertures large enough to provide sufficient SSA for the entire volume of cislunar space. The question remaining is how generous of an assumption is it that these challenges could be overcome in the first place, and how long until something like this is achievable? Even so, the ability for a constellation of just three satellites to sufficiently view and observe all cislunar space, and the ability for that constellation to do so in an effective way that is used for proper operational purposes is quite different.

As the cislunar SSA challenge currently stands, if a means by which large enough apertures could be available, the tyranny of distance problem could quickly be resolved (literally) due to an ability to see far enough, and with enough fidelity from the Earth's surface or already well understood Earth orbits in LEO, MEO, HEO, or GEO. However, since that is not yet available, other options must be explored. Frueh, Howell, DeMars, and Bhadauria propose potential Earth-Moon distant retrograde orbits and various Earth-Moon Lyapunov orbits as possible starting places for establishing lunar orbits, but each of these potential answers brings with it their own set of challenges separate from those presented in this chapter.⁸⁰ Size and location constraints appear to be repeating dead ends and limiting factors for cislunar SSA assets, but another option exists: lunar-based assets. Whether observed and operated from the Earth's surface, the lunar surface, or a future orbital *Lunar Gateway*, this option provides a potential solution to aperture and location restrictions. As mentioned earlier in this chapter, companies like LeoLabs and ExoAnalytic Solutions employ a network of surface-based sensors that can be observed, monitored, and controlled from other locations on the Earth; consider a network of sensors on the surface of the Moon employed in a similar fashion. This possibility provides a viable solution. The problem, and further challenge, with this option is of course the fact that humans have not

⁸⁰ Carolin Frueh et al., "Cislunar Space Situational Awareness," in *31st AAS/AIAA Spaceflight Mechanics Meeting* (Charlotte, North Carolina (Virtual), 2021), 4–6, https://engineering.purdue.edu/people/kathleen.howell.1/Publications/Conferences/2021_AAS_FruHowDeMBha.pdf.

been on the surface of the moon since 1972 and considerable steps would be required prior to using a network of sensors on the lunar surface as would be operationally desirable—the means to place these sensors on the lunar surface and consideration for legality of such action with respect to international agreements, are two of those steps that immediately come to the forefront. While there are likely other solutions to achieving cislunar and lunar, still, none of these options is a singular and complete solution, rather, they are viable starting places.

Recalling once again the three categories of SSA from the ESA definition, note that SWE has not been mentioned at all to this point. However, ubiquitous aspects of operating in space must be planned for where SWE plays a critical role. Questions of how charged particles and solar events impact satellites in cislunar space differently than how they impact those in Earth-orbital space must be addressed and planned for. Additionally, unknowns of how position, navigation, and timing (PNT) capabilities will incorporate into cislunar SSA beg the question of if there will be a PNT system that does not rely on reference to atomic clocks on the surface of the Earth and relation to Greenwich Mean Time (GMT) or Universal Time (UT)—consider this as Moon time. The Deep Space Atomic Clock (DSAC) is an emerging technology that may resolve this unknown.⁸¹ If future settlement is an end goal, it would assert that a cislunar SSA network operate on Moon time and be separate from any Earth PNT data; Moon time will be different than a Moon time zone that maintains relation to GMT or UT as a +/- X hours as is done around the Earth and for manned space missions.

The additional question of how debris will impact cislunar space is relevant. The concern over debris in space, specifically around Earth, is large enough that the National Aeronautics and Space Administration (NASA) has a dedicated program whose purpose is to “conduct measurements of the orbital environment and develop the technical consensus for adopting mitigation measures to protect the users within it.”⁸² This program is called

⁸¹ Megan Wallace, “Deep Space Atomic Clock (DSAC),” NASA, June 18, 2019, <http://www.nasa.gov/directorates/heo/scan/engineering/technology/dsac>.

⁸² “Explore Orbital Debris,” NASA Orbital Debris Program Office, 1979, <https://orbitaldebris.jsc.nasa.gov/>.

the Orbital Debris Program Office (ODPO), and another one of its responsibilities is to maintain a historical catalog of trackable space debris. In the same way, it will be necessary to track debris throughout cislunar space, especially as the immediate space around the Moon, as well as the Moon itself, becomes more populated. The greatest difference from the Earth to the Moon in this aspect is the nature of the atmosphere around each celestial body. Due to the density of the Earth's atmosphere in combination with its gravitational pull, natural "cleansing" removes smaller debris at lower altitudes; however, at higher altitudes, these effects are much less apparent, and the result is that debris may remain in orbit for a significant amount of time.⁸³ While the Moon's atmosphere might provide a similar cleansing effect, it will be to a lesser degree because the density of the Moon's atmosphere and the gravitational force exerted by the Moon are both less than the relative density and gravity of the Earth. Will NASA's ODPO extend its oversight to cislunar space, or will a new program be established to monitor this potentially lethal threat? In the 20th century space race, many lessons about debris were learned the hard way after irreversible damage was done, the same leniency cannot be extended into cislunar space.

C. OPERATIONAL REQUIREMENTS

In recognition of the technical challenges outlined in the previous section, the following operational requirements would present a minimum threshold of capability necessary in order to achieve a semblance of cislunar SSA.

- Ability to detect objects at distances beyond the Moon and L2 Lagrange Point region, potentially twelve times further than the current range of GEO assets. Understanding the difficulty of how sensors are optimized in space, a difficult design decision would not only be about what sort of sensors to use, but also the location and placement of those sensors.

⁸³ Defense Intelligence Agency, *2022 Challenges to Security in Space: Space Reliance in an Era of Competition and Expansion* (Washington, DC: Defense Intelligence Agency, 2022), 39, https://www.dia.mil/Portals/110/Documents/News/Military_Power_Publications/Challenges_Security_Space_2022.pdf; Moltz, *The Politics of Space Security*, 52; Jerry Jon Sellers, "Understanding Space: An Introduction to Astronautics," in *Understanding Space: An Introduction to Astronautics*, ed. Douglas H. Kirkpatrick, Revised Second Edition (New York: McGraw-Hill Custom Publishing, 2004), 81.

- Ability to achieve a fine enough resolution that the detection has utility and provides useful information. The volume of space is not the only obstacle, but consistently being able to find the proverbial needle in the haystack that is cislunar space. Again, recognizing the limitations of different sensors, it is likely that a cislunar SSA network would require an array of assets in different categories—possibly to include placement on the Earth’s surface, in Earth-orbital space, at the Lagrange Points, and on the lunar surface—that could work together to constantly sift through the information provided. For example a broadband scanning asset could detect an object and queue a narrowband precision asset to track that object rather than one asset doing the complete action alone—this system could then be mimicked from the surface of the Earth and from the surface of the Moon.
- Ability to relay resolved detections to controllers in an effective, reliable, and timely manner. If a structure of cislunar SSA is to be created, it must not only have the ability to maintain recognition of the Moon and the volume of space surrounding it, but it must also be able to communicate that information to controllers on Earth, in a future *Gateway*, or on the lunar surface. While lunar settlement and possible future habitation is a goal in some aspects of cislunar space, prior to that, the need to maintain connection to the Earth remains constant.
- Ability to create such a network of cislunar SSA assets taking into account the location of those assets. While prioritizing the volume of space around the Moon, it may be required that assets in Earth orbit are used in conjunction with assets on the lunar surface, for example. Other possible locations to consider remain the Earth’s surface or future solidified lunar orbits. Each of these options provides their own challenges that are seen in many current space assets already. Consideration for ground station location, the number of stations or relay points, and even potential relay satellites would all go into this decision. If using the lunar surface, some temporary means of cislunar SSA would still be required prior to the creation of those assets on the lunar surface.

D. CONCLUSION

The work is cut out for the state, coalition, or commercial company that endeavors to create a cislunar SSA network. While addressing the challenges that have been brought forth in this chapter, different decisions and approaches may weigh various tradeoffs differently, but the overarching question is what strategy would be most effective for developing such a network of SSA sensors for cislunar space? Conquering the vast distance is no simple task, nor is discerning the best way to optimize different sensors and targeted orbits, or locations, of operation. Many questions still remain. Will trends of *technological nationalism* emerge similar to how they did for Earth orbit SSA in the 1960s; will the apparent paradigm shift toward *commercial internationalism* continue from the 2020s; or will another strategy present the best solution? Will telescopes and radars be as effective and useful in cislunar space if observing from a location other than the Earth or will new technologies make an unexpected impact? The foundational nature of SSA in cislunar space remains significant for any nation regardless of the strategy they employ. This dilemma along with others will be further compared and analyzed in Chapter V. Chapter III will next extrapolate similarly unique technical and operational challenges and requirements regarding cislunar infrastructure.

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III. CASE STUDY 2: INFRASTRUCTURE

Dr. Antoine Picon, of the Harvard University Graduate School of Design, describes infrastructure as “the kind of thing you should forget about.”⁸⁴ Pointing out that the prefix “infra-” means “under,” the word literally means the under structure; while the last chapter described space situational awareness (SSA) as foundational to cislunar space operations, it may be more accurate to attribute such an adjective to infrastructure.⁸⁵ Although the term is often exclusively associated with physical things, such as bridges, power grids, and phone lines, this chapter will propose that in addition to the physical entities of infrastructure, the relationship to the economy must also be considered when identifying a cislunar space power strategy.

While physical infrastructure is more easily understood, the link between it and the economy is sometimes less clear. Weinzierl and Sarang propose that an existing space-for-Earth economy, along with a desired space-for-space economy, are really what drive sustainable operations when it comes to space activity in producing goods and services that benefit the Earth as well as future space activity that similarly benefits space’s development.⁸⁶ This economic incentive is ultimately what drives countries, coalitions, and private companies to continue investing (literally and figuratively) in the physical infrastructure. Due to the influence that physical infrastructure and the economy have on one another, it will be important to further consider the optimization and proper utilization of each when considering a cislunar space power strategy. Where it could be argued from the last chapter that cislunar SSA may best align with a *commercial internationalist* strategy, Weinzierl and Sarang appear to suggest a strategy more in line with *global space consortium* would be most beneficial in the area of cislunar infrastructure concluding:

The development of the space-for-space economy must not be undermined by earthly geopolitical rivalries, such as that between the United States and China. These conflicts will unavoidably extend into space at least to some

⁸⁴ “Infrastructure,” Harvard University, 2023, <https://www.harvard.edu/in-focus/infrastructure/>.

⁸⁵ Harvard University.

⁸⁶ Matthew Weinzierl and Mehak Sarang, “The Commercial Space Age Is Here,” *Harvard Business Review*, February 12, 2021, <https://hbr.org/2021/02/the-commercial-space-age-is-here>.

extent . . . If not kept in check, such rivalries will not only distract attention and resources from borderless commercial pursuits but also create barriers and risks that hamper private investment . . . The growing space-for-space economy offers exceptional potential to be a force for unity—but it’s the job of the world’s governments not to get in the way.⁸⁷

This chapter will identify the physical infrastructure that has benefited Earth-orbital space for comparison’s sake—including the space-for-Earth economy versus the space-for-space economy—and will set a baseline of potentially expected capabilities. Additionally, the chapter will discuss possible orbital, space-based, infrastructure options to exist in lunar orbit as well as lunar-based infrastructure options to exist on the lunar surface. Finally, it will explore the unique technical and operational challenges and requirements of construction, supply, and manufacturing in cislunar space in order to more fully facilitate the strategic discussion that will follow in Chapter V.

A. SPACE-FOR-EARTH AND SPACE-FOR-SPACE ECONOMIES

For as long as humans have ventured into space it has been for the fundamental purpose of benefiting someone, some nation, or some alliance on the Earth. Whether using space for national security purposes, for enhancing quality of life through the internet or global telecommunications, for agricultural optimization through Earth observation, or for further progressing scientific development and understanding, the beneficiaries of these services ultimately have remained on the Earth. Not only have these beneficiaries remained on the Earth, but the predominant majority of the physical infrastructure has also remained on the Earth. The terrestrial physical infrastructure that supports the United States (US) civil space-for-Earth economy consists of facilities such as research centers, flight centers, institutes of study, laboratories, assembly facilities, engineering and safety centers, testing and training facilities, and launch facilities.⁸⁸ Weinzierl and Sarang refer to this phenomenon as the space-for-Earth economy stating that “this economy is booming” and “projection for its future are optimistic.”⁸⁹ A byproduct of these terrestrial aspects of

⁸⁷ Weinzierl and Sarang.

⁸⁸ Jim Wilson, “NASA Centers and Facilities,” NASA, 13 2023, <http://www.nasa.gov/about/sites/index.html>.

⁸⁹ Weinzierl and Sarang, “The Commercial Space Age Is Here.”

physical infrastructure are the orbital aspects: satellites. Enabled by the terrestrial facilities—for design, test, and launch—it is these orbital assets that ultimately generate and yield the benefit that is the space-for-Earth economy. Embracing the suggestion of Dr. Picon, many daily comforts that are taken for granted on Earth are provided via the space-for-Earth economy and a complete appreciation of them can only come when this economy is absent. The Earth’s physical space infrastructure and its space-for-Earth economy have a pseudo-symbiotic relationship where the success or failure of one directly affects the other in the same way: when the physical infrastructure is functioning properly, it enables the space-for-Earth economy to provide more to the people on Earth. Whether seen as a technological breakthrough, quality of service to a consumer, or profit, the positive feedback of this relationship is quickly evident. Similar results are easily discerned when the opposite result is present when the physical infrastructure fails to function properly. Not only do these terrestrial and orbital elements of the physical infrastructure exist for the Earth, but the sheer magnitude in which they exist—as is evident by observing the surplus of facilities and the continually increasing number of satellites in Earth-orbital space—heavily contributes to the success of this relationship.

Recognizing that long-term habitation of space and/or on the Moon is a current goal, Weinzierl, both individually and also with Sarang, addresses the need for a “large-scale, largely self-sufficient, developed” space-for-space economy where goods and services are “produced in space for use in space.”⁹⁰ However, in stark contrast to the current upward trend of the space-for-Earth economy, the space-for-space economy is still “struggling to get off the ground.”⁹¹ This contrast of the cislunar space economy to the Earth-orbital space economy is mirrored when looking to the physical cislunar infrastructure in relation to the physical Earth-orbital space infrastructure—mainly in the fact that the physical cislunar infrastructure is practically non-existent. Not only is this infrastructure not currently present, but it is also necessary to consider the time it will take

⁹⁰ Weinzierl, “Space, the Final Economic Frontier,” 176; Weinzierl and Sarang, “The Commercial Space Age Is Here.”

⁹¹ Weinzierl and Sarang, “The Commercial Space Age Is Here.”

to build it up to a point where it is operationally effective and functioning properly enough to be comparable to what benefits the Earth.

The venture to support cislunar space infrastructure is more than just the creation of things that will make up the physical infrastructure and the development of a flourishing space-for-space economy; rather, there is also a focus required to maintain sustainable operations that will enable cislunar industrialization and further exploration over time. Dr. James Vedda suggests that this be done through intentionally designing the greater cislunar infrastructure such that it can facilitate a broad range of objectives rather than just a precise and specific mission.⁹² That is easier said than done, though, because even elements of the greater Earth space infrastructure are still designed for specific missions and purposes 60 years after the endeavor began. Is it realistic to expect better results and a different model in cislunar space? Certainly, questions of funding, material, manufacturing, and space allocation (both in terms of volume in cislunar space, for orbital space-based assets, and area on the surface of the Moon, for lunar-based assets) come to mind. The ultimate question of how this should be done remains; the answer lies in the strategy being pursued.

It is fair to imagine a future, fully developed, cislunar space infrastructure as one that mimics the space-for-Earth infrastructure. In the same way, then, it would be understandable to predict that this cislunar infrastructure will be made up of elements on the surface of the Moon—lunar-based infrastructure—and throughout cislunar space—space-based infrastructure. Throughout the rest of this chapter, a multitude of examples will be provided as evidence that economic incentive to establish a space-for-space economy is already present. Within that understanding, the attention will be primarily on the generation of lunar-based, and orbital space-based physical infrastructure components and the challenges associated with each.

B. TECHNICAL CHALLENGES

While some of the challenges associated with developing a cislunar space infrastructure overlap with the challenges discussed in the previous chapter, primarily

⁹² James A. Vedda, “Cislunar Development: What to Build and Why,” *Aerospace*, April 17, 2018, 3, <https://csps.aerospace.org/sites/default/files/2021-08/CislunarDevelopment.pdf>.

concerning the tyranny of distance in cislunar space and the chaotic orbits around the Moon, this section will not repeat these challenges. Rather, this section will predominantly address the challenges associated with construction, supply, and manufacturing in cislunar space and on the Moon in order to create the kind of cislunar space infrastructure that has been described in the previous section. This will include the development of lunar-based and orbital-based physical infrastructure components.

The only challenge that relates to the vast distance of cislunar space, is an analysis and comparison of the tradeoffs associated with building in space when considering two courses of action: first, building in Earth-orbital space prior to transporting a finished product to the Moon, or second, transporting partial products to some lunar orbit where building would then be complete. In order to capture the full breadth of this challenge it is first necessary to identify the way that building in space has been done in the past. The *International Space Station (ISS)* will serve as a central example. Not only does the *ISS* serve as a cornerstone illustration of scientific contribution to the space-for-Earth economical infrastructure, but it's development also highlights the relationship between physical infrastructure and the space-for-Earth economy. Additionally, it is an example of how strategic themes of *technological nationalism* can morph into those of *commercial internationalism* while leading to future possibilities of *global space consortium* as earlier authors have suggested.

Dr. Lawrence DeLucas categorizes the *ISS* as “the largest scientific and technological cooperative program in history.”⁹³ Initially announced by President Reagan in 1984, the *ISS* achieved initial operational capability in 2000 when the first crew arrived to live aboard.⁹⁴ Also described as “the result of unprecedented scientific and engineering collaboration,” the reputation of the *ISS* and the utility it has added over the last twenty-

⁹³ Lawrence J. DeLucas, “International Space Station,” *Acta Astronautica* 38, no. 4–8 (1996): 614, [https://doi.org/10.1016/0094-5765\(96\)00056-2](https://doi.org/10.1016/0094-5765(96)00056-2).

⁹⁴ Flint Wild, “What Is the International Space Station?,” NASA, October 30, 2020, <http://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-the-iss-58.html>; Giles Alston, “Diplomacy in Orbit,” *Royal Institute of International Affairs* 53, no. 5 (1997): 116, <https://www.jstor.org/stable/40475932>.

three years speak for themselves, but that is not why it was chosen as an example.⁹⁵ Rather, the primary focus here is the modular assembly of the *ISS* while in low-Earth orbit (LEO) and the challenges that would be involved if the same method were to be used as a possible means to establish a cislunar space infrastructure.

The *ISS* components were built on the Earth, transported into space, and then, like a Lego set, each component was assembled in orbit using, “complex robotic systems and humans in spacesuits.”⁹⁶ Without an expansive, multi-national, physical space infrastructure, this would have been impossible. Despite the *ISS* being primarily composed of eleven modules and six nodes, there are thirty-six additional components that make up the likes of habitation, life-support, and energy collection; each of these fifty-three components was designed, built, and tested on the Earth’s surface prior to being launched and assembled in LEO.⁹⁷ Not only were these efforts primarily enabled through the Earth-based infrastructure, but the additions and iterations of expansion that took place in order for the *ISS* to reach the form and likeness it depicts today lasted until 2010.⁹⁸ An amazing accomplishment, the success of this effort has lasted over three decades. It would not have been possible without the ability to build in a modular fashion over a considerable amount of time while being supported by a robust physical infrastructure. Are these same resources and this substantial timeline available for a cislunar space infrastructure that might seek to create something similar to the *ISS*?

The Gateway Program is one key component of the greater Artemis Program. It will be a “human-tended space station” that will orbit the Moon.⁹⁹ The parallel of the *Lunar Gateway* to the *ISS* is impossible to ignore; however, many of the key enabling aspects that

⁹⁵ “History and Timeline of the ISS,” ISS National Laboratory, accessed April 25, 2023, <https://www.issnationallab.org/about/iss-timeline/>.

⁹⁶ NASA, *Reference Guide to the International Space Station: Utilization Edition* (Houston, TX, 2015), 75, <https://www.nasa.gov/sites/default/files/atoms/files/np-2015-05-022-jsc-iss-guide-2015-update-111015-508c.pdf>.

⁹⁷ NASA, 27–42; Mark Garcia, “International Space Station Facts and Figures,” NASA, January 4, 2023, <http://www.nasa.gov/feature/facts-and-figures>.

⁹⁸ NASA, *Reference Guide to the International Space Station*, 86–87.

⁹⁹ Mars, “Gateway Overview.”

made the *ISS* a success are not yet identified for the *Gateway*. Many reports provide updates only as recent as 2020 when the European Space Agency (ESA), the Canadian Space Agency (CSA), Japanese Aerospace Exploration Agency (JAXA), the Italian Space Agency (ASI), and commercial company SpaceX made commitments to support the *Gateway*.¹⁰⁰ As these agencies collaborate, anticipated contributions range from launch capability to individual modules.¹⁰¹ Like the *ISS*, the *Gateway* is intended to be modular in nature, but the how and where of the assembly have not yet been made public. However, the International Space Exploration Coordination Group (ISECG)—the closest existing body to model a *global space consortium* strategy—calls attention to a necessary “stepwise development” and “phased approach” to expand lunar-based infrastructure that will inherently support the *Gateway* and additional lunar scientific exploration.¹⁰² The ISECG has gone so far as to outline measures of performance required in order to consider a minimum lunar space-based infrastructure: categories of power generation (300 kilowatts), communications (1 gigabit per second), and additional systems that are to be determined.¹⁰³ The ISECG notional Lunar Surface Exploration Scenario does imply *Gateway* “buildup” as early as 2022 until the first module of the *Gateway* would be in lunar orbit around 2027, with additional modules to follow—similar to the *ISS*.¹⁰⁴ Re-focusing on the primary challenge being analyzed, this trend certainly implies an intent to assemble the *Gateway* modules in lunar orbit. Now, the challenge is no longer about where and how the building will take place; rather, the challenge now becomes how the physical infrastructure components from the Earth will support, facilitate, and supply that building effort in lunar orbit.

¹⁰⁰ Mars; International Space Exploration Coordination Group, *The Global Exploration Roadmap Supplement October 2022: Lunar Surface Exploration Scenario Update* (Washington, DC: NASA, 2022), 16, https://www.globalspaceexploration.org/wp-content/isecg/GER_Supplement_Update_2022.pdf.

¹⁰¹ Mars, “Gateway Overview.”

¹⁰² International Space Exploration Coordination Group, *The Global Exploration Roadmap Supplement October 2022*, 3, 23–24.

¹⁰³ International Space Exploration Coordination Group, 23.

¹⁰⁴ NASA, *Reference Guide to the International Space Station*, 36.

Regardless of how successfully a buildup takes place in cislunar space, there is—and always will be—some dependence on the Earth, simply due to the fact that cislunar infrastructure will not in the foreseeable future have the ability to support itself like the Earth can support its own infrastructure. Circumstances currently exist on the Moon that make complete replication of the Earth’s infrastructure impossible. While efforts can be made to mimic the successful infrastructure on Earth, it will not be fully the same for quite some time. A clear example of this is the readily breathable, life-supporting, atmosphere on Earth, in which humans, animals, and plants can all live and grow. Such a simple enabling feature creates a certain amount of inherent dependence for lunar infrastructure as needs for these assets and capabilities cannot now be achieved independently on the Moon. In order to provide these basic needs, a significant amount of supply and transportation infrastructure will be necessary in a much more robust way than has been used for the *ISS*.

So, while cislunar infrastructure will be able to mirror the successful Earth infrastructure in many ways, there will be inherent differences and new needs. Not only does supply from the Earth require consideration, but also supply to and from the *Gateway* to the lunar surface. In this way, there will be elements of physical infrastructure both on the surface of and in orbit around the Moon, just like the terrestrial and orbital elements of physical infrastructure that support the Earth. The addition then being an added element of cislunar physical infrastructure that will remain linked to the Earth where much of this supply will come from, at least initially. ESA is one of many international space agencies that are not only working together in support of the *Gateway*, but they are also working toward these expansive supply requirements to support both surface-based and orbital lunar physical infrastructure. ESA’s Large Logistics Lander aims to be one piece of supply support between the *Gateway* and the lunar surface while Moonlight aims to provide a communications and navigation network around the Moon’s south pole, not unlike global positioning system (GPS).¹⁰⁵

¹⁰⁵ Jeff Foust, “NASA and ESA Sign Lunar Cooperation Statement,” *SpaceNews*, September 26, 2022, <https://spacenews.com/nasa-and-esa-sign-lunar-cooperation-statement/>; “Moonlight: What is ESA’s Moonlight Initiative?” European Space Agency, September 11, 2022, https://www.esa.int/Applications/Telecommunications_Integrated_Applications/Moonlight.

Aside from the assembly/construction and supply challenges in space, the manufacturing challenges remain. The buildup for the *Gateway* is a start, but the ability to manufacture and create things in space will truly be the tipping point for when a cislunar space-based economy begins. While there is not currently anything located in cislunar space to start this space-for-space economy, many technologies and processes have been in development in Earth-orbital space for longer than many might know, and all that it will take to kickstart the cislunar space-for-space economy is the transportation of these developments to cislunar space and the growth of their efforts in scale. The rest of this section will highlight some examples of these developments and the intent to leverage their success in LEO to success in cislunar space.

A key enabler in the advancement of space manufacturing is the opportunity that microgravity provides. Sarah Lewin quotes then-president and CEO of Made In Space, Andrew Rush, as he describes an effective analogy of how manufacturing in space is naturally similar to multiple ways manufacturing is already done on Earth:

We generally make things by subjecting them to a different environment. We make food by cooking it in fire, heating it up and causing chemical reactions. We make steel by heating things up at high temperature and maybe, depending on the steel, [in a] high-pressure environment. We can quench things; we can make things cold to make different materials or improve on those materials. Really, space-enabled materials are just another version of that, but instead of throwing something in a furnace and heating it to 1,000 degrees Fahrenheit [540 degrees Celsius] or something, we take it to space.¹⁰⁶

In more traditional manufacturing and engineering terms, Rush is comparing the subjugation of materials to a microgravity environment in space to heat treating or cold treating a material, a common practice used in order to optimize a material for a specific performance design. Lewin even refers to space as “the perfect construction zone” because of the unique benefits it provides, going as far as to assert that this unique environment, coupled with the decreasing cost of launching into space, may make “the space station

¹⁰⁶ Sarah Lewin, “Making Stuff in Space: Off-Earth Manufacturing Is Just Getting Started,” Space.com, May 11, 2018, <https://www.space.com/40552-space-based-manufacturing-just-getting-started.html>.

environment” key to future manufacturing.¹⁰⁷ Another company taking advantage of the microgravity environment to pursue effects in the field of space manufacturing is Axiom. Avoiding the effects of viscosity and crystallization, Axiom is able to more efficiently create heavy metal fluoride glass, a critical input to many optical fiber products; similarly, the negative effects of convection, sedimentation, and hydrostatic pressure are avoidable in microgravity, allowing uniformity in the creation of superalloys.¹⁰⁸ Despite the difference in gravitational force in LEO versus the Moon, the principle retains high utility for future cislunar manufacturing.

In addition to the microgravity environment, three-dimensional (3D) printing is a technology that continues to grow interest for application in cislunar space and even the lunar surface. Companies like Redwire are already heavily involved in the application of 3D printing in space for manufacturing needs; their Additive Manufacturing Facility (AMF) has been aboard the *ISS* since 2016 and has facilitated the creation of 200 tools and parts.¹⁰⁹ Advertised for specific cislunar and potential *Gateway* application, the Archinaut, another Redwire product, promotes a solution to “traditional” satellite and infrastructure design constraints because it will have the ability to create “reconfigurable persistent platform structures” that can be used for “large scale applications.”¹¹⁰ These capabilities pose potential in the area of space-based cislunar infrastructure. But a company called ICON is developing 3D printing technology more suited to aid in the area of lunar-based infrastructure. Known initially for 3D printing full-scale homes on Earth, ICON will now take its large-scale equipment to the Moon as part of follow-on Artemis missions where it

¹⁰⁷ Lewin.

¹⁰⁸ “Fiber Optics,” Axiom Space, accessed April 27, 2023, <https://www.axiomspace.com/manufacturing/fiber-optics>; Axiom Space, “Alloys & Superalloys,” Manufacturing, accessed April 27, 2023, <https://www.axiomspace.com/manufacturing/alloys-superalloys>.

¹⁰⁹ “Additive Manufacturing Facility (AMF),” Redwire Space, accessed April 27, 2023, <https://redwirespace.com/products/amf/>.

¹¹⁰ “Archinaut,” Redwire Space, accessed April 27, 2023, <https://redwirespace.com/products/archinaut/>.

will attempt to build structures using regolith.¹¹¹ Barring the success of this application, possibilities of in-situ construction on the Moon open.

Of course, the limitation of all these companies—except ICON—is that starting material still has to come from somewhere, namely Earth. While the cost of launch is continuing to diminish, a more independent cislunar space economy would need to end up more in line with ICON to get these materials on its own, using the resources found in cislunar space. Growing interest in the mining of celestial bodies provides potential opportunities here as well, especially with discoveries of water on the Moon.¹¹² In 2009, the Lunar CRater Observation and Sensing Satellite (LCROSS) uncovered evidence of water ice in a shaded area near the Moon’s south pole, and since then NASA has confirmed “most definitive information about the presence of water.”¹¹³ This confirmed presence of water at the lunar south pole provides future opportunities for cooling equipment and preparing rocket fuel in addition to the life-support qualities of drinking, but more immediately it provides an overwhelming incentive to invest more time and resources to this area of the lunar surface.¹¹⁴ Part of the Artemis Program includes the establishing of a lunar Base Camp that will be located at the Moon’s south pole; this discovery of water ice, among other qualities about the lunar south pole, make it an ideal location for Artemis Base Camp.¹¹⁵ While not quite the discovery of a breathable atmosphere, the finding of, and ability to harvest water ice provides countless possibilities in support of a greater cislunar infrastructure and the furthering of a more independent space-for-space economy where the reliance on Earth is reduced as much as possible. Supplementary utility may

¹¹¹ Rachael Zisk, “How ICON Will Bring Its 3D Printing Tech to the Moon,” *Fast Company*, November 30, 2022, <https://www.fastcompany.com/90817898/how-icon-will-bring-its-3d-printing-tech-to-the-moon>.

¹¹² Brian Dunbar, “Moon to Mars Overview,” NASA, June 29, 2018, <http://www.nasa.gov/topics/moon-to-mars/overview>.

¹¹³ Brian Dunbar, “LCROSS Impact Data Indicates Water on Moon,” NASA, November 13, 2009, http://www.nasa.gov/mission_pages/LCROSS/main/prelim_water_results.html.

¹¹⁴ Brian Dunbar, “Moon’s South Pole in NASA’s Landing Sites,” NASA, April 15, 2019, <http://www.nasa.gov/feature/moon-s-south-pole-in-nasa-s-landing-sites>.

¹¹⁵ Lonnie Shekhtman, “NASA’s Artemis Base Camp on the Moon Will Need Light, Water, Elevation,” NASA, January 26, 2021, <http://www.nasa.gov/feature/goddard/2021/nasa-s-artemis-base-camp-on-the-moon-will-need-light-water-elevation>.

come forward as additional mining efforts progress; however, the intentions of mining for power sources and other elements will be examined in greater depth in Chapter IV.

C. OPERATIONAL REQUIREMENTS

In recognition of the challenges outlined in the previous section, the following operational requirements would present a minimum threshold of capability necessary in order to achieve a semblance of cislunar infrastructure.

- Ability to effectively establish a minimum level of cislunar infrastructure from the Earth such that it is capable of supporting initial building blocks of the greater cislunar infrastructure, like the *Gateway*, as independently as possible.
- Ability to produce a minimum of 300 kilowatts of power generation and maintain a data rate of 1 gigabit per second in order to have sufficient communication.¹¹⁶ While the ISECG is not the authority to manage these measures of performance for a baseline of lunar-based infrastructure requirements, this is a fair starting point to aim for.
- Ability for global leadership to endure with patience and longevity the time it will take for the building block efforts of cislunar infrastructure to become profitable and self-sufficient. As with the *ISS*, the complete process lasted over three decades, while that magnitude of timeline may not be realistic for cislunar space and/or the Moon, it is no secret that the process will take time. Dr. Vedda advocates for doing something right rather than doing it fast.¹¹⁷
- Ability to continue leveraging the opportunistic conditions of space, such as microgravity, to advance cislunar infrastructure needs where methods known and used on Earth may be more comfortable. The capability of adapting and seeing

¹¹⁶ International Space Exploration Coordination Group, *The Global Exploration Roadmap Supplement* October 2022, 23.

¹¹⁷ Vedda, *Becoming Spacefarers*, 13.

these variables as openings to be innovative are inherently at the core of space faring individuals and need to remain.

- Ability to successfully begin mining water ice at the lunar south pole. The life-sustaining properties of water have value in other avenues that will enable a more independent cislunar infrastructure.
- Ability to optimize storage and use of the material used for 3D printing in space. Until a capability similar to ICON's regolith 3D printing on the surface becomes available, the material used in capabilities like AMF is precious. The application of this technology opens avenues for significant development in the aid of creating the initial lunar-based infrastructure, and while the cost of launching more of this material is becoming increasingly affordable, it is still extremely expensive and as such, it ought not be used carelessly.

D. CONCLUSION

As with the previous chapter, after reviewing the challenges associated with physical infrastructure and its relationship to the economy, the remaining question is what kind of strategy will most effectively overcome these challenges to create the kind of infrastructure necessary in cislunar space and on the Moon. The *ISS* has demonstrated that it is not likely that any nation can effectively create such a successful space infrastructure alone. Will strategies in line with *commercial internationalism* continue to be the most successful or will a more inclusive strategy aligning with *global space consortium* be necessary as Weinzierl and Sarang suggest. Will the leadership of the nations or coalitions endeavoring to accomplish this have the wherewithal to see it through, given the projected time it will take? Will capabilities like 3D printing continue to provide utility as they have up to now? Without a strong cislunar infrastructure, long term presence in cislunar space and on the Moon will be practically impossible. This will be further compared and analyzed in Chapter V. Chapter IV will next extrapolate similarly unique technical and operational challenges and requirements regarding energy needs in cislunar space.

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IV. CASE STUDY 3: ENERGY

Chapter III identified and discussed some anticipated challenges of sustaining cislunar operations while requiring supplies from the Earth. This challenge was primarily framed in the context of material in order to facilitate the development of necessary infrastructure; however, this challenge is relevant when considering electrical power and fuel sources as well. The ability to harvest energy sources to meet power and fuel requirements will be vital if sustained human presence and settlement in cislunar space are to be accomplished. Beyond power and fuel, though, the collection and distribution of energy sources from cislunar space—for continued use in cislunar space—will support other manned efforts and the greater cislunar space industry, as part of a future, space-for-space economy that was also mentioned in Chapter III.

Traditionally, spacecraft are designed for a specific mission with many precise requirements that are engineered within factors of safety to meet defined measures of performance: amount of fuel, organic power source/expected source degradation, and amount of oxygen (if the mission is manned), to name a few. These factors ultimately provide engineers an ability to project an expected lifespan of that spacecraft; therefore, if these factors contributing to the lifespan of the spacecraft can be elongated through the harvesting of energy sources that exist in cislunar space, it is clear that it would be highly desirable to do so. Naturally, then, it would make sense that all space-faring nations would have the same invested interest in these possibilities.

The concept of many interested parties simultaneously pursuing valuable resources in a new place draws an eerily similar parallel to the gold rush of the early western United States (US); many speculate the possibility that cislunar space may become the backdrop of a new and more dangerous gold rush because of this.¹¹⁸ This is quite a concerning

¹¹⁸ Nicole M. Breen, “Can the Outer Space Treaty Prevent Conflicts in Orbit in the 21st Century?” (master’s thesis, Naval Postgraduate School, 2018), 115, <http://hdl.handle.net/10945/59607>; Alexander Jones, “Mining Outer Space: The New Gold Rush,” *International Banker*, March 16, 2016, <https://internationalbanker.com/brokerage/mining-outer-space-new-gold-rush/>; Renu Rangela, “Space Is under the Threat of Becoming a Battleground for Mining Companies,” *International Business Times*, January 15, 2016, <https://www.ibtimes.com.au/space-under-threat-becoming-battleground-mining-companies-1500792>.

analogy, given the violent history that the gold rush has associated with it. The gold rush embodied the attitude of first-come-first-served in a free-for-all environment; will the same be true of the energy sources in cislunar space? Will whoever—whether it be a nation, coalition, or private company—gets to these resources first naturally acquire the vast majority of them and create a strangle-hold on the market for these resources? While this analogy is helpful, it is far from perfect: at the time, gold was a known element with a known value, whereas the various resources of cislunar space are not necessarily known and their value has yet to be determined. Gold was sought to obtain wealth, whereas the resources of cislunar space are being sought for utility and sustainment (while wealth will likely be a byproduct of this, it is not necessarily the primary intent). Also, the U.S. owned the land of the west, whereas there is no sovereignty or ownership of the Moon or other celestial bodies in cislunar space. Finally, there was an established national authority over gold mining, whereas there is no currently established international authority over lunar or asteroid mining.

Acknowledging these differences between the gold rush and the potential gold-rush-like scenario that may develop in cislunar space, this analogy certainly emphasizes the sense of urgency that must be had when considering how this fits into a greater cislunar space strategy and the potential importance of simply doing something first. While Dr. Vedda's recommendation of doing something right rather than doing it fast still rings true—especially if hasty action may lead to conflict—the opportunity to be first allows a nation, coalition, or company to set a certain precedent. In this context, will a self-serving strategy like *space dominance* be the most effective in harnessing these energy sources and getting to them quickly; will a more innovative and creative strategy like *technological nationalism* be more effective given the fact that large scale mining like this has never been done before; or will a collaborative strategy like *commercial internationalism* prove most viable in avoiding conflict?

This chapter will discuss the various energy sources that have been used in space before, for comparison's sake, while also identifying the potential future energy sources that may be harvested from cislunar space. Finally, it will distinguish specific, unique, technical and operational challenges and requirements regarding cislunar energy sources

in order to more fully facilitate the comparative strategic discussion that will follow in Chapter V.

A. SOURCES

Spacecraft have generally used any combination of three energy sources for the purpose of electrical power to function over the course of their expected lifespans: energy from the Sun, energy from batteries, and energy from Radioisotope Thermoelectric Generators (RTGs).¹¹⁹ Not unlike the design specification that was discussed in Chapter II, different combinations of these energy sources will be used based on the specific mission, destination, and purpose of a particular spacecraft.

Certainly, the most ubiquitous and common source of energy in space comes from the Sun. Harnessed through solar panels, the energy from the Sun is able to be converted into electricity, which is then multipurposed for whatever needs the spacecraft has. Of course, there is a direct relationship between the efficacy of this energy source and the spacecraft's relative distance from the Sun; the further a spacecraft travels from this energy source, the less utility solar energy will have. Fortunately, cislunar space, in its entirety, is close enough in proximity to the Sun that this factor is of little concern. Additional consideration must be given to the orbital mechanics of the various celestial bodies in cislunar space and the time spacecraft will spend in the umbra and penumbra regions—the areas where a spacecraft is in the shadow of the celestial body it is orbiting and unable to receive energy from the Sun— while orbiting the Earth, Moon, or other celestial body.¹²⁰ This consideration will also be relevant when choosing the site of the Artemis Base Camp and its position relative to the Sun. Chapter III pointed out that the lunar south pole was chosen primarily for the presence of water ice, but it is also an area that is “bathed in sunlight for extended periods of time, over 200 Earth days of constant illumination.”¹²¹

¹¹⁹ “What Powers a Spacecraft?,” NASA, September 4, 2019, <https://rps.nasa.gov/news/35/what-powers-a-spacecraft/>; “Radioisotope Thermoelectric Generators (RTGs),” NASA, September 25, 2018, <https://solarsystem.nasa.gov/missions/cassini/radioisotope-thermoelectric-generator>.

¹²⁰ Carlos R. Ortiz and Steven L. Rickman, *Method for the Calculation of Spacecraft Umbra and Penumbra Shadow Terminator Points*, NASA Technical Paper 3547 (Houston, TX: Lyndon B. Johnson Space Center, 1995), 2, <https://ntrs.nasa.gov/api/citations/19950023025/downloads/19950023025.pdf>.

¹²¹ Dunbar, “Moon’s South Pole in NASA’s Landing Sites.”

While this placement is optimal for using the energy from the Sun, there are still substantial periods of time where the area is not in view of the Sun and as a result, additional energy sources will be required.

After the Sun, onboard batteries are the next most common energy source. Batteries provide an alternative, organic, energy source that spacecraft can use while in the umbra and/or penumbra regions. The size, weight, and placement of these batteries must be considered when designing a spacecraft, as each of these variables has an impact on launch calculations and, therefore, a direct contribution to the cost of the spacecraft as well. Batteries also may not be rechargeable and are, then, like fuel, precious to spacecraft operators because once the batteries are used up, the energy source is gone. Rechargeable batteries will be a must for use on the Moon as alternatives and/or backups to the energy provided from the Sun.

Finally, after onboard batteries, the option of RTGs as an energy source is available. The National Aeronautics and Space Administration (NASA) explains that RTGs are used to generate electricity through the thermal difference created when plutonium-238 falls apart—or decays, creating plutonium dioxide—and generates heat in contrast with the cold of space.¹²² These RTGs are able to compensate for the deficiencies in solar power and batteries: as spacecraft travel further from the Sun, this energy source is able to power the spacecraft, where solar power ceases to be effective, and this source has much greater longevity than any batteries would provide.¹²³ While RTGs are extraordinarily reliable and durable, the decay of the radioisotope is something that must be taken into consideration; as the radioisotope decays over time, the power produced similarly decays.

It is fair to say that the combination of energy sources through the Sun, batteries, and RTGs will provide sufficient energy sources when it comes to electrical power and starting criteria for lunar settlement. However, in order to enable a more self-sufficient space-for-space economy, there still remains a requirement for harvesting the energy sources in cislunar space—recall that it is not electrical power alone that is necessary, but

¹²² NASA, “Radioisotope Thermoelectric Generators (RTGs).”

¹²³ NASA, “What Powers a Spacecraft?”

also fuel and life-support. The manner of harvesting these resources will have to be lunar mining.

While the thought of mining on the Moon may seem like a notion of science-fiction, Breen points out that it is a concept that many space enthusiasts have discussed for centuries, citing Russian scientist Konstantin Tsiolkovsky (from the late 1800s through the early 1900s) and authors Garrett Serviss and Isaac Asimov (through their books *Edison's Conquest of Mars* and *Catch That Rabbit*, respectively) as a few examples.¹²⁴ More recently, the likes of Jeff Bezos and Elon Musk have been cited, calling the ability to extract resources from the Moon “crucial” to the success of colonization, with potential to extend even to Mars.¹²⁵ This is all the more reason that the harvesting of these resources must be considered when developing a cislunar space strategy.

The Moon's regolith has been found to contain valuable rare-earth minerals, platinum-group minerals, titanium, and volatiles—to include Helium-3 (He-3) and water ice.¹²⁶ This discovery is immense and, while none of these resources are insignificant, the remainder of this chapter will focus primarily on the volatiles rather than the minerals, as their discovery has been the most significant and simultaneously presents potential solutions to the unresolved fuel and life-support needs.

A potential energy source for fuel needs in cislunar space, He-3, has been found to be “abundant and accessible” on the Moon, while also being “almost nonexistent” on Earth.¹²⁷ In fact, NASA estimates that there are at least a million tons of He-3 contained in the Moon's regolith.¹²⁸ If this substantial amount of He-3 is able to be successfully harvested, many experts believe that it can be used to produce nuclear fusion—producing

¹²⁴ Breen, “Can the Outer Space Treaty Prevent Conflicts,” 107–8.

¹²⁵ Chloe Cornish, “Interplanetary Players: A Who's Who of Space Mining,” *Financial Times*, October 19, 2017, <https://www.ft.com/content/fb420788-72d1-11e7-93ff-99f383b09ff9>.

¹²⁶ Deborah A. Peacock, “Mining on the Moon: Yes, It's Really Going to Happen,” *Mining Engineering Magazine*, January 2017, 23, <http://i2massociates.com/downloads/MiningMoonSMEJan2017.pdf>.

¹²⁷ Peacock, 23.

¹²⁸ Loura Hall, “Harnessing Power from the Moon,” NASA, August 6, 2017, <http://www.nasa.gov/feature/harnessing-power-from-the-moon>.

more energy than fission with far less radioactive waste—and, therefore, propulsion and fuel for continued space travel at a minimum.¹²⁹ One hurdle to still overcome, though, is that the technology to produce fusion reactors does not yet exist on Earth. Despite the discovery of He-3 in such abundance on the Moon, it would be reasonable to assume that fusion would first be mastered in the controlled environment of Earth prior to being employed to the Moon; due to this reality, it is hard to consider this as a viable option until sometime in the distant future.

A second potential energy source for fuel, and life-support is the water ice briefly mentioned in Chapter III. The severely cratered surface of the Moon creates permanently shaded lunar cold traps (LCTs), also referred to as permanently shadowed regions (PSRs), especially near the lunar poles.¹³⁰ While the obvious life-sustaining qualities of water provide exciting life-support opportunities, there are many more potential uses for this volatile when breaking it down into its fundamental elements of hydrogen and oxygen. The expanded possibilities extend from life-support to greenhouse environment potential, electrical power production and storage, and, most of all, rocket fuel—pointing to the fact that “the preferred fuel/oxidizer propellant combination is hydrogen/oxygen.”¹³¹ Proper harvesting of this volatile is so significant that Professor Donald Burt claims that the “the main product of future lunar mining is likely to be oxygen.”¹³²

B. TECHNICAL CHALLENGES

While both He-3 and water ice present potential solutions with respect to energy sources that can further facilitate electrical power, fuel, and life-support requirements in cislunar space, many substantial challenges remain: how will these volatiles be harvested, what technology is required to harvest them, and what are the legal parameters concerning their harvest?

¹²⁹ Peacock, “Mining on the Moon,” 23–24.

¹³⁰ Peacock, 24; Leonard David, “Can NASA’s Artemis Moon Missions Count on Using Lunar Water Ice?,” Space.com, May 18, 2023, <https://www.space.com/moon-lunar-ice-poles-artemis-program>.

¹³¹ Peacock, “Mining on the Moon,” 24.

¹³² Donald M. Burt, “Mining the Moon,” *American Scientist* 77, no. 6 (1989): 574, <https://www.jstor.org/stable/27856008>.

The primary means of harvesting these volatiles, as well as the other minerals that were initially mentioned, is mining. Mining on Earth is conventionally divided into surface and subsurface (underground) mining. Burt advocates that there is an excessive risk associated with underground mining on the Moon due to the possibility of “losing atmosphere in the vacuum of a crack.”¹³³ In other words, the cavern (crack) that is created in order to access resources underground must be structurally supported to avoid collapse. On Earth, underground mines are pressurized in addition to being physically reinforced with braces or beams; due to the atmospheric differences in space/on the Moon, this pressurization method would result in excessive risk. This threat provides incentive against underground mining, while the naturally occurring characterization of the lunar regolith (described as having been “pulverized,” meaning that there is no need for additional or excessive crushing) adds incentive in favor of surface mining.¹³⁴ This combination of incentives yields a suggestion that the manner of harvest would predominantly, if not exclusively, be surface mining. Follow-on procedures such as milling, smelting, refining, distilling, and solvent extracting would still be necessary prior to using the products in other ways. Further challenges presented by the lunar environment, like extreme temperature fluctuation and gravitational differences, make mimicking processes on Earth extremely difficult and raise the question of whether all of these follow-on procedures could realistically occur on the Moon, or in space at all.¹³⁵ Of course, others suggest that a future, central-processing facility on the Moon would be able to provide these services; however, the solutions to overcoming the lunar environment are absent.¹³⁶ While the solution may very well end up being a central-processing facility, it has yet to be identified how this facility will ultimately overcome these challenges. The act of mining the resources is only the first—and relatively simple—step, depending on what the intended use of each product might be.

¹³³ Burt, 575.

¹³⁴ Burt, 575.

¹³⁵ Burt, 576–77.

¹³⁶ Peacock, “Mining on the Moon,” 24–27.

After the resources are mined, these various follow-on procedures resolve the resources for use, like how a diamond must be refined for placement on an engagement ring after being harvested. In this case, rather than cutting and shaping the diamond, processes like milling, smelting, refining, distilling, and solvent extracting result in usable lunar resources. Much of the milling, smelting, and refining processes heavily rely on regents—substances which “act on another in a chemical reaction”—that are primarily not present on the Moon.¹³⁷ Many common regents used in these processes, such as hydrogen, carbon, nitrogen, fluorine, and chlorine, would have to be brought from Earth to this central-processing facility in order to carry out these processes in ways that are done on Earth; this only adds to the already daunting supply requirements that were previously identified in Chapter III.¹³⁸ Burt identifies that many of these refining processes “seem more or less possible from a chemical and thermodynamic standpoint,” but that tradeoffs of cost, efficiency, and safety would then become paramount.¹³⁹

Following the determination that the means of harvesting will be through surface mining, the remaining questions revolve around the technology necessary to effectively mine these resources—in addition to the technology needed to overcome the challenges of the follow-on procedures. Entities ranging from national space organizations to private companies are exploring different potential solutions to this technological challenge, and, unsurprisingly, all current solutions generally revolve around the implementation and use of robotic assets and robotic systems on the surface of the Moon.¹⁴⁰ The use of robotics is not a new or particularly surprising result; however, some features of these robotic assets may bring this idea into contention over fear of their use resulting in conflict. During the 20th century space race, the Union of Soviet Socialist Republics (USSR) aggressively opposed the use of the U.S. space shuttle due to the manipulator arm and cargo bay features

¹³⁷ M.J. Pearse, “An Overview of the Use of Chemical Reagents in Mineral Processing,” *Minerals Engineering* 18, no. 2 (February 2005): 139, <https://doi.org/10.1016/j.mineng.2004.09.015>.

¹³⁸ Burt, “Mining the Moon,” 576.

¹³⁹ Burt, 577.

¹⁴⁰ International Space Exploration Coordination Group, *The Global Exploration Roadmap Supplement October 2022*, 15–19; Moon Express, “Moon Express Inc: Redefine Possible,” accessed June 12, 2023, <https://moonexpress.com/>.

that were viewed as manned antisatellite weapons.¹⁴¹ The notion that spacecraft features could be perceived with malicious intent remains a point of discussion in the 21st century space race too. Breen cites an infographic, while now dated, depicting three possible means by which space mining might take place: named the “on-site technique,” the “tow truck technique,” and a capsule technique.¹⁴² Each method provides spacecraft features not unlike the shuttle’s, which other nations might oppose.¹⁴³ Dr. Vedda advocates for features like those on the shuttle, and those mentioned in each of the methods proposed by Breen, but he also asserts that the operation of the spacecraft inherently need to facilitate activity that might similarly be perceived as threatening in order to achieve sustainability: namely proximity operations/on-orbit servicing.¹⁴⁴ The existence of these features and the operational use of them—whether for mining or other sustainable efforts—leads to the final questions that must be addressed: are there any legal roadblocks to lunar mining and what technologies will be required to effectively execute lunar mining?

Chapter I outlined the legal structure of space as well as the questionable validity that the Moon Agreement of 1979 presents with respect to the use of lunar resources. But, when it comes to sovereignty and ownership, the answer is clear: no nation, coalition, or company can claim the Moon. While it can be argued that mining on the Moon is not an assertion of sovereignty or ownership, the sale of resources therein may proclaim otherwise. Fortunately, President Obama’s signing of the Spurring Private Aerospace Competitiveness and Entrepreneurship Act of 2015 (SPACE Act of 2015) allows U.S. citizens and commercial companies to “legally participate in mining activities in space.”¹⁴⁵ While there is no longer any ambiguity for U.S. citizens or U.S. commercial companies, many argue that a lack of international agreement on guidelines surrounding lunar mining presents a high risk of conflict surrounding the activity and the profits that it is likely to

¹⁴¹ Moltz, *The Politics of Space Security*, 197.

¹⁴² Breen, “Can the Outer Space Treaty Prevent Conflicts,” 118–19.

¹⁴³ Breen, 118–19.

¹⁴⁴ Vedda, “Cislunar Development.”

¹⁴⁵ Breen, “Can the Outer Space Treaty Prevent Conflicts,” 115; Library of Congress, “Summary of H.R. 2262 (114th): U.S. Commercial Space Launch Competitiveness Act,” GovTrack.us, accessed June 12, 2023, <https://www.govtrack.us/congress/bills/114/hr2262/summary#libraryofcongress>.

produce.¹⁴⁶ Many experts in the space field suggest that there is a fleeting opportunity to proactively establish some kind of international agreement in order to avoid this potential conflict.¹⁴⁷

Countries other than the U.S. are adopting laws regarding space resources; as recently as 2017, Luxembourg adopted a law granting private companies that operate out of Luxembourg ownership of “space resources they extract.”¹⁴⁸ While the imperfect gold rush analogy surely implies that whatever nation, coalition, or company that first obtains these resources will have the opportunity to set the precedent for how the market of the resources will operate, as nations begin adopting laws like the U.S. and Luxembourg have, that assertion comes into question. The Luxembourg government referred to the law as an effort to “promote international cooperation in order to progress on a future governance scheme and a global regulatory framework of space resources.”¹⁴⁹ It was mentioned earlier in this chapter that the gold rush had a particularly violent history associated with it; could it be that laws like these present a legal and practical solution for how space resources might more properly be handled while also avoiding conflict? Or, perhaps, only a few nations will adopt laws like these and some international regulatory authority will be required if conflict is to be avoided.

Of course, if all of these technology and legal challenges are properly resolved, the figurative elephant in the room remains the unknown of whether there will be enough of these volatiles to achieve the goal of sustained human presence and prolonged operations in and through cislunar space. Pascal Lee, of the SETI Institute and Mars Institute based out of NASA’s Ames Research Center, points out that the existence of LCTs/PSRs does

¹⁴⁶ Jesse Dunietz, “Floating Treasure: Space Law Needs to Catch Up with Asteroid Mining,” *Scientific American*, 28 2017, <https://www.scientificamerican.com/article/floating-treasure-space-law-needs-to-catch-up-with-asteroid-mining/>; Brearley, “Mining the Moon,” 60; Breen, “Can the Outer Space Treaty Prevent Conflicts,” 116–17.

¹⁴⁷ Moltz, “Toward Cooperation or Conflict on the Moon?,” 99–101; Joan Johnson-Freese and David Burbach, “The Outer Space Treaty and the Weaponization of Space,” *Bulletin of the Atomic Scientists* 75, no. 4 (2019): 139–40, <https://doi.org/10.1080/00963402.2019.1628458>.

¹⁴⁸ Jeff Foust, “Luxembourg Adopts Space Resources Law,” SpaceNews, July 17, 2017, <https://spacenews.com/luxembourg-adopts-space-resources-law/>.

¹⁴⁹ Foust.

not guarantee the presence of these critical volatiles, and that “something becomes a ‘resource’ only if it’s economically cheaper and less risky to extract on site than to import from elsewhere.”¹⁵⁰ While the widely accepted assumption currently is that lunar mining and the exploitation of these volatiles will provide relatively cheap and plentiful access to energy sources that can be used for electrical power, fuel, and life-support, it does ultimately remain only an assumption for the time being.

Moreover, there are still challenges to be addressed with the energy sources already being used in space, as they will have to sustain all efforts until any He-3 and/or harvested water ice becomes operationally effective and fruitful. The challenge of optimizing energy from the Sun, based on one or many locations around the lunar south pole, the challenges of manufacturing large enough solar panels to support a human settlement, and the challenge of maintaining a supply of batteries and/or maintaining the ability to recharge them remain.

C. OPERATIONAL REQUIREMENTS

In recognition of the technical challenges outlined in the previous section, the following operational requirements would present a minimum threshold of capability necessary in order to meet energy needs in cislunar space.

- Ability to continue leveraging energy from the Sun, batteries, and RTGs. These energy sources provide power to spacecraft and have proven to be reliable—that reliability will be essential if there are any hopes of harvesting other potential sources.
- Ability to effectively overcome the stigma of the space shuttle’s manipulator arm and cargo bay on similar spacecraft in cislunar space. Harvesting lunar resources will not likely be practical without advanced robotic assets and robotic systems, and acceptance of these solutions across the global space community may be a required step for technological success.

¹⁵⁰ David, “Can NASA’s Artemis Moon Missions Count on Using Lunar Water Ice?”

- Ability to refine and execute the follow-on procedures necessary after initial harvest of lunar volatiles. Milling, smelting, refining, distilling, and solvent extracting are each highly technical and highly complicated procedures that require regents to be provided from Earth, and the ability to harvest these resources will be moot if these follow-on procedures are not able to be implemented in space. Where Chapter III highlighted ways that the space environment was advantageous for certain manufacturing, this challenge presents ways that it could be disadvantageous.
- Ability to establish agreement over the authority of lunar resources. The proactive opportunity to make the rules before they are needed is fleeting. Perhaps such an agreement could be achieved through global ratification of the Moon Agreement of 1979, maybe the establishment of a new agreement, the establishment of an international regulatory authority, or even through an amendment to another agreement?
- Ability to get back to the Moon. While a return to the Moon feels imminent, it has still yet to be accomplished. This is obviously a necessary first step.

D. CONCLUSION

As with the previous two chapters, the remaining question ultimately asks what kind of strategy will most effectively overcome the challenges associated with the harvesting of energy resources in cislunar space, recalling that the ultimate goal is to support sustained cislunar operations through supplying power, fuel, and possibly life-support systems. The gold rush analogy emphasizes the urgency of returning to the Moon as quickly as possible; whether the authority over the resources to be harvested is understood or not, the expression of possession being nine-tenths of the law, coupled with this urgency, seems to lean toward a strategy in line with *space dominance*. However, the technological needs for lunar harvest and the follow-on procedures required to use them align with a strategy more toward *technological nationalism*. Of course, there is also consideration for a strategy that will seek to avoid conflict like *commercial internationalism*. Will harvested resources fulfill the needs they are expected to fulfill, and

will there be enough of them? Will agreements over technology and legal authority be clear and united? Chapter V will synthesize the discussions and questions posed in Chapters II, III, and IV in order to provide a robust analysis of how each proposed cislunar space strategy might provide solutions to the challenges addressed in the respective chapters.

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V. STRATEGY COMPARISON AND CONCLUSION

This thesis began by asking what kind of strategy is needed to establish and develop cislunar space power. In search of an appropriate answer, four potential cislunar space strategies were identified and viewed on a spectrum of cooperation. From least cooperative to most cooperative, the four strategies are: *space dominance*, *technological nationalism*, *commercial internationalism*, and *global space consortium*. This chapter will analyze these four potential cislunar space strategies as they relate to the technical and operational challenges presented through the three case studies of space situational awareness (SSA), infrastructure, and energy. Possible solutions and shortcomings of each strategy will also be identified in order that a recommendation advocating for the implementation of one in preference over the others can take place as an answer to the initial question posed. Finally, policy recommendations surrounding that recommended cislunar space strategy will be made while also identifying areas for further research as different nations, coalitions, and companies continue actively venturing into cislunar space.

A. CASE STUDY SUMMARIES

Chapters II, III, and IV of this thesis presented case studies in the areas of SSA, infrastructure, and energy as areas vital to the success of future cislunar operations and possible lunar settlement. As such, it was established that any cislunar space strategy must seriously consider how that strategy might impact these areas. Recalling that aspects of each of these proposed strategies overlap with one another, the inherent qualities of each continue to stand alone and may provide the implementing nation, coalition, or company with advantages in the cislunar domain. The remainder of this section will briefly summarize the notable takeaways from each case study prior to a review of how each proposed cislunar space strategy might be implemented in these areas.

The SSA case study identified the difficulty of effectively detecting, classifying, identifying, and tracking objects—at a high enough resolution that they provide utility to operators—across the vast distance of cislunar space, while prioritizing the volume of space immediately surrounding the Moon. Design tradeoffs of available optical sensing

(telescopes) and radar technologies were discussed in addition to the possibilities of placing assets in various locations, such as the lunar surface, the Lagrange Point regions, and the Earth's surface. The nature of lunar orbits were evaluated as unstable and chaotic, offering an additional obstacle when weighing the various compromises associated with all of these options.

The infrastructure case study identified the pseudo-symbiotic relationship between the terrestrial and orbital elements of the Earth's physical space infrastructure and its space-for-Earth economy, and how a similar relationship could be created with the development of lunar-based and orbital physical cislunar infrastructure toward a future space-for-space economy. Construction, supply, and manufacturing obstacles were noted along with how there will be an initial dependence on the Earth until the physical cislunar infrastructure can develop and mature. Lunar mining for water ice and the use of three-dimensional (3D) printing were recognized as exciting areas of potential exploitation and breakthrough in the near future.

The energy case study identified the various resources—primarily Helium-3 and water ice—that may be leveraged as means of producing electrical power, fuel, and life-support requirements in cislunar space to further enhance a future human settlement and a self-sustaining space-for-space economy. After concluding that the predominate method of harvesting these resources would likely be lunar surface mining, obstacles regarding the technological needs and legal roadblocks that currently exist were discussed. Opportunities for development were recognized with respect to overcoming the negative connotation and stigma of certain advanced robotic capabilities, as well as clarifying who, or what, has authority over lunar resources.

As each of the four proposed cislunar space strategies are applied to these three cases the inherent qualities of each continue to stand alone.

1. Space Dominance

A cislunar space strategy of *space dominance* provides an implementing nation with the ability to act exclusively in its own best interests. Rooted in realism, this strategy does not require national leadership to consider the perception of other nations or allies;

rather, this strategy enables self-serving action to always prevail through the means available to the implementing nation. Whether those means are military might, national economic investment, or advanced scientific capability, as long as the nation implementing this strategy maintains those means, their opportunity to seize the advantage in cislunar space and everything that it offers is available. Chiefly, the greatest benefit of employing a strategy like *space dominance* is that it can be done alone, and the desires of the implementing nation do not rely on anyone or anything other than themselves. This can result in enhanced nationalism and pride as well as a national step toward hegemony—or cislunar space hegemony in this case.

Of course, in addition to the benefits, there are also disadvantages to implementing a strategy of *space dominance*. When a nation has plentiful means, the will of that nation can be exerted without a second thought, but when those means run out or cease to be effective—due to the loss of military supremacy, an economic recession, or the loss of a scientific capability to complete the earlier examples—the strategy also ceases to be as effective and the implementing nation can no longer exert its will with as much ease. The limiting factor in a strategy like this, then, is the ability to maintain sufficient means that give a nation dominance over others. A natural byproduct of hegemony is that it pushes other nations away and can create international resentment and even enemies. While the hegemon enjoys the benefits of dominating, other nations may also band together to offset the hegemon if/when a weakness or lack of means presents itself.

All three case studies acknowledge that a significant amount of work must be done in order to effectively use the cislunar domain. While a cislunar space strategy of *space dominance* may one day in the future be useful to a nation, at this infantile stage it is not a strategy that could be recommended. The gold rush analogy examined in the energy case study echoes the potentially violent ramifications of a strategy like *space dominance* and begs the question of whether that result is one that any nation, coalition, or private company could manage. It is simply unrealistic that any lone nation would be able to effectively achieve the required capabilities to then control cislunar space in a truly overwhelming fashion. The various anticipated costs of effectively dominating cislunar space and the Moon are entirely too high right now for a single nation to pursue on its own.

2. Technological Nationalism

A cislunar space strategy of *technological nationalism* benefits from many of the same advantages as *space dominance* in the way that it is also a strategy that can be effectively employed by one nation with little to no dependence on others. This similarly fosters a strong sense of nationalism and pride throughout a country and does not put the success of the strategy outside the control of the implementing nation. Recalling that a strategy of *technological nationalism* is rooted in technocracy more than realism, McDougall's definition of the term—as well as the fact that *technological nationalism* does not necessarily strive to achieve hegemony—retains a strong differentiation between *technological nationalism* and *space dominance*: “the institutionalization of technological change for state purposes.”¹⁵¹ In this framework of technocracy, *technological nationalism* has the inherent benefit of fostering trends of innovation and creativity to achieve new developments. This can have additional benefits of enhancing a national economy and workforce through new activities in areas that may not be embraced under other strategies.

Disadvantages of a strategy like *technological nationalism* consist primarily of national sustainability: longevity in leadership, longevity in development, and longevity in goals. Without a consistent national direction chartered by that nation's leadership, it would be extremely difficult for state-sponsored entities to continue pursuing efficacy in cislunar space. Using the United States' (US) national government as an example, every four years it is possible that the priorities, funding, and direction of the country will shift if a president of differing ideology than the predecessor is elected. Likewise, if the national focus of development and enhancing technological change shifts away from cislunar space, it is difficult to imagine that a strategy rooted in technocracy would be successful. The journey into cislunar space must be considered more like a marathon than a sprint, so the required longevity and consistency of the implementing nation have more potential to result in failure.

While the case studies identified a significant amount of work that would be required in order to effectively harness cislunar space, that work is not all new to space

¹⁵¹ McDougall, *The Heavens and the Earth*, 5.

faring nations. One nation has landed humans on the Moon before (the 1969 U.S. landing of *Apollo 11*—and five subsequent missions); coalitions have built space stations before (the *International Space Station* as one example); and numerous nations have landed robotic probes or rovers onto celestial bodies before (China’s *Chang’e 4* Moon landing as an example). None of these accomplishments in cislunar space are explicitly new anymore, rather, the cumulation of previous accomplishments on a larger scale is what is required—specifically the magnitude of supply chain and lunar mining that will be required in order to sustain settlement and the space-for-space economy. It can certainly be anticipated that continuous innovation and creativity will still be necessary in order to overcome the significant amount of work necessary, the challenge then becomes sustaining such a high level of innovation and creativity. This fact makes *technological nationalism* another strategy that would be difficult to recommend. A significant amount of overlap exists between *technological nationalism* and *space dominance*, so it is not necessarily surprising that neither strategy appears to have a positive trajectory when it comes to the emerging requirements of cislunar space.

3. Commercial Internationalism

A cislunar space strategy of *commercial internationalism* shifts the focus from a single nation to the combined efforts of the implementing nation and partners, whether in the form of a coalition with other nations or contractual agreements with commercial companies. This stark difference between the previous strategies brings with it new and unique advantages. The greatest benefit that partners bring is the ability to distribute collective burdens of cislunar space across many contributors. Not only does this load-sharing principle apply as a generality, but these partners provide opportunity for the implementing nation to also leverage specific strengths of those partners where the implementing nation alone may be weak. The proverb “many hands make light work” resounds in terms of costs and available technologies, such as the purchasing of a product or capability that a commercial company may have developed. Additionally, a strategy of partners immediately demands legitimacy due to the strategy being one of mixed political ideations and individual national interests. The number of, and diversity of, partners provide an opportunity to set precedent, and eventually, to establish international cislunar

norms where a lone-nation strategy (like *space dominance* or *technological nationalism*) would not. While this strategy diverges from the previous strategies, there is still some overlap. In this case, that overlap exists in the fostering of creativity and innovation, but rather than that creativity and innovation being under the direction of the state, it is spread across the various partners, providing significantly greater flexibility and increasing the probability that the feats of creativity and innovation will provide where needs are required.

While the benefits of *commercial internationalism* compound with the addition of partners, certain disadvantages also compound. The criticality of longevity in implementing a cislunar space strategy has already been examined. Under this strategy, longevity and consistency have to not only be maintained within the leadership of the implementing nation, but also the leaderships of the partners as well. There is a double-edged sword here in that there theoretically exists a direct correlation between the number of partners and better results, since the best contributions of each partner will be summed. But, at the same time, the more partners involved, the more organizations need to remain aligned—a task far easier said than done. The more time it takes to ensure that all partners remain aligned, the more time it takes for effective steps to be taken in cislunar space.

In contrast to the first two strategies, *commercial internationalism* provides the added partnerships that will likely be required to achieve effective use of cislunar space. The SSA case study in particular highlighted that there is already a paradigm shift of sorts taking place in space: whereas the 20th century space race employed strategies more aligned with *technological nationalism*, now the 21st century space race is employing strategies more aligned with *commercial internationalism*. Similarly, the energy case study highlighted opportunities for greater development in advanced robotic assets, a task far more aptly pursued by partners that specialize in such technologies; while the National Aeronautics and Space Administration (NASA) provides similar specialization, the sheer scale of allied and commercial innovations provide more—and sometimes cheaper—options than those provided by NASA exclusively. These examples, plus the invaluable chance to establish international cislunar norms reenforce the claim that effective use of cislunar space will require partnerships of some kind and, as such, there is a very good chance that a strategy like *commercial internationalism* will be most effective in the future.

4. Global Space Consortium

A cislunar space strategy of *global space consortium* maintains the benefits of partners while adding a level of cooperation and harmony that no other strategy comes close to. If a cislunar space strategy got to the point where the number of partners became global, and an entity were created to govern over the cislunar domain on behalf of the planet, not only would the load of each individual nation be lighter, but there would also theoretically be peace through all of cislunar space. Therefore, if this collective unity of effort were maintained, there would not be need for conflict, so in a sense, *global space consortium* strives for peace in cislunar space.

While this may sound like the obvious choice for a cislunar space strategy, it might be too good to be true. If it is difficult to maintain continuity of effort through one country, as was discussed in *technological nationalism*; it is then more difficult with partners, as was discussed in *commercial internationalism*. How much more difficult will it be to maintain this continuity on a global scale? It is almost impossible to imagine a situation where every country's leadership would be in unison over something. Consider the legal concerns that resulted from the largely accepted cornerstone of the space legal structure: the Outer Space Treaty. Despite it being a treaty that was met with overwhelming global support, Brazil, Columbia, Congo, Ecuador, Indonesia, Kenya, Uganda, and Zaire opposed it through the Bogotá Declaration of 1976.¹⁵² This declaration resulted in the Moon Agreement of 1979, a treaty that few beyond the seven previously mentioned countries have signed and ratified, and a treaty that arguably holds very little legal validity as a result. While this lack of unanimity is not something unique to *global space consortium*, the principle shown through this example highlights the difficulty with which such a large body can achieve agreement. The energy case study pointed to an opportunity where similar legal clarifications, such as laws governing lunar resources and the SPACE Act of 2015, could be resolved; while this example only serves as one where a single country (or

¹⁵² Haris A. Durrani, "The Bogotá Declaration: A Case Study on Sovereignty, Empire, and the Commons in Outer Space," *Columbia Journal of Transnational Law*, December 26, 2018, https://www.academia.edu/35362196/The_Bogot%C3%A1_Declaration_A_Case_Study_on_Sovereignty_Empire_and_the_Commons_in_Outer_Space.

two individual countries if Luxembourg were included) acts, the ratification of the Artemis Accords serves as an international example where multiple nations have taken collective action toward agreement. Perhaps *global space consortium* is the best avenue for solving concerns like this building a community of like-minded states that could lead to an effective treaty.

The infrastructure case study highlighted Weinzierl and Sarang’s advocacy for a strategy aligned with *global space consortium*, expressing that “earthly geopolitical rivalries . . . will unavoidably extend into space” with negative results, and that it remains “the job of the world’s governments not to get in the way.”¹⁵³ Despite the cliché of advocating for world peace, the point made is just. The overwhelmingly positive benefits that would result from global unity in the cislunar domain could set forth a standard of cooperation that would be difficult to oppose. *Commercial internationalism* identified the necessity of partnerships that will likely be required in cislunar space, and with the requirement of these partners, why would global leaders not simultaneously strive for harmony in this emerging domain?

B. CISELUNAR SPACE STRATEGY RECOMMENDATION

Given the nature of how each of the four proposed strategies aims to overcome the difficult challenges ahead in the cislunar domain, the strategy that best promises success in the areas of SSA, infrastructure, and energy is that of *commercial internationalism*. As was noted in the previous section, effective use of the cislunar domain will require an immense amount of work in each of these areas, so much that it is difficult to imagine a circumstance where a lone nation or single private company is able to achieve it without help. A strategy like *commercial internationalism* relies on the cooperation of various nations and a multitude of private companies in such a way that the whole becomes greater than the sum of its parts; by drawing out the best attributes of each partner, this strategy more appropriately distributes the burden of such a monumental task and will likely result in the more beneficial strategy for developing and establishing cislunar space power.

¹⁵³ Weinzierl and Sarang, “The Commercial Space Age Is Here.”

C. POLICY RECOMMENDATIONS

The following policy recommendations are presented as tools intended to bolster a cislunar space strategy of *commercial internationalism*. Each policy is designed to maximize the strengths of this strategy and minimize the weaknesses in such a way that it may provide an avenue to develop and establish cislunar space power for its members. In addition, these policies would ultimately support a way to meet the operational requirements that were outlined in each of the three case studies presented in chapters II, III, and IV.

- The greatest strength of *commercial internationalism* is its ability to leverage the input of partners, and so, a policy that will naturally bring the best partners together is essential. The previously mentioned Artemis Accords represents an excellent start. Outlined as a set of principles “intended to apply to civil space activities,” these accords originally created a coalition of eight signatories (Australia, Canada, Italy, Japan, Luxembourg, United Arab Emirates, United Kingdom, and the United States) in October of 2020.¹⁵⁴ Since October of 2020, nineteen nations (Bahrain, Brazil, Columbia, Czech Republic, Ecuador, France, India, Israel, Mexico, New Zealand, Nigeria, Poland, Republic of Korea, Romania, Rwanda, Saudi Arabia, Singapore, Spain, Ukraine) have become signatories to these accords.¹⁵⁵ China and Russia are notably absent. This exceptional increase only further demonstrates the benefit a policy like this represents; it can even be suggested that this policy might be the catalyst upon which cislunar space power will be built.
- Chapters I and IV identified a lack of sufficient legal clarification with respect to the cislunar domain. Many experts have been cited throughout this thesis offering recommendations and suggestions for how this clarification might be resolved, and while all of these recommendations are viable options, this thesis will

¹⁵⁴ Office of the Secretary of State, *Artemis Accords* (Washington, DC: Department of State, 2020), 8–16, <https://www.nasa.gov/specials/artemis-accords/img/Artemis-Accords-signed-13Oct2020.pdf>.

¹⁵⁵ “The Artemis Accords,” Artemis, 2017, <https://www.nasa.gov/specials/artemis-accords/index.html>.

advocate for a policy that imposes the creation of a governing body over cislunar space. Johnson-Freese and Burbach refer to this as vaguely as “an international body,” while Brearley draws a parallel from the International Seabed Authority to a similar type of organization with respect to cislunar space—a possible International Cislunar Authority.¹⁵⁶ Whether a new entity is created, or one is derived through an existing body, such an entity is crucial to establish authority over this area. This body can therefore compensate for *commercial internationalism*’s greatest weakness in longevity; a body dedicated to cislunar governance would be able to maintain more consistency than any individual nation, coalition, or company’s leadership. While the compensation for longevity would be significant, there would also be the matter of adjudicating admission to this future governance body, and it is important to emphasize that not every nation, coalition, or private company would be granted access, and therefore the opportunity to exert influence over the cislunar domain. This restricted admittance differentiates this body from one that might be created through a *global space consortium* strategy.

- A coordinated policy to address the inspection of future facilities on the Moon would be wise to consider—not unlike existing policy currently in place regarding facilities on Antarctica. The nations that are signatories of the Artemis Accords and China/Russia are all publicly planning the creation of such facilities.¹⁵⁷ As these facilities continue to be developed, questions of verification need to be addressed and there exists an opportunity to mutually consent to inspection without compromising national interests or the business of private companies.
- Finally, more than just a policy, but an overarching theme that should be implemented in the spirit of cooperation and good faith with allies and private

¹⁵⁶ Johnson-Freese and Burbach, “The Outer Space Treaty and the Weaponization of Space,” 140; Brearley, “Mining the Moon,” 53.

¹⁵⁷ International Space Exploration Coordination Group, *The Global Exploration Roadmap Supplement October 2022*, 3; Ling Xin, “Chinese Scientists Hold First Conference to Discuss Moon Base Plans,” *South China Morning Post*, April 12, 2023, <https://www.scmp.com/news/china/science/article/3216684/chinese-scientists-hold-first-conference-discuss-building-crewed-moon-base>.

companies, nations ought to prioritize friendship, partnership, trust, and confidence rather than treat relationships as exclusively transactional customer exchanges. While additional geopolitical factors outside of cislunar space will heavily influence the level of friendship extended to some possible partners—like China and Russia for example—the cooperative nature of these relationships offer opportunities that can help to solidify the enduring efforts of a strategy like *commercial internationalism*.

D. SUGGESTIONS FOR FUTURE RESEARCH

As the Artemis Program actively seeks to return to the Moon, plentiful opportunities will be available to test different aspects of different strategies in combination with various policies. Nations may find that more or less cooperation is necessary and opt to implement a different strategy than one aligned with *commercial internationalism*; however, as the partnerships with other nations and private companies continue to grow, a rare opportunity to evaluate the relative success of a strategy/policy in real-time is available. Interest in cislunar space will only continue to grow as the incentive for further investments—in terms of money, time, and resources, and political buy-in—also grows.

Future events like the outcome of Russia’s invasion of Ukraine, the success of the Artemis missions, and the changing state of global economy, will provide opportunities to see how the three current space powers progress through the 21st century space race. Observation of other space-faring nations, emerging coalitions, and new private companies will also add to the dynamic that will collectively contribute to future cislunar space strategy and ongoing development.

This thesis has evaluated the perspectives of cislunar space strategy from the unclassified viewpoint by gathering open-source literature and unclassified summaries of national documentation. There would certainly be further opportunities to examine cislunar endeavors from a classified viewpoint beyond what was explored here.

E. CONCLUSION

The current commander of United States Space Command, General James H. Dickenson, said that “cislunar capabilities are the key to the Moon.”¹⁵⁸ As the 21st century space race is in full effect, it presents a different problem set to leaderships around the world than the 20th century space race did. The passage of time brings with it exciting and unique changes: a new global power structure, new interests in space, completely different technological factors, the addition of successful private companies, and more strategic options to consider. This thesis has sought to answer the question of what kind of strategy is needed to establish and develop cislunar space power, and by analyzing four possible strategies as they pertain to the areas of SSA, infrastructure, and energy, it found that a strategy rooted in cooperation and partnerships like *commercial internationalism* promises to provide the greatest advantage in cislunar space.

¹⁵⁸ James A. Dickinson, “Space Support to the Naval Warfighter” (Presentation presented at the Naval Space Summit, Monterey, CA, March 30, 2023).

LIST OF REFERENCES

- Alston, Giles. "Diplomacy in Orbit." *Royal Institute of International Affairs* 53, no. 5 (1997): 116–18. <https://www.jstor.org/stable/40475932>.
- Axiom Space. "Alloys & Superalloys." Accessed April 27, 2023. <https://www.axiomspace.com/manufacturing/alloys-superalloys>.
- . "Fiber Optics." Accessed April 27, 2023. <https://www.axiomspace.com/manufacturing/fiber-optics>.
- Betts, Richard K., ed. *Conflict after the Cold War: Arguments on Causes of War and Peace*. 4th ed. Boston: Pearson, 2013.
- Brearley, Andrew. "Mining the Moon: Owning the Night Sky?" *Astropolitics* 4, no. 1 (2006): 43–67. <https://doi.org/10.1080/14777620600762790>.
- Breen, Nicole M. "Can the Outer Space Treaty Prevent Conflicts in Orbit in the 21st Century?" Master's thesis, Naval Postgraduate School, 2018. <http://hdl.handle.net/10945/59607>.
- Burt, Donald M. "Mining the Moon." *American Scientist* 77, no. 6 (1989): 574–79. <https://www.jstor.org/stable/27856008>.
- Chatters, Edward P., and Brian J. Crothers. "Space Surveillance Network." In *AU-18 Space Primer*, 249–58. Maxwell Air Force Base, AL: Air University Press, 2009. <https://www.jstor.org/stable/resrep13939.26>.
- Cornish, Chloe. "Interplanetary Players: A Who's Who of Space Mining." *Financial Times*, October 19, 2017. <https://www.ft.com/content/fb420788-72d1-11e7-93ff-99f383b09ff9>.
- Crotts, Arlin. *The New Moon: Water, Exploration, and Future Habitation*. New York: Cambridge University Press, 2014.
- David, Leonard. "Can NASA's Artemis Moon Missions Count on Using Lunar Water Ice?" Space.com, May 18, 2023. <https://www.space.com/moon-lunar-ice-poles-artemis-program>.
- DeCoster, Mallory, Ra'id Awadallah, David Blodgett, Erin Fowler, Stergios Papadakis, Benjamin Schmachtenberger, and Morgan Trexler. "On-Orbit Assembly and Manufacturing of Large Structures to Enable Space Situational Awareness." In *AIAA SCITECH 2023 Forum*, 1–11. National Harbor, MD & Online: American Institute of Aeronautics and Astronautics, 2023. <https://doi.org/10.2514/6.2023-1118>.

- Defense Intelligence Agency. *2022 Challenges to Security in Space: Space Reliance in an Era of Competition and Expansion*. Washington, DC: Defense Intelligence Agency, 2022. https://www.dia.mil/Portals/110/Documents/News/Military_Power_Publications/Challenges_Security_Space_2022.pdf.
- DeLucas, Lawrence J. "International Space Station." *Acta Astronautica* 38, no. 4–8 (1996): 613–19. [https://doi.org/10.1016/0094-5765\(96\)00056-2](https://doi.org/10.1016/0094-5765(96)00056-2).
- Dolman, Everett C. *Astropolitik: Classical Geopolitics in the Space Age*. London: Frank Cass, 2002.
- Dunbar, Brian. "LCROSS Impact Data Indicates Water on Moon." NASA. November 13, 2009. http://www.nasa.gov/mission_pages/LCROSS/main/prelim_water_results.html.
- . "Moon to Mars Overview." NASA. June 29, 2018. <http://www.nasa.gov/topics/moon-to-mars/overview>.
- . "Moon's South Pole in NASA's Landing Sites." NASA. April 15, 2019. <http://www.nasa.gov/feature/moon-s-south-pole-in-nasa-s-landing-sites>.
- Dunietz, Jesse. "Floating Treasure: Space Law Needs to Catch Up with Asteroid Mining." *Scientific American*, August 28, 2017. <https://www.scientificamerican.com/article/floating-treasure-space-law-needs-to-catch-up-with-asteroid-mining/>.
- Durrani, Haris A. "The Bogotá Declaration: A Case Study on Sovereignty, Empire, and the Commons in Outer Space." *Columbia Journal of Transnational Law*, December 26, 2018. https://www.academia.edu/35362196/The_Bogot%C3%A1_Declaration_A_Case_Study_on_Sovereignty_Empire_and_the_Commons_in_Outer_Space.
- European Space Agency. "Moonlight: What is ESA's Moonlight Initiative?" September 11, 2022. https://www.esa.int/Applications/Telecommunications_Integrated_Applications/Moonlight.
- ExoAnalytic Solutions. "Space Domain Awareness." Accessed April 2, 2023. <https://exoanalytic.com/space-domain-awareness/>.
- Foust, Jeff. "Chinese Rocket, Not Falcon 9, Linked to Upper Stage on Lunar Impact Trajectory." *SpaceNews*, February 13, 2022. <https://spacenews.com/chinese-rocket-not-falcon-9-linked-to-upper-stage-on-lunar-impact-trajectory/>.
- . "Luxembourg Adopts Space Resources Law." *SpaceNews*, July 17, 2017. <https://spacenews.com/luxembourg-adopts-space-resources-law/>.

- . “NASA and ESA Sign Lunar Cooperation Statement.” *SpaceNews*, September 26, 2022. <https://spacenews.com/nasa-and-esa-sign-lunar-cooperation-statement/>.
- Frueh, Carolin, Kathleen Howell, Kyle J DeMars, and Surabhi Bhadauria. “Cislunar Space Situational Awareness.” In *31st AAS/AIAA Spaceflight Mechanics Meeting*. Charlotte, North Carolina (Virtual), 2021. https://engineering.purdue.edu/people/kathleen.howell.1/Publications/Conferences/2021_AAS_FruHowDeMBha.pdf.
- Gallagher, Nancy. “Space Governance and International Cooperation.” *Astropolitics* 8, no. 2–3 (2010): 256–79. <https://doi.org/10.1080/14777622.2010.524131>.
- . *Towards a Reconsideration of the Rules for Space Security*. College Park, MD: University of Maryland, 2005. https://publicpolicy.umd.edu/sites/default/files/2019-08/space_rules2006.pdf.
- Garcia, Mark. “International Space Station Facts and Figures.” NASA, January 4, 2023. <http://www.nasa.gov/feature/facts-and-figures>.
- Gates, Michele, Brian Muirhead, Bo Naasz, Mark McDonald, Dan Mazanek, Steve Stich, Paul Chodas, and Jim Reuter. “NASA’s Asteroid Redirect Mission Concept Development Summary.” In *2015 IEEE Aerospace Conference*, 1–13. IEEE, 2015. <https://doi.org/10.1109/AERO.2015.7119163>.
- Hall, Loura. “Harnessing Power from the Moon.” NASA, August 6, 2017. <http://www.nasa.gov/feature/harnessing-power-from-the-moon>.
- Harvard University. “Infrastructure.” 2023. <https://www.harvard.edu/in-focus/infrastructure/>.
- Howell, Elizabeth. “SOHO: Spying on the Sun.” *Space*, April 15, 2016. <https://www.space.com/18501-soho-solar-heliospheric-observatory.html>.
- International Space Exploration Coordination Group. *The Global Exploration Roadmap Supplement October 2022: Lunar Surface Exploration Scenario Update*. Washington, DC: NASA, 2022. https://www.globalspaceexploration.org/wp-content/isecg/GER_Supplement_Update_2022.pdf.
- ISS National Laboratory. “History and Timeline of the ISS.” April 25, 2023. <https://www.issnationallab.org/about/iss-timeline/>.
- Johnson-Freese, Joan. *Space as a Strategic Asset*. New York: Columbia University Press, 2007.
- Johnson-Freese, Joan, and David Burbach. “The Outer Space Treaty and the Weaponization of Space.” *Bulletin of the Atomic Scientists* 75, no. 4 (2019): 137–41. <https://doi.org/10.1080/00963402.2019.1628458>.

- Jones, Alexander. “Mining Outer Space: The New Gold Rush?” *International Banker*, March 16, 2016. <https://internationalbanker.com/brokerage/mining-outer-space-new-gold-rush/>.
- Kennedy, John F. “Address to Joint Session of Congress May 25, 1961.” *Historic Speeches*, May 25, 1961. <https://www.jfklibrary.org/learn/about-jfk/historic-speeches/address-to-joint-session-of-congress-may-25-1961>.
- Kennewell, John A, and Ba-Ngu Vo. “An Overview of Space Situational Awareness.” In *Proceedings of the 16th International Conference on Information Fusion*, 1029–36. Perth, Western Australia: IEEE, 2013. <https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6641108>.
- Klein, John J. *Space Warfare: Strategy, Principles, and Policy*. London: Routledge, 2006.
- Lambeth, Benjamin S. *Mastering the Ultimate High Ground: Next Steps in the Military Uses of Space*. Santa Monica, CA: RAND Corporation, 2003. https://www.rand.org/pubs/monograph_reports/MR1649.html.
- LeoLabs. “Our Vertex.” Accessed April 17, 2023. <https://leolabs.space/vertex/>.
- . “Welcome to LeoLabs.” Accessed April 2, 2023. <https://leolabs.space/about-us/>.
- Lewin, Sarah. “Making Stuff in Space: Off-Earth Manufacturing Is Just Getting Started.” *Space.com*, May 11, 2018. <https://www.space.com/40552-space-based-manufacturing-just-getting-started.html>.
- Library of Congress. “Summary of H.R. 2262 (114th): U.S. Commercial Space Launch Competitiveness Act.” *GovTrack.us*. Accessed June 12, 2023. <https://www.govtrack.us/congress/bills/114/hr2262/summary#libraryofcongress>.
- Lupton, David E. *On Space Warfare: A Space Power Doctrine*. Maxwell Air Force Base, AL: Air University Press, 1988.
- Mars, Kelli. “Gateway Overview.” *Gateway*, August 17, 2016. <http://www.nasa.gov/gateway/overview>.
- McDougall, Walter A. *The Heavens and the Earth: A Political History of the Space Age*. New York: Basic Books, 1988.
- Molotov, Vladimir Agapov, Zakhary Khutorovsky, Vasily Rumyantsev, Vadim Biryukov, Nasredin Minikulov, Makhmud Gulyamov et al. *Faint High Orbit Debris Observations with ISON Optical Network*. Moscow, Russia: Keldysh Institute of Applied Mathematics, 2009. https://amostech.com/TechnicalPapers/2009/Orbital_Debris/Molotov.pdf.

- Moltz, James Clay. "The Changing Dynamics of Twenty-First-Century Space Power." *Journal of Strategic Security* 12, no. 1 (April 2019): 15–43. <https://doi.org/10.5038/1944-0472.12.1.1729>.
- . *The Politics of Space Security: Strategic Restraint and the Pursuit of National Interests*. 3rd ed. Stanford, CA: Stanford University Press, 2019.
- . "Toward Cooperation or Conflict on the Moon?: Considering Lunar Governance in Historical Perspective." *Strategic Studies Quarterly* 3, no. 3 (2009): 82–103. <https://www.jstor.org/stable/26268666>.
- Moon Express. "Moon Express Inc: Redefine Possible." Accessed June 12, 2023. <https://moonexpress.com/>.
- Mueller, Karl P. "Totem and Taboo: Depolarizing the Space Weaponization Debate." *Astropolitics* 1, no. 1 (January 2003): 4–28. <https://doi.org/10.1080/1477-760391832499>.
- NASA. "The Artemis Accords." 2017. <https://www.nasa.gov/specials/artemis-accords/index.html>.
- . "Comparison: Webb vs. Hubble Telescope." Accessed March 18, 2023. <https://jwst.nasa.gov/content/about/comparisonWebbVsHubble.html>.
- . "Explore Orbital Debris." NASA Orbital Debris Program Office, 1979. <https://orbitaldebris.jsc.nasa.gov/>.
- . "Radioisotope Thermoelectric Generators (RTGs)." September 25, 2018. <https://solarsystem.nasa.gov/missions/cassini/radioisotope-thermoelectric-generator>.
- . *Reference Guide to the International Space Station: Utilization Edition*. Houston, TX, 2015. <https://www.nasa.gov/sites/default/files/atoms/files/np-2015-05-022-jsc-iss-guide-2015-update-111015-508c.pdf>.
- . "What Powers a Spacecraft?" September 4, 2019. <https://rps.nasa.gov/news/35/what-powers-a-spacecraft>.
- National Science & Technology Council. *2022 National Cislunar Science and Technology Strategy*. Washington, DC: White House, 2022. <https://www.whitehouse.gov/wp-content/uploads/2022/11/11-2022-NSTC-National-Cislunar-ST-Strategy.pdf>.
- NorthStar Earth & Space. "NorthStar: Empowering Humanity to Preserve Our Planet." NorthStar Earth & Space Inc. Accessed April 14, 2023. <https://northstar-data.com/space/>.

- Office of the Secretary of State. *Artemis Accords*. Washington, DC: Department of State, 2020. <https://www.nasa.gov/specials/artemis-accords/img/Artemis-Accords-signed-13Oct2020.pdf>.
- Olsen, Richard C. *Remote Sensing from Air and Space*. 2nd ed. Bellingham, WA: SPIE Press, 2016.
- Ortiz, Carlos R., and Steven L. Rickman. *Method for the Calculation of Spacecraft Umbra and Penumbra Shadow Terminator Points*. NASA Technical Paper 3547. Houston, TX: Lyndon B. Johnson Space Center, 1995. <https://ntrs.nasa.gov/api/citations/19950023025/downloads/19950023025.pdf>.
- Peacock, Deborah A. “Mining on the Moon: Yes, It’s Really Going to Happen.” *Mining Engineering Magazine*, January 2017. <http://i2massociates.com/downloads/MiningMoonSMEJan2017.pdf>.
- Pearse, M.J. “An Overview of the Use of Chemical Reagents in Mineral Processing.” *Minerals Engineering* 18, no. 2 (February 2005): 139–49. <https://doi.org/10.1016/j.mineng.2004.09.015>.
- Rangela, Renu. “Space Is under the Threat of Becoming a Battleground for Mining Companies.” *International Business Times*, January 15, 2016. <https://www.ibtimes.com.au/space-under-threat-becoming-battleground-mining-companies-1500792>.
- Redwire Space. “Additive Manufacturing Facility (AMF).” Product Spec Sheet. Accessed April 27, 2023. <https://redwirespace.com/products/amf/>.
- . “Archinaut.” Accessed April 27, 2023. <https://redwirespace.com/products/archinaut/>.
- Robinson, George S., and Harold M. White. *Envoys of Mankind: A Declaration of First Principles for the Governance of Space Societies*. Washington, DC: Smithsonian Institution Press, 1986.
- Schinger, Jessy Kate, Victoria Samson, and Nivedita Raju. “Don’t Delay Getting Serious about Cislunar Security.” *War on the Rocks*. July 6, 2022. <https://warontherocks.com/2022/07/dont-delay-getting-serious-about-cislunar-security/>.
- Sellers, Jerry Jon. “Understanding Space: An Introduction to Astronautics.” In *Understanding Space: An Introduction to Astronautics*, edited by Douglas H. Kirkpatrick, Revised Second Edition., 79–90. New York: McGraw-Hill Custom Publishing, 2004.

- Shekhtman, Lonnie. “NASA’s Artemis Base Camp on the Moon Will Need Light, Water, Elevation.” NASA, January 26, 2021. <http://www.nasa.gov/feature/goddard/2021/nasa-s-artemis-base-camp-on-the-moon-will-need-light-water-elevation>.
- Thaller, Michelle, and Rob Gutro. “NASA – ‘L2’ Will Be the James Webb Space Telescope’s Home in Space.” NASA Mission News. June 23, 2010. <https://www.nasa.gov/topics/universe/features/webb-l2.html>.
- Thomas, L. Dale, Jeffrey M. Hanley, Jennifer L. Rhatigan, and Deborah Neubek. “NASA’s Constellation Program: The Final Word.” *Systems Engineering* 16, no. 1 (2013): 71–86. <https://doi.org/10.1002/sys.21219>.
- Toyoma, Gentoku. “Countering Threats in Space through International Cooperation.” *Space Policy* 55 (February 2021): 1–8. <https://doi.org/10.1016/j.spacepol.2020.101387>.
- United Nations General Assembly. *United Nations Treaties and Principles on Outer Space*. New York: United Nations, 2002. <https://digitalcommons.unl.edu/spacelawdocs/10/>.
- United Nations Office for Outer Space Affairs. “Treaties.” Accessed January 28, 2023. <https://www.unoosa.org/oosa/en/aboutus/history/treaties.html>.
- Vedda, James A. *Becoming Spacefarers: Rescuing America’s Space Program*. Bloomington, IN: Xlibris Corp, 2012.
- . “Cislunar Development: What to Build and Why.” Aerospace, April 17, 2018. <https://csps.aerospace.org/sites/default/files/2021-08/CislunarDevelopment.pdf>.
- Wallace, Megan. “Deep Space Atomic Clock (DSAC).” NASA, June 18, 2019. <http://www.nasa.gov/directorates/heo/scan/engineering/technology/dsac>.
- Weinzierl, Matthew. “Space, the Final Economic Frontier.” *Journal of Economic Perspectives* 32, no. 2 (Spring 2018): 173–92. <https://doi.org/10.1257/jep.32.2.173>.
- Weinzierl, Matthew, and Mehak Sarang. “The Commercial Space Age Is Here.” *Harvard Business Review*, February 12, 2021. <https://hbr.org/2021/02/the-commercial-space-age-is-here>.
- White House. *National Space Policy of the United States of America*. Washington, DC: White House, 2010. <https://www.hsdl.org/c/abstract/?docid=22716>.
- . *National Space Policy of the United States of America*. Washington, DC: White House, 2020. <https://www.hsdl.org/c/abstract/?docid=847883>.

———. *United States Space Priorities Framework*. Washington, DC: White House, 2021. <https://www.whitehouse.gov/wp-content/uploads/2021/12/United-States-Space-Priorities-Framework--December-1-2021.pdf>.

Wild, Flint. “What Is the International Space Station?” NASA, October 30, 2020. <http://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-the-iss-58.html>.

Wilson, Jim. “NASA Centers and Facilities.” NASA, 13 2023. <http://www.nasa.gov/about/sites/index.html>.

Wolter, Detlev. *Common Security in Outer Space and International Law*. Geneva: UNIDIR, 2006.

Xin, Ling. “Chinese Scientists Hold First Conference to Discuss Moon Base Plans.” *South China Morning Post*, April 12, 2023. <https://www.scmp.com/news/china/science/article/3216684/chinese-scientists-hold-first-conference-discuss-building-crewed-moon-base>.

Zisk, Rachael. “How ICON Will Bring Its 3D Printing Tech to the Moon.” *Fast Company*, November 30, 2022. <https://www.fastcompany.com/90817898/how-icon-will-bring-its-3d-printing-tech-to-the-moon>.

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