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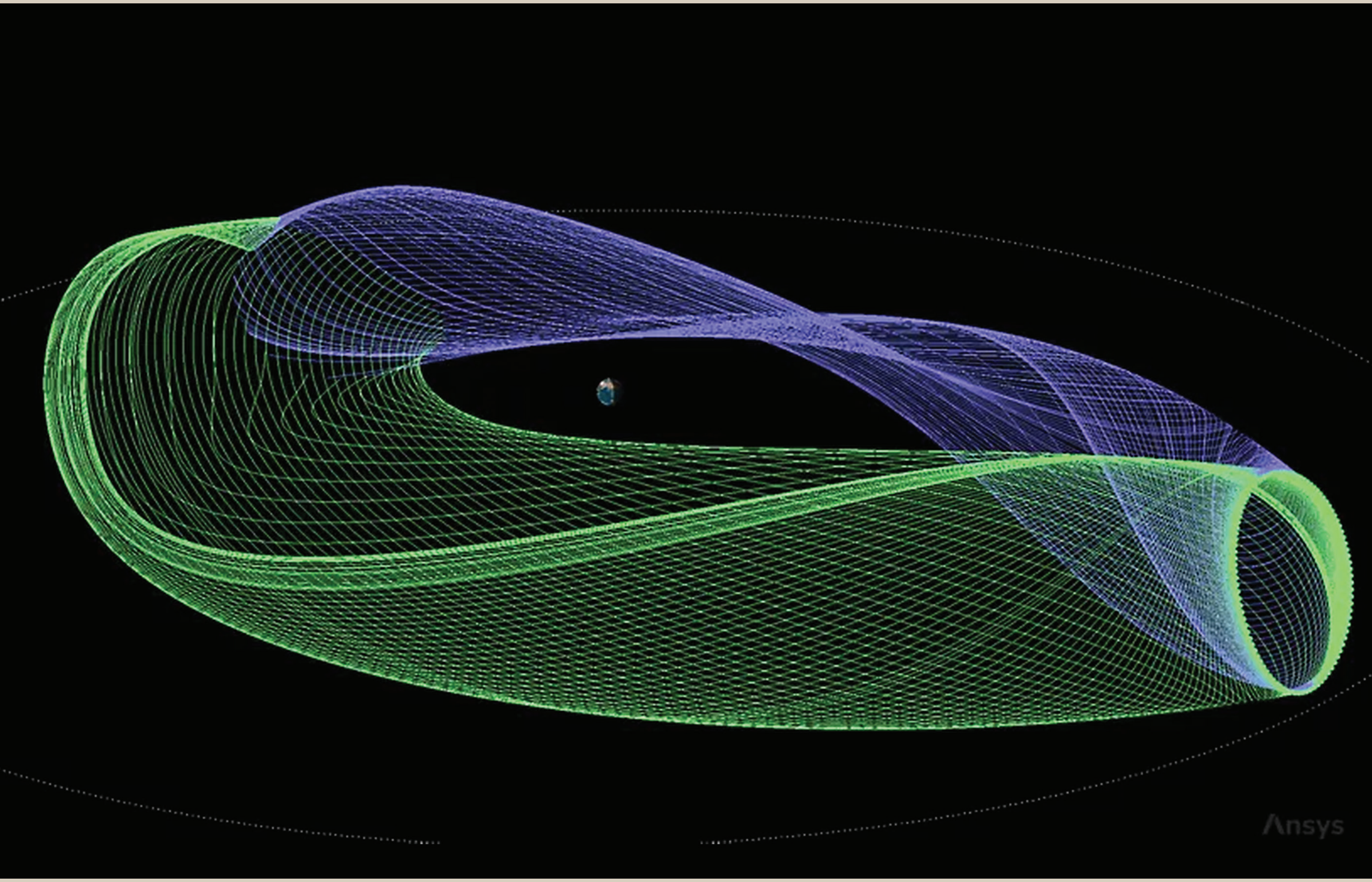
Understanding Space Frontier Areas: Strategy in Cislunar Space and Beyond

By Todd Pennington



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Cover: Stable (green) and unstable (purple) manifold arcs associated with an Earth-Moon L1 halo orbit in the circular-restricted three-body problem (CR3BP), illustrating low-energy dynamical pathways used for cislunar transfer design. (Image credit: Ansys, with image resolution upscaling for printing performed by ChatGPT Enterprise.)

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Center for Strategy and Military Power
Institute for National Strategic Studies
Strategic Perspectives, No. 45

Series Editor: R. Kim Cragin

National Defense University Press
Washington, D.C.
January 2026

This study was reviewed and approved by NDU's component Office of Human Research Protection on 18 October 2025 (case number 2410-155830) in accordance with DODI 3216.02 and NDUI 9010.01.

First printing, January 2026

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Acknowledgments

The author thanks the many people and organizations that generously provided time and expertise to the development of this paper. First and foremost, the author is grateful to the experts who participated in research interviews as part of this study, and to the focus group participants whose feedback on the qualitative assessment tool was essential. Kim Cragin, Jeffrey Mankoff, and the peer-review team provided invaluable feedback on earlier drafts of this paper. The Air Force Research Laboratory's Space Vehicles Directorate and the Space Force's 19th Space Defense Squadron were of great assistance in developing the author's understanding of operations in cislunar space and beyond. Any technical insights about Space Frontier Areas contained in this paper reflect their generously shared expertise; any errors are the author's alone. Bruce McClintock and Jordan Logue of RAND provided a lively forum for discussions of operational astrography (the delineation of regions of cislunar space); these discussions were important in refining the strategic concept of Space Frontier Areas that is central to this paper. Finally, INSS Research Interns Sam Chang (of Georgetown University) and Emmy Kanarowski (of Cornell University) were of great assistance to the author in the development of this paper, and on many other matters.

Executive Summary

Distant reaches of space loom as a strategic horizon. The vast majority of space operations have, so far, been limited to a few families of near-Earth orbits. However, space beyond geostationary Earth orbit, or xGEO, is likely to become important for strategic purposes in the near future. This is especially true of cislunar space, that region of space in which the gravity of Earth's moon is significant. This paper refers to xGEO and cislunar space as *Space Frontier Areas*, since missions there have not yet reached sufficient scale to cluster into patterns of use.

Current strategic thought on activities in Space Frontier Areas is largely bipolar, with some experts emphasizing their near-term security implications and others emphasizing much longer-term economic potential. This bipolarity tends to suggest a zero-sum choice between imminent security needs or long-term economic opportunity, constraining policymakers' ability to identify trade-offs and make nuanced choices about risk and priorities in space operations.

This paper proposes an analytical framework for improving the coherence of strategic thought about Space Frontier Areas. It postulates four strategic purposes served by activities in Space Frontier Areas (prestige, governance, security, and resources), and a framework in which each purpose can be weighted by its importance and immediacy in a given time frame. Relying on data derived from research interviews with several experts in space operations, it demonstrates that this framework can produce more coherent strategic perspectives about activities in Space Frontier Areas.

Reducing bipolarity in strategic thought about Space Frontier Area improves the realism and nuance of the context in which leaders must make decisions about time, attention, and resources to be devoted to space operations.

Introduction

Outer space beyond the limits of most present-day space activities looms as a strategic horizon. The prospects of water ice at the lunar south pole, asteroids rich in rare earth minerals, and human habitation on other worlds inspire adventurers, motivate scientists and investors, and irritate skeptics. Risks and opportunities in new frontiers of space operations also concern military leaders: as national interests expand to beyond Earth orbit, the potential for competition and conflict follows. Former Vice Chairman of the Joint Chiefs of Staff General James Cartwright has suggested there is a "normal pattern" of expansion into a new domain: exploration is followed by routinizing communications, followed by national security, followed by the commercial sector.[1]

States have undertaken missions to the Moon and beyond since the first days of the space age.[2] However, such missions have remained exceptional, with the vast majority of space activities confined to near-Earth orbit. Advances in technology and an emerging new space race with China are likely to change that. Spacefaring actors' aspirations for new moves at scale into Space Frontier Areas should drive new ways of thinking about space and spacepower.

This paper explores ways that activities in Space Frontier Areas have strategic significance for the United States in the near future. It first defines the concept of Space Frontier Areas and characterizes their key attributes. It next reviews the existing relevant literature, identifying generally agreed matters and highlighting those matters where strategic perspectives diverge. It concludes that the literature tends to center on tends to center on security and resource interests with substantially less emphasis on the prestige and governance qualities of activities in Space Frontier Areas. It then proposes a framework for advancing strategic thinking about activities in Space Frontier Areas and reports the results of research testing that framework.

Part I: Defining and Characterizing Space Frontier Areas

Most sources on what this paper terms *Space Frontier Areas* focus on one (or both) of two conceptions of outer space beyond the limits of contemporary satellite operations: exgeostationary Earth orbit (xGEO) space, or cislunar space. *Cislunar* and *xGEO* have long sufficed as terms of reference because the principal use of each term is to distinguish distant regions of space from more familiar near-Earth orbit families: low Earth orbit (LEO), medium Earth orbit (MEO), geostationary Earth orbit (GEO), and highly elliptical orbit (HEO). The U.S. Space Force's capstone doctrine publication divides space into three grand "orbital regimes" based on gravitational dominance. The geocentric regime is dominated by Earth's gravity (and is home to all current "key orbital trajectories," the "orbits for mission execution and power projection."[3]

In U.S. Space Force doctrine, the geocentric regime is nested within the cislunar regime, which is dominated by the interacting gravity of Earth and its Moon. The cislunar regime in turn is nested within the solar regime, dominated by the Sun's massive gravitational field.[4] As discussed below, other sources define and delineate space beyond the geocentric regime differently.

At present, no agreed convention for further delineation of xGEO or cislunar space has gained general acceptance. Several such frameworks have been proposed.[5] Some proposals would distinguish regions of space beyond near-Earth orbits with reference to spatial distances between Earth, its Moon, and other celestial bodies.[6] Others divide regions of xGEO or cislunar space into zones centered on sources of gravitational attraction,[7] zones from which spacecraft may present a threat to Earth or satellites in Earth orbit,[8] or dynamic potential (such as space in vicinity of Lagrange points, where the gravity of two celestial bodies—such as Earth and its moon—are in gravitational equilibrium).[9]

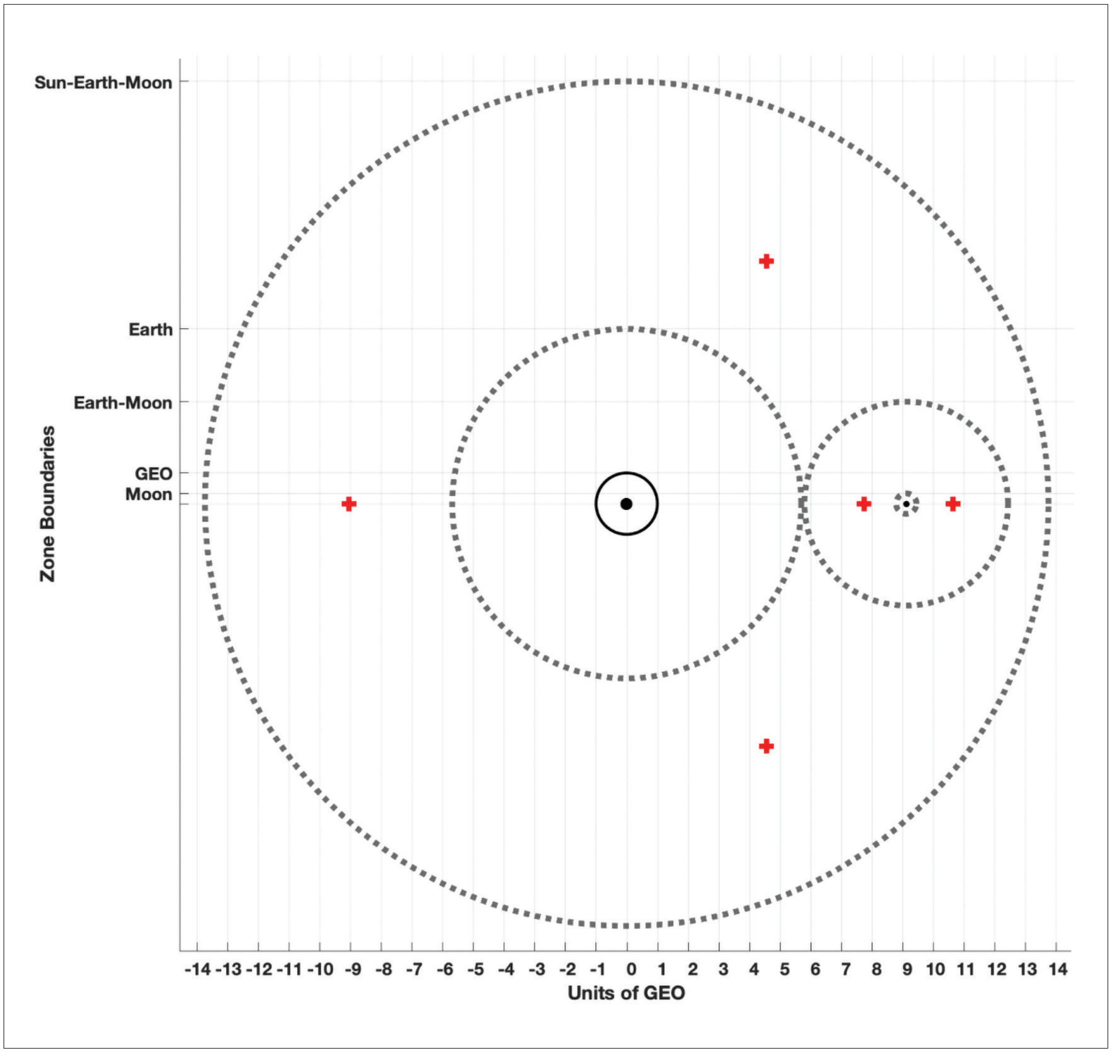
Each of these frameworks for delineation has merit as a basis for describing or understanding some aspect of novel space operations. However, any effort to distill the gravitational complexity of Space Frontier Areas like xGEO or cislunar space into a simplified model quickly encounters a limit to that model's utility.[10] The variety of possible orbits and trajectories in and between regions of Space Frontier Areas is enormous. As the use and exploration of space beyond Earth orbit matures, the patterns of usage that emerge will simplify the task of describing them.

The titles of contemporary key orbital trajectories correspond to regions of space in which actual uses of outer space have matured and clustered, forming recognizable patterns that quickly became the basis for delineating space. Such delineation by clustered use becomes convenient, or even necessary, as access to a frontier is normalized to the point that patterns emerge.

Regions that are vast or geographically diverse have historically been delineated with reference to the lines along which uses have clustered. For example, the designation of historic trade routes such as the "Silk Roads" did not rely on their inherent geographic or spatial qualities for delineation. Although traders on the Silk Roads may have favored specific pathways between nodes of economic importance because of qualities such as distance, terrain, and population centers located along the way, it was the clustered usage of the paths along those trade routes (rather than their physical qualities) that came to define them.[11]

There are a theoretically infinite number of Earth-circling orbital trajectories. However, actual uses of Earth orbit have mostly clustered in the four "key orbital trajectories" described in U.S. Space Force doctrine: LEO, MEO, HEO, and GEO. Although the conventional titles for these orbital regimes bespeak factors such as altitude, eccentricity, inclination, and/or period match, the common quality of each orbital trajectory significant enough to earn a title is that the clustering of space missions there has formed recognizable patterns of use. A brief look at how these legacy orbital regimes came to have distinct identities is in order before turning our attention toward more distant frontiers.

Figure 1. Example of framework for further delineation of cislunar space, in this case by spherical zones around celestial bodies. In this model, Earth is at center, and the Moon is at about nine times distance from Earth of Geostationary Earth Orbit; the Earth-Moon Lagrange points are shown as red crosses.



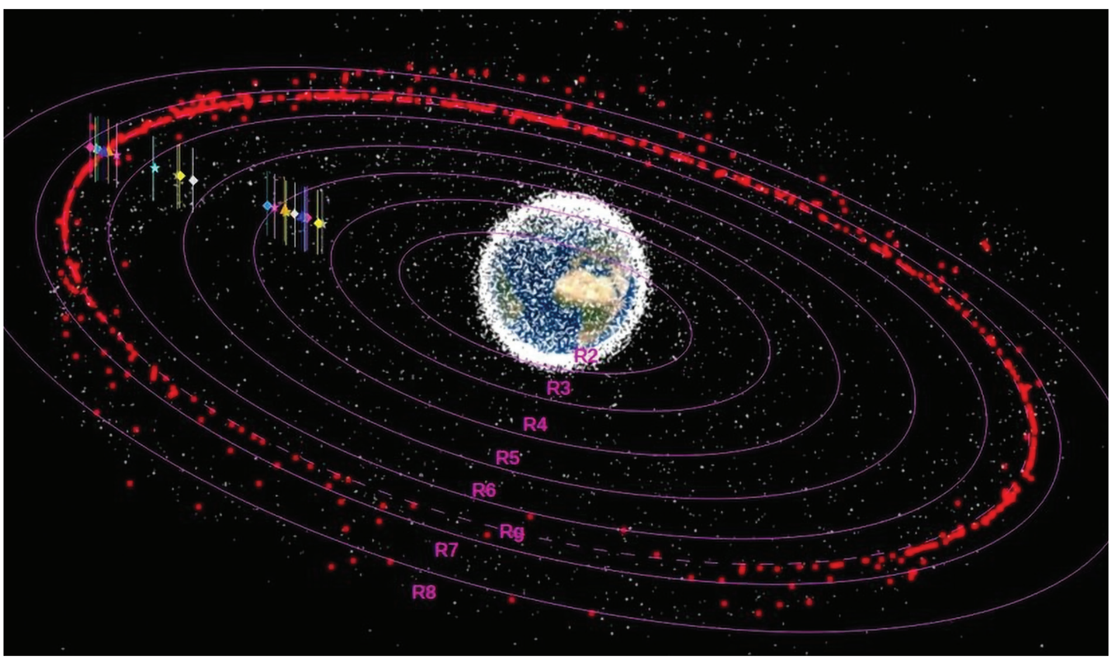
Source: Marcus J. Holzinger et al., *A Primer on Cislunar Space*, AFRL 2021-1271 (Wright-Patterson Air Force Base: Air Force Research Laboratory, 2021), figure 3, https://www.afrl.af.mil/Portals/90/Documents/RV/A%20Primer%20on%20Cislunar%20Space_Dist%20A_PA2021-1271.pdf.

The Qualities and Titles of Legacy Earth Orbits

Low Earth orbit (LEO) is characterized by the clustered use of outer space at altitudes between the lowest sustainable orbit and approximately 2,000 kilometers (km) above Earth's mean sea level.[12] The nominal distinctive of *low* Earth orbit is *low* orbital altitude. Uses cluster within LEO because it is the easiest and most cost-effective orbit to reach, and because many space missions (for example, Earth imagery, communication with low-power devices on Earth, very low latency data transfer) are optimized at low orbital altitudes.[13] Patterns of usage also cluster below 2,000 km because as orbital altitude approaches this upper limit of LEO, the harmful radiological effects of the Earth's inner Van Allen Belt become significant and damage satellite components not designed for long endurance in high-radiation environments.[14]

Geostationary Earth orbit (GEO) is defined by the clustered use of space at approximately 0° inclination (directly above the equator), in a circular orbit 35,786 km above Earth's mean sea level. In such an orbit, the time it takes a satellite to complete an orbit around Earth matches the time it takes the Earth to complete a full rotation on its axis. In this orbit, a satellite seems

Figure 2. Visualization of satellites at LEO, MEO, and GEO altitudes. In this image, satellites in LEO are depicted in white, and satellites in GEO are depicted in red.

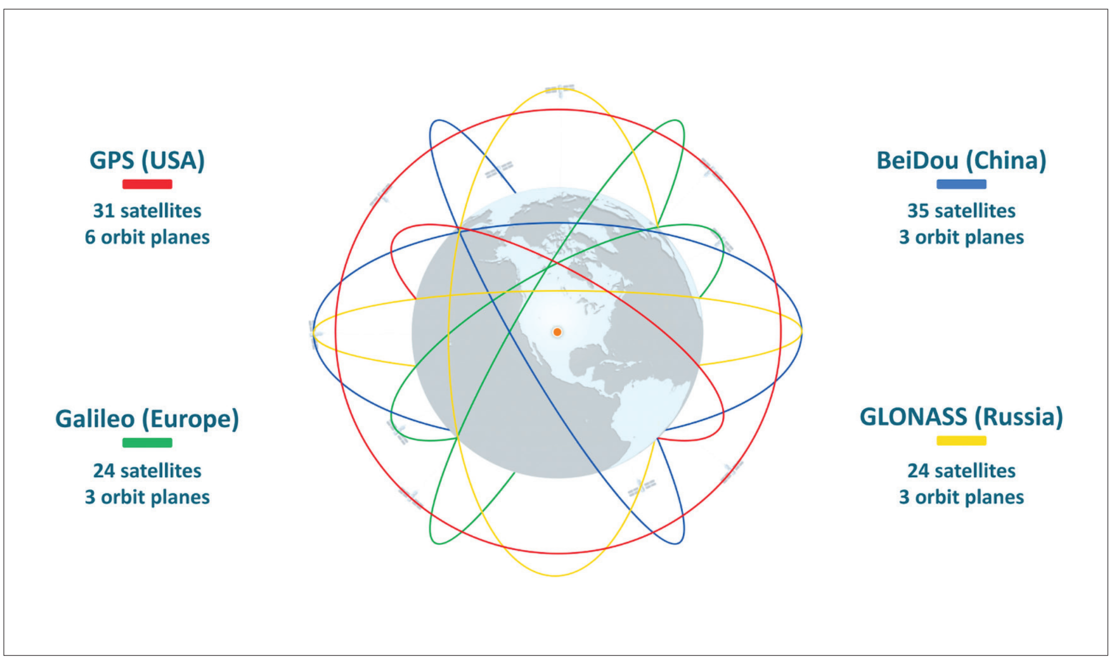


Source: Jacobo Varela et al., "MHD Study of Planetary Magnetospheric Response During Extreme Solar Wind Conditions: Earth and Exoplanet Magnetospheres Applications," *Astronomy & Astrophysics* 659 (March 2022), A10, https://doi.org/10.1051/0004-6361/202141181.

to be "stationary above the same spot on the planet,"[15] and holds almost a third of the Earth's surface continuously in its field of regard.[16] The perception of a "*stationary*" satellite is the nominal distinctive of Geo*stationary* Earth orbit. Uses cluster in GEO because a satellite in this orbit enjoys a constant view of the same areas of Earth's surface. This is useful for functions like satellite broadcast and communications that benefit from constant view of fixed antennas and ground stations on Earth.

While GEO is a circular orbit, the trajectory of a satellite in highly elliptical orbit (HEO) is an elongated ellipse. "Eccentricity" describes the extent to which a satellite's orbit deviates from a perfect circle; the path of highly eccentric orbits are very elongated ellipses. Although HEO is possible at any inclination and in a wide range of eccentricity, patterns of satellites in HEO generally cluster in high-eccentricity polar orbits. Space missions such as missile warning and communications cluster in HEO for optimized coverage of polar regions, providing long dwell time over one polar region. Satellites in HEO often perform similar functions as those in GEO, but a satellite in GEO does not have an optimized view of polar regions due to the curvature of the Earth and obscuration by the Earth's atmosphere. The high eccentricity of the orbit also means

Figure 3. Visualization of GNSS constellations in MEO. The orbital trajectories are illustrative only and do not depict all orbital planes in actual use.



Source: "Global Navigation Satellite System (GNSS) and Satellite Navigation Explained," Inertial Labs, November 7, 2024, https://inertiallabs.com/gnss-and-satellite-navigation-explained.

that a satellite in HEO traverses a wide range of altitudes; HEO perigee (the lowest altitude point of an Earth orbit) can be at lower altitude than most satellites in LEO, while HEO apogee (the highest point of an Earth orbit) can exceed 45,000 km: this is 10,000 km farther from Earth than GEO altitude.[17] The *highly* eccentric, which is to say *elliptical,* orbit at high/polar inclination is the nominal distinctive of highly elliptical orbit.

Medium Earth orbit (MEO) refers to the region of space between LEO and GEO altitudes. Only one space mission clusters in MEO: Global Navigation Satellite Systems (GNSS).[18] GNSS operate as constellations; a user on Earth must normally have line-of-sight to three or more satellites in the constellation to calculate location. From MEO, a GNSS constellation of manageable size can keep three or more satellites in view of almost any point on Earth. However, satellites in MEO encounter Van Allen Belt radiation more than satellites in any other contemporary Earth orbit. The balance of constellation size and global coverage is so favorable in MEO that nations deploying GNSS constellations accept as an operational necessity the additive cost and technical complexity of incorporating radiation shielding into the design of GNSS satellites. It is only because satellites performing this important mission cluster in MEO that its designation as such is in common use. Its nominal distinctive is its intermediacy: *medium* Earth orbit is the space *between* LEO and GEO.

Clustered Use as a Basis for Delineating Regions of Space

To the extent the terms *xGEO* or *cislunar* suffice today to describe regions of space beyond contemporary Earth orbits, it is because space operations there have not reached levels that cluster into patterns. However, this paper looks ahead to a time when missions to these regions of space are expected to expand substantially, forming patterns of clustered use in and between regions of xGEO and cislunar space. This clustering will probably not develop in all regions of space at the same pace. Use of new areas of space is likely to cluster in and between some regions before others.[19] This sequenced normalization of operations in new regions of space motivates this paper's usage of the term *Space Frontier Areas* in the context of the strategic analysis provided here.

As uses cluster in some regions or trajectories of Space Frontier Areas, those regions will lose their "frontier" quality. New patterns of motion beyond Earth orbit will become new "key orbital trajectories," with new titles based on how these activities cluster into recognizable patterns. Sustained activity in novel trajectories and outposts on celestial bodies will bring new Space Frontier Areas, ever more distant from Earth, within the reach of human-directed activity. New terms of delineation for both regions of void space and areas of celestial bodies are likely to emerge as new uses cluster in formerly frontier areas.[20] At the same time, other areas of xGEO and cislunar space may endure as Space Frontier Areas, perhaps for decades or centuries, if missions there remain challenging, exceptional, and rare.

xGEO: An Astrodynamic "Et Cetera"

The concept of xGEO has salience in space operations because GEO has become an informal boundary in present-day strategic thought about space operations. Typical definitions of xGEO in the literature on spacepower include no outer limit. United States doctrine for Joint Space Operations describes xGEO as extending from "35,780 kilometers . . . to infinity," encompassing cislunar space (including Earth's Moon), but also Jupiter, and Pluto, and other galaxies.[21] Some of these celestial bodies, and the vast regions of space between and around them, are of greater near-term strategic interest than others, though regions of space nearest to Earth are of greatest near-term strategic interest.[22] The concept of xGEO space is useful today for distinguishing activities in the legacy Earth orbits from activities in Space Frontier Areas. However, distinction of one vast region of space from another is probably the limit of its utility: a concept defined in terms of its opposite "can have no fixed character."[23]

Certain qualities of GEO probably contribute to its salience as a point of astrographic delineation. The GEO belt is in some ways a distant planar extension of the equator, itself a major conceptual boundary in terrestrial geography. Visual depictions of satellites in GEO resemble a narrow Saturn-like ring around Earth: it *looks like* a boundary. The vast majority of all spacecraft ever launched in human history have launched to one of the near-Earth orbital regimes; most of their dwell time is at or below GEO altitude.[24] These factors may tend to foster the perception of GEO as an outer limit for "routine" space operations.

GEO is not the astrodynamic limit of "Earth orbit." Earth's gravity dominates the movement of resident space objects far beyond GEO. Out to distances of about 100,000 km from Earth, approximately 2.7 times the distance from Earth to GEO, spacecraft can sustain Earth orbit under principles of space flight substantially similar to those governing contemporary near-Earth orbits. At about 100,000 km from Earth lies what some have coined the "Worden Line," so-named for Dr. Simon "Pete" Worden, to whom is attributed the observation that at approximately this altitude, options for spacecraft maneuver change, requiring less energy for more substantial maneuver.[25]

However, even beyond the Worden Line the gravity of Earth predominates motion. Only beyond the Earth's Hill Sphere (found at approximately 1.5 million km from Earth—42 times the distance of GEO from Earth) is the attractive force of Earth's gravity sufficiently attenuated that "a spacecraft will eventually be drawn to another gravitational field" in heliospheric space (where the gravity of the Sun predominates).[26]

Thus, the term *xGEO* functions as a sort of astrodynamic *et cetera*, suggesting (not without cause) that the key orbits and trajectories, space mission types, and strategic considerations that will eventually mature in distant regions of space are not yet fully understood. However, one region of xGEO space is of special interest for strategic purposes: cislunar space.

Cislunar: The Next Frontier

As a general proposition, *cislunar* refers to Earth's Moon, free space in the vicinity of the Moon, and regions of free space within the Earth-Moon system (including the free space around the Earth-Moon Lagrange points). However, the literature includes many varied and bespoke definitions (see figure 4). In the absence of a generally agreed definition of cislunar space, writers tend to adopt or propose one harmonious with their project's focus.

Figure 4. Selected Definitions of *Cislunar*

"[T]he region of space in the Earth-Moon system beyond GEO, including the Moon's orbit and all of the Earth-Moon Lagrange points."[1] This definition is from a Johns Hopkins University Applied Physics Laboratory report and, like many definitions of "cislunar," has GEO as an inner boundary. However, objects traveling in orbits or trajectories in cislunar space may nevertheless pass through space nearer to Earth than GEO.

"The spherical volume of space extending from geosynchronous Earth orbit to and including the Moon's orbit and the Earth-Moon Lagrange points."[2] This definition is from a technical paper on cislunar activities and is notable for including "spherical volume" in its parameters. However, the features of the Earth-Moon system recited in this definition all lie within a few degrees of the Earth-Moon system's ecliptic plane. A visualization from a Chinese journal seeks to capture both the spherical and ecliptic plane aspects of cislunar space (see figure 5).

"The combined Earth-Moon two body gravitational system."[3] This definition is from the capstone doctrine publication of the U.S. Space Force and achieves technical accuracy through breadth rather than descriptive precision of the particular gravitational features of cislunar space.

"The region of space beyond low-Earth orbit out to and including the region around the surface of the Moon."[4] This definition from the NASA Authorization Act of

2022 begins at "low-Earth orbit." It is unclear whether this is an unconventional reference to all near-Earth orbits or whether this definition intentionally includes regions of space below GEO altitudes relevant for lunar missions. This definition is also not clear as to whether it contemplates a "lunar corridor" between Earth and the Moon or whether space "out to" the Moon includes the broader conceptions of Earth-Moon system space found in other definitions.

"The Cislunar region is considered to be space in which the gravitational effect of the Sun, Earth, and Moon have significant influence over a spacecraft. The region can be further refined to typically trafficked areas within the vicinity of the Moon"[5] (see figure 6). This definition seeks to capture the full astrodynamic scope of the region while carving a smaller (less than half of cislunar space) "trafficked area" in which spacecraft have actually operated or are expected to operate. The "trafficked area" label is an example of delineation (at a very generalized level) by clustered use.

The preceding definitions do not explicitly refer to the lunar surface as part of "cislunar space." However, some definitions do, such as the definition of "cislunar space" found in the National Cislunar Science and Technology Strategy: "The three-dimensional volume of space beyond Earth's geosynchronous orbit that is mainly under the gravitational influence of the Earth and/or the Moon. Cislunar space includes the Earth-Moon Lagrange point regions, . . . trajectories utilizing those regions, and the Lunar surface."[6]

Notes

[1] Steve Parr and Emma Rainey, eds., *Cislunar Security National Technical Vision* (Baltimore: Johns Hopkins Applied Physics Laboratory, November 2022), 1–2, https://www.jhuapl.edu/sites/default/files/2022-12/CislunarSecurityNationalTechnicalVision.pdf.

[2] Adam P. Wilmer, "Space Domain Awareness Assessment of Cislunar Periodic Orbits for Lagrange Point Surveillance for Lagrange Point Surveillance" (Master's thesis, Air Force Institute of Technology, 2021), 1, https://apps.dtic.mil/sti/pdfs/AD1166533.pdf.

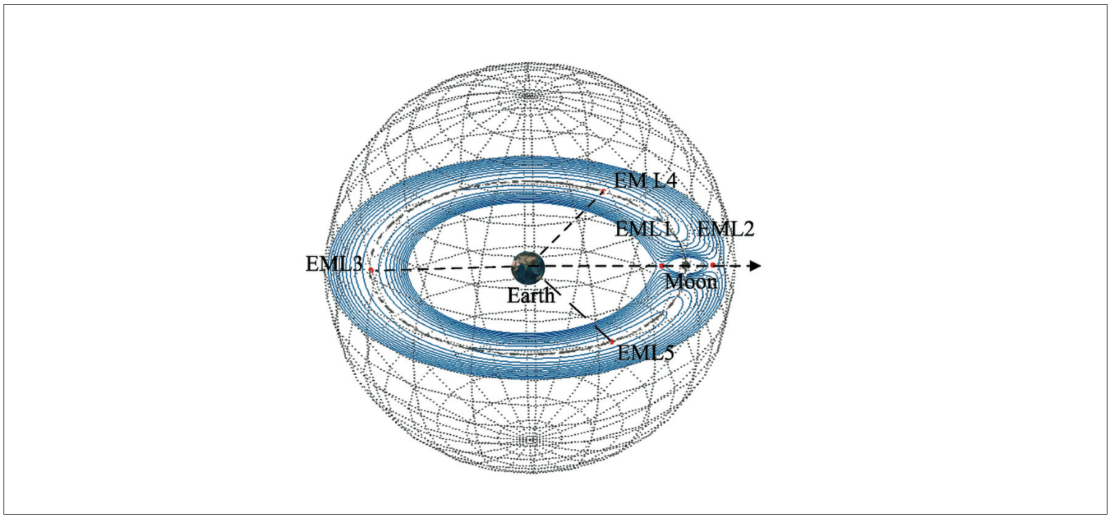
[3] *Spacepower: Doctrine for Space Forces* (Washington, DC: U.S. Space Force, June 2020), 6, https://www.spaceforce.mil/portals/1/space%20capstone%20publication_10%20aug%202020.pdf.

[4] NASA Act of 2022, Pub. L. No. 117-167, 136. Stat. 1372 (August 9, 2022) § 10802 (4).

[5] Jacobo Varela et al., "MHD Study of Planetary Magnetospheric Response During Extreme Solar Wind Conditions: Earth and Exoplanet Magnetospheres Applications," *Astronomy & Astrophysics* 659 (March 2022), A10, https://doi.org/10.1051/0004-6361/202141181.

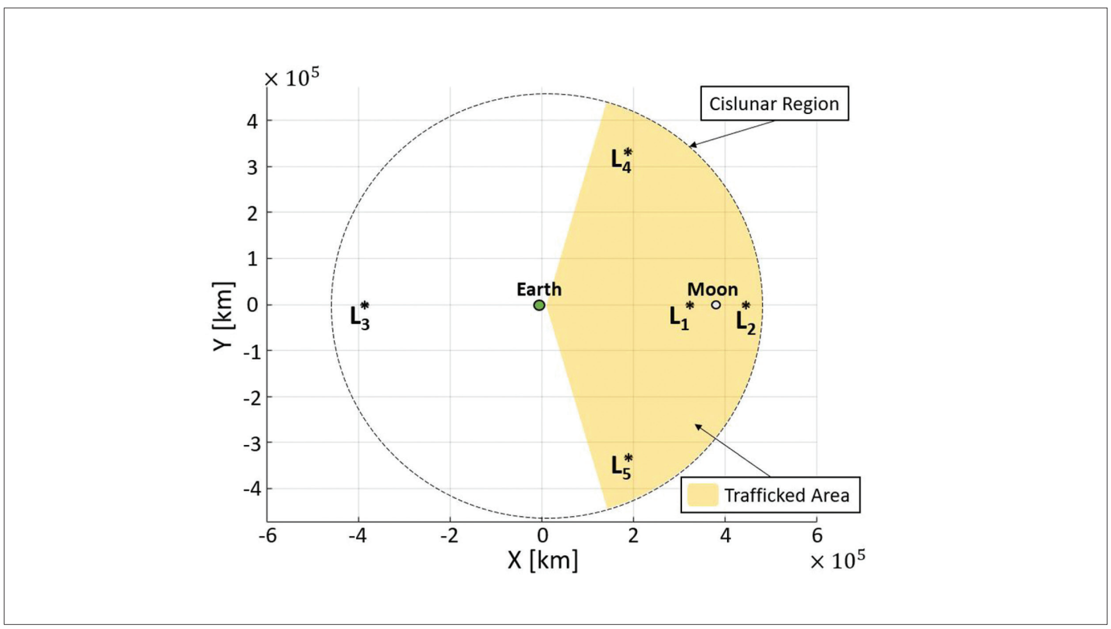
[6] *National Cislunar Science & Technology Strategy* (Washington, DC: National Science & Technology Council, November 2022), 3, https://bidenwhitehouse.archives.gov/wp-content/uploads/2022/11/11-2022-NSTC-National-Cislunar-ST-Strategy.pdf.

Figure 5. Conception of cislunar space capturing its spherical and ecliptical aspects



Source: Jacobo Varela et al., "MHD Study of Planetary Magnetospheric Response During Extreme Solar Wind Conditions: Earth and Exoplanet Magnetospheres Applications," *Astronomy & Astrophysics* 659 (March 2022), A10, https://doi.org/10.1051/0004-6361/202141181.

Figure 6. Conception of cislunar space including "space trafficked area" (a type of delineation by clustered use) shaded in yellow



Source: Brian Baker-McEvilly et al., "A Comprehensive Review on Cislunar Expansion and Space Domain Awareness," *Progress in Aerospace Sciences* 147 (May 2024), figure 1, https://doi.org/10.1016/j.paerosci.2024.101019.

Regardless of the particular definition applied, the term *cislunar* is at best useful as a comparative term of reference. It distinguishes near-Earth space from adjacent Space Frontier Areas. However, no single label is likely to suffice for a region with as much astrodynamic diversity as cislunar space. Rather, as space operations expand beyond GEO, the patterns of clustered activity that emerge will probably become the basis for further delineation of cislunar space.

Defining Space Area Frontier

The concept of "area" in the phrase *Space Frontier Area* should be understood broadly. An area of space could be a three-dimensional volume of void space, a particular orbit or family of orbits, or portions of the atmosphere (if any), surface, or sub-surface of a celestial body. For purposes of this paper, Space Frontier Area means a region of space or a celestial body, which:

- possesses astrodynamic, positional, or physical characteristics making it potentially useful for a strategically significant purpose
- has been reached by human-directed space missions, or is the focus of current or planned missions
- is only reachable with sufficient expense or difficulty that it is not yet the subject of routine uses for strategically significant activities.

The concept of Space Frontier Area will remain meaningful as space operations are normalized there and some regions or trajectories in xGEO and cislunar space gain new titles. It provides a useful definitional limit for the portions of xGEO space relevant for near-future strategic thought. It is also a durably useful term of reference to distinguish enduring "frontier" areas of cislunar space from areas of the Earth-Moon system in which new uses begin to cluster. The term Space Frontier Areas also connotes a quality common to all frontiers: moving into a frontier is often a high-stake bet on the future.

Characterizing Space Frontier Areas (SFA)

Building on this definitional foundation, how do the physical and dynamic characteristics of Space Frontier Areas differ from space near Earth? And how do these physical and dynamic characteristics bear on matters of strategy? The discussion below highlights some important characteristics of Space Frontier Areas, though the examples given are necessarily illustrative rather than exhaustive.

SFA in Earth Orbit

One does not need to encounter the effects of lunar gravity in cislunar space to find a Space Frontier Area. Earth orbit, under principles of physics comparable to the contemporary near-Earth orbital regimes, is possible at altitudes much greater than GEO: Earth's gravity dominates the motion of resident space objects as far as 100,000 km from Earth. Most space between GEO and 100,000 km from Earth is a Space Frontier Area, which could become useful for many purposes.

For example, future necessity may incentivize development of satellites designed to provide space services to terrestrial users (or to spacecraft in near-Earth orbit) from beyond GEO. Such necessity could arise from debris-producing events contaminating lower-altitude orbits to an extent that they become impractical for spacecraft operations. In the future, need may arise to operate certain systems at increased standoff distance from antisatellite weapons on Earth or in lower-altitude orbits. Conflict on Earth could damage launch sites or make their use unacceptably risky; prestaging satellites as a ready reserve in the relative safety of distant Earth orbit beyond GEO could be an important technique for reconstitution of battle-damaged satellites in contemporary key orbital trajectories.[27] These distant Earth orbits could also be a source of new vulnerabilities: an adversary could initiate an attack on satellites in near-Earth orbits (or against targets on Earth itself) from the relative safety, concealment, and gravitational advantage of distant regions of space beyond GEO.[28]

The Moon as SFA

The Moon orbits Earth[29] at a distance of about 238,900 km, and is tidally locked (that is, the Moon's rotation on its axis matches that of its orbit around the Earth). As a result, Earth only ever sees one side of the Moon (its "near side"), while areas of Earth visible from the Moon change continually with the Earth's rotation.[30] The Moon is less massive than Earth, exerting a force of gravitational attraction only 1/6 that of Earth.

Under the legal regime established in the Outer Space Treaty of 1967,[31] the Moon and other celestial bodies are treated as part of "outer space" for most purposes.[32] Consistent with this approach, "cislunar space" is sometimes defined to include the Moon itself.[33] However, a gravity-producing rocky "planetary mass object" such as the Moon enables different types of activities than are possible in free space.[34] One can go to the Moon and on the surface of the Moon do things more like activities on Earth than like spacecraft operations. Though the Moon orbits Earth and the Earth-Moon system orbits the Sun, a person or object on the surface of Earth or on the surface of the Moon is not considered to be "in orbit." Rather, such a person or object is said to be "on" that celestial body. The physical and dynamic properties of free space and celestial bodies are fundamentally different.[35] Celestial bodies are not a source of conflict today, "as their effective control is as yet beyond the technical capabilities of even the most advanced spacefaring states."[36] However, that may change as access to the Moon and other celestial bodies increases.

NASA's Apollo missions of the late 1960s and early 1970s, the only human Moon landings to date, made the prospect of human colonization of the Moon seem possible. However, half a century later missions to the Moon remain rare and exceptional. Since 1980, only 30 space missions have reached lunar space; only 10 saw fully or partially successful controlled landings on the Moon. Of these post-Apollo missions, only two (both operated by China) have returned specimens from the Moon to Earth.[37]

Most experts believe that important physical resources like water ice, rare earth elements, and Helium-3 (^3He) are present on the Moon. However, those resources do not appear to be evenly distributed on the lunar surface.[38] Water ice is believed to be concentrated at the lunar poles, in deep craters that exist in perpetual darkness.[39] Similarly, certain high-altitude points of the lunar surface near the lunar poles are "peaks of eternal light." These are illuminated by the Sun perpetually, providing uninterrupted access to solar energy. The peaks of eternal light never endure the bitterly cold lunar night (which lasts for as long as 14 Earth days).[40] Such selenographic considerations may intensify competition for access to relatively small regions of the lunar surface.[41] These regions of the Moon may become the location of new, clustered uses while other parts of the lunar surface and subsurface may endure as Space Frontier Areas for a long time.

Lunar Orbit as SFA

The rocky mass of the Moon is not evenly distributed, resulting in varying mass concentrations (MASCONs) for different regions of the lunar surface. Since gravity is a function of mass, this results in variations in lunar gravity over different regions of the Moon. Although the Moon has no atmosphere exerting drag on satellites in lunar orbit, its small mass relative to Earth and uneven distribution of that mass mean that frozen orbit (that is, stable, repeating orbit) around the Moon is only possible at four inclinations in the near-lunar environment.[42] As distance from the Moon increases, the significance of the Moon's variable MASCONs are attenuated, but the gravity of Earth becomes a factor in the motion of objects in space. Understanding motion in this "three-body problem" is one of the most important aspects of understanding Space Frontier Areas.

Motion in the Three-Body Problem

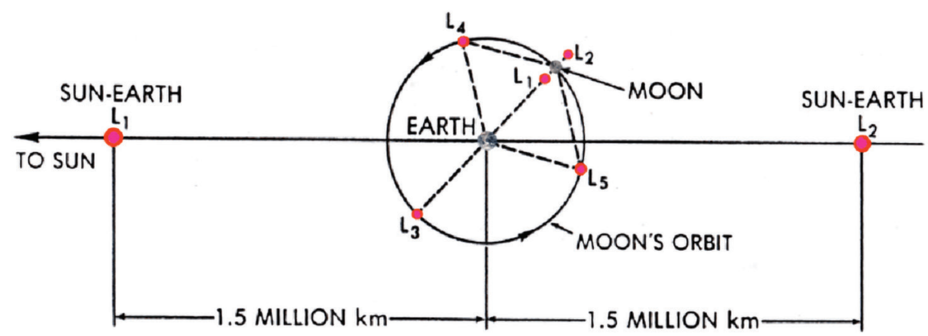
Before discussing motion in the three-body problem, a comparative description of the two-body problem is in order. In Earth orbit, the motion of a satellite is governed by the "two-body problem," the mathematical expression of how satellites orbit a planet. The planet and the satellite comprise the two "bodies" in the problem; their mass and velocity are the key variables in the equation. When the force of Earth's gravitational attraction on a satellite is in equilibrium with the force of acceleration tending to throw the satellite away from Earth, the trajectory of the satellite becomes a continuous free-fall around the planet: it orbits the Earth. The two-body problem equation usually suffices to describe the motion of planets in our solar system around the Sun. It also suffices to describe the orbit of natural and artificial satellites around planets.

However, at great distance from Earth other variables not accounted for in the two-body problem become significant. Newton's Universal Law of Gravitation tells us that every point mass in the universe attracts every other point mass in the universe by a force proportional to the product of the two masses and inversely proportional to the square of the distance between them.[43] At great distances the attractive force of gravity that a planet exerts on its natural or artificial satellites becomes very attenuated, and other forces (such as gravitational attraction to another celestial body) become relevant to understanding a satellite's motion. These minor perturbing forces reach artificial satellites in Earth orbit as well. Their impact is usually negligible in the short term but accumulates to significance over time. Satellites in most orbital regimes must perform occasional station-keeping maneuvers to sustain a precisely designed orbit.[44]

Forces that are minor perturbing forces in near-Earth orbit become significant variables at greater distances. In a system like the Earth-Moon system, "in which two bodies revolve around their center of mass under the influence of their mutual gravitational attraction," the motion of a third body, such as a spacecraft, "attracted by the previous two but not influencing their motion" is mathematically expressed as a three-body problem.[45] Unlike the two-body problem, for which closed-form analytical solutions exist, there is no known closed-form analytical solution to the three-body problem.[46] Motion is only explained (and space operations in three-body problem trajectories are only possible) due to mathematical principles of numerical integration that permit "certain general, qualitative statements regarding the motion without actually solving the equations of motion."[47]

Even more realistic trajectories can be postulated by also taking the Sun's gravity into account in a "four-body problem" (Sun, Earth, Moon, and spacecraft). The four-body problem (or a more complex n-body problem) may be required to explain motion at extreme distances

Figure 7. Lagrange points of the Earth-Moon system, at approximate scale, with Sun-Earth Lagrange Points 1 and 2 to illustrate much larger scale of Lagrange Points of the Sun-Earth system. The pattern of Lagrange Points and their enumeration (1 to 5) is the same for each two-body system.



Source: Martin Lo and Shane Ross, "The Lunar L1 Gateway—Portal to the Stars and Beyond," AIAA Space 2001 Conference and Exposition, Albuquerque, New Mexico, 2001, figure 2, http://dx.doi.org/10.2514/6.2001-4768.

from Earth. At this scale, trajectories around the major gravitational features may take months or years to resolve.[48] However, within most volumes of Space Frontier Areas, the three-body problem suffices for understanding the motion of spacecraft.

The concept of "gravitational features" is important in volumes of space where three-body problem motion occurs. In a two-body system like the Earth-Moon system, the two large celestial bodies exert predominant gravitational attraction. At five locations in the ecliptic plane of a two-body system, gravitational features known as Lagrange points arise where the combined gravitational attraction of the two bodies and the inertial effects associated with their mutual orbital motion balance. In the rotating reference frame of the system, an object in the vicinity of a Lagrange point can maintain a stable or quasi-stable orbit about a location in free space that preserves a fixed geometric relationship with respect to both primary bodies.[49] There are five Lagrange points around the Earth-Moon system, and five Lagrange points around the Sun-Earth system (and around every Sun-planet system in our solar system) (see figure 7).

Motion in the two-body problem is always elliptical, and always planar. Neither of these propositions is necessarily true of motion in the three-body problem.[50] Further, orbits in the three-body problem do not necessarily encircle a single point: objects in the three-body problem may transit two or more gravitational features (celestial bodies or Lagrange points) in periodic orbits, quasi-periodic orbits, or nonrecurring trajectories.[51] The interaction of gravitational forces in the three-body problem is more complex, and the effect of perturbing forces is more pronounced, than in the two-body problem. As a result, trajectories in three-body motion tend to propagate in a chaotic manner.[52]

Depending on how an object encounters space near a gravitational feature, the object will tend to be pulled toward the feature, pulled away from the feature, or kept in motion near the feature. These differing trajectory propagation outcomes are referred to, respectively, as stable, unstable, and center manifolds. Within certain levels of predictive relevance, these manifolds can be calculated and predicted. Spacecraft trajectories can be designed to approach an identified manifold with the qualities appropriate for the desired trajectory (to either remain in vicinity of the gravitational feature, or to follow a curved trajectory around it). By these maneuvers, a spacecraft can remain in orbit around a Lagrange point, sustain multilobed orbit around two or more gravitational features, maneuver in nonrepeating trajectories throughout the system, or transfer from one region of space to another with very low expenditure of propellant. Due to the chaotic propagation of trajectories in these gravitationally complex environments, it is difficult to predict the actual trajectory a spacecraft will experience when navigating in or around a gravitational feature. Frequent, small maneuvers are often necessary to sustain a particular desired trajectory in Space Frontier Areas.[53]

This chaotic propagation of trajectories in Space Frontier Areas is a source of both risk and opportunity. If a spacecraft is observed conducting a maneuver, it can be difficult to assess whether it is merely conducting station-keeping, or initiating a potentially concerning trajectory change.[54] Trajectories in Space Frontier Areas may take days or weeks to resolve, requiring substantial space domain awareness resources to detect and characterize spacecraft activities.[55]

However, the complex gravitational effects producing chaotic propagation of trajectories also enable useful low-energy transfer trajectories: transit across and between regions of space with very little expenditure of propellant. NASA has long used low-energy transfers around celestial bodies to enable missions of science and exploration in the solar system. Gravity-assisted low-energy transfer maneuvers in Space Frontier Areas were used commercially as early as the 1997 recovery of AsiaSat-3 (see figures 8–10). The ability to harness the astrodynamic potential of motion in the three-body problem invites a new way of thinking about proximity in space operations: as a function of energy or time rather than physical distance. "Certain points that are far away in distance (and time) are quite close together in terms of the propulsive effort required to move from one to the other."[56]

Figure 8. Hughes AsiaSat-3 Salvage

The use of cislunar space for low-energy transfers between orbital regimes has been understood for many years. A well-known early example of this was the Hughes AsiaSat salvage operation.

AsiaSat-3 was a communications satellite launched in 1997 by Hong Kong–based Asia Satellite Telecommunications Company, Ltd. It suffered a mission anomaly, and instead of successful insertion into its planned Geostationary Earth Orbit (GEO), AsiaSat-3 ended up in an unusable orbit at 51° inclination. After its insurers declared the satellite a total loss and made payment to AsiaSat, the insurers transferred the satellite to Hughes Electronics Corporation (which had designed the satellite) under an arrangement whereby Hughes and the insurance underwriters would share profits if AsiaSat-3 could be recovered.

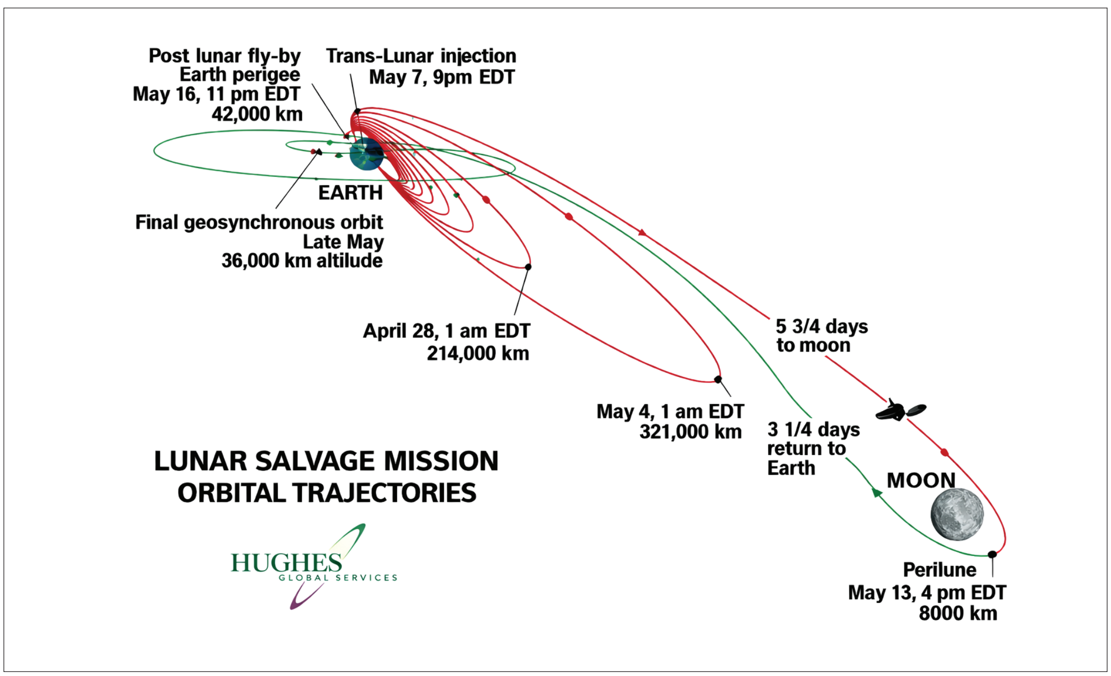
AsiaSat-3 lacked sufficient onboard fuel for conventional maneuvers to change its altitude and inclination to reach GEO. However, engineers at Hughes were able to occasionally fire AsiaSat-3's motors to increasingly elongate AsiaSat-3's orbit around Earth until the satellite was at sufficient distance from Earth that its orbit encompassed space at lunar distances.

AsiaSat-3 completed three passages through cislunar space at distances reaching the orbital path of the Moon. The first was a 6-day transit to lunar space for an initial pass around the Moon itself (6,200 kilometers from the Moon at closest approach). On this initial lunar pass, the gravity of the Moon pulled AsiaSat-3 around the far side of the Moon until the combined forces of AsiaSat-3's velocity and Earth's gravity pulled AsiaSat-3 back toward Earth. After its initial lunar pass AsiaSat-3 entered a phasing orbit which, over 2 weeks, again passed through space at lunar distance (though at a time of the system's monthly orbital cycle that it did not, on that pass, make close approach to the Moon). On its third pass through space at lunar distances, AsiaSat-3 again passed around the Moon (within 36,000 kilometers at closest approach). After this second transit around the Moon, AsiaSat-3 was oriented such that it could be inserted into GEO (at 152° West, over the equatorial Pacific south of the Hawaiian Islands) one month after its initial lunar encounter.

Although Hughes's salvage operation returned AsiaSat-3 to GEO, the operation consumed about half of the satellite's propellant, leaving it unsuited for its intended use as a broadcast satellite. (A broadcast satellite requires recurring station-keeping maneuvers to sustain a precise location in GEO.) Additionally, one of its solar panels did not deploy correctly, possibly due to heating and cooling cycles experienced during cislunar transit exceeding the satellite's operating design. Through its Hughes Global Services business line, Hughes redesignated the satellite as HGS-1 and offered its services as a communications satellite (a mission more tolerant than broadcast of east-west drift in GEO). After about a year, the satellite was sold to PanAmSat, which operated it as PAS-22 at 60° West (over Guyana and northern Brazil) for 3 years. As its propellant neared depletion, PAS 22 was decommissioned and boosted to a graveyard orbit about 300 kilometers above GEO, where it remains today.

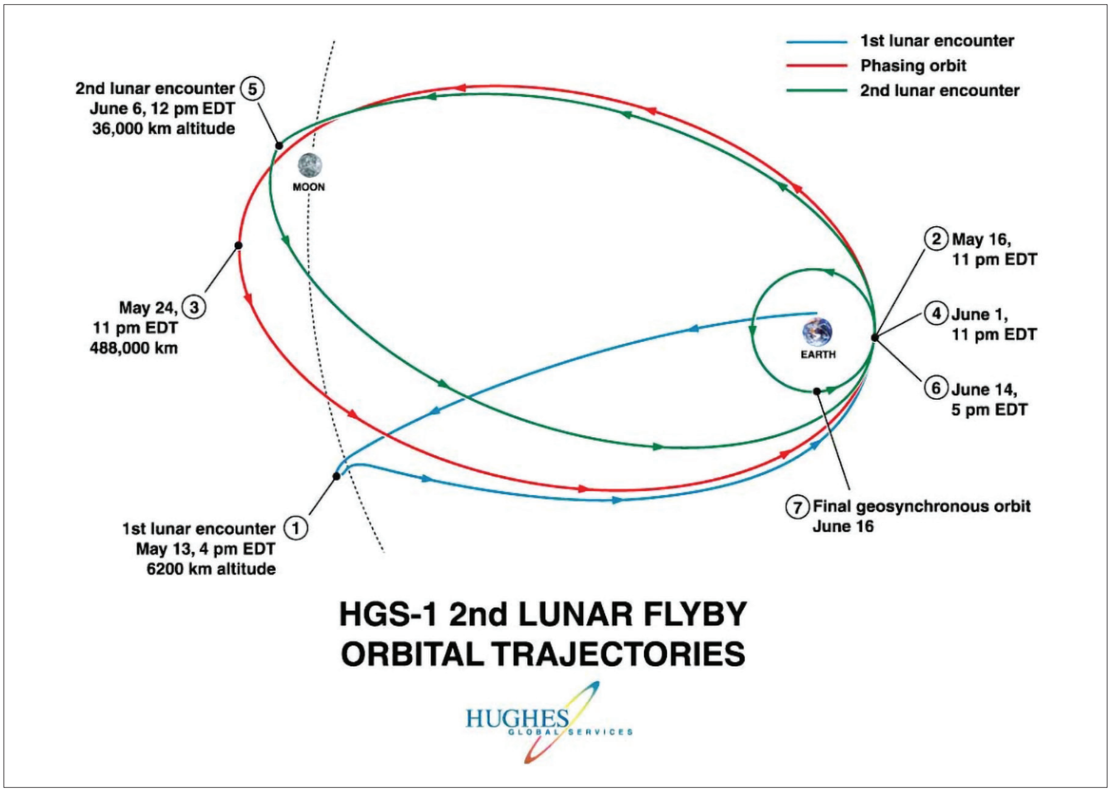
Sources: This narrative is derived from Shawn Willis, "To the Moon: Strategic Competition in the Cislunar Region," *Æther: A Journal of Strategic Airpower & Spacepower* 2 (Winter 2023), 17–30, https://www.jstor.org/stable/48751535>; Rex Ridenoure, "Beyond GEO, Commercially: 15 Years... and Counting," *The Space Review*, May 13, 2013, <https://www.thespacereview.com/article/2295/1; Gunter Krebs, "AsiaSat 3, 3S/HGS 1/PAS 22," *Gunter's Space Page*, n.d., https://space.skyrocket.de/doc_sdat/asiasat-3.htm.

Figure 9. Side view of key milestones for AsiaSat-3 salvage mission



Source: Rex Ridenoure, "Beyond GEO, Commercially: 15 Years... and Counting," The Space Review, May 13, 2013, https://www.thespacereview.com/article/2295/1. (The original low-resolution image was digitally enhanced for inclusion here by ChatGPT Enterprise).

Figure 10. Top view of key milestones for AsiaSat-3 salvage mission

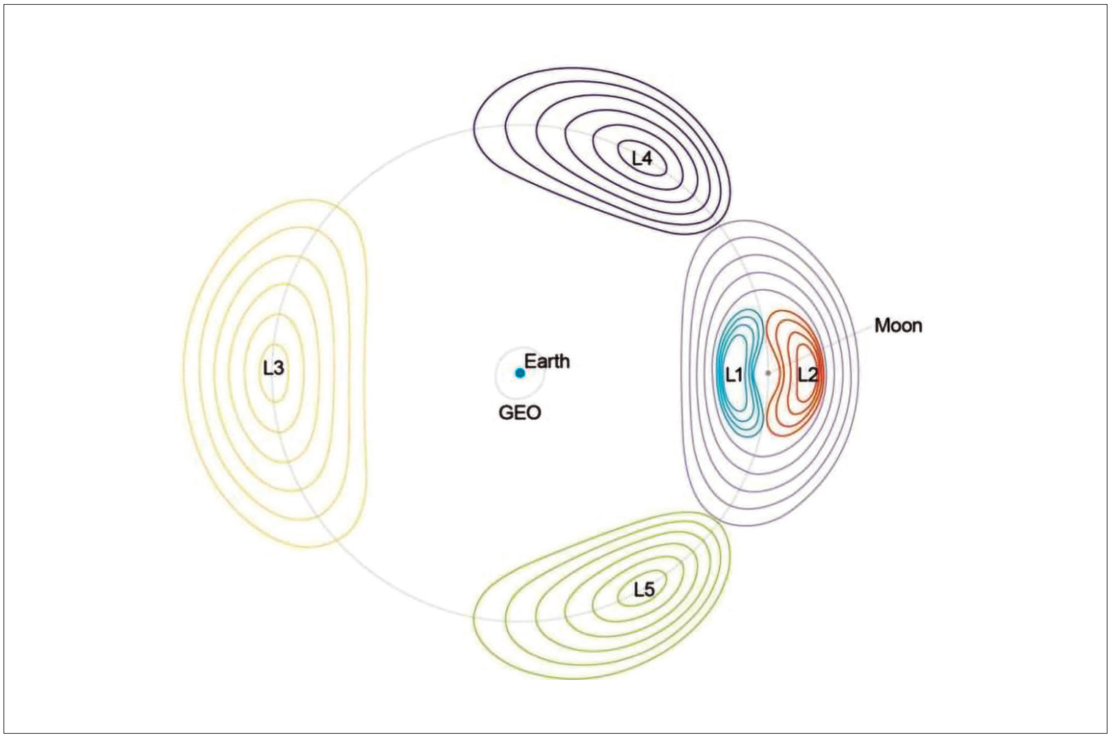


Source: Rex Ridenoure, "Beyond GEO, Commercially: 15 Years... and Counting," *The Space Review*, May 13, 2013, https://www.thespacereview.com/article/2295/1.

Lagrange Points in Space Frontier Areas

The term *Lagrange point* is somewhat misleading. Although the gravitational phenomenon the term describes can be definitionally centered on a point, it is the ability to orbit or maneuver *around* the point that is of importance. And there is a lot of space in a "Lagrange zone" around a Lagrange point. The volume of space in which periodic or quasi-periodic orbits are possible in the vicinity of any of the Lagrange points is many times the volume of space in any of the major contemporary orbital regimes (see figure 11). At GEO, a satellite's orbital period lasts a single day; in orbit families around Lagrange points, orbital periods may endure for many days or weeks.[57] Orbit and maneuver near a Lagrange point is more like patrolling an ocean than landing on an island.[58] Lagrange orbits are least stable around the co-linear Lagrange points (L1, L2, and L3, in line with the two major celestial bodies of the system). Lagrange orbits are most stable in space closest to L4 and L5 (each occurring at the far angle of an equilateral triangle formed by the two major celestial bodies of the system and the Lagrange point).[59]

Figure 11. Top view of Earth-Moon system Lagrange Points, at approximate scale



Note: GEO belt around Earth, for scale.

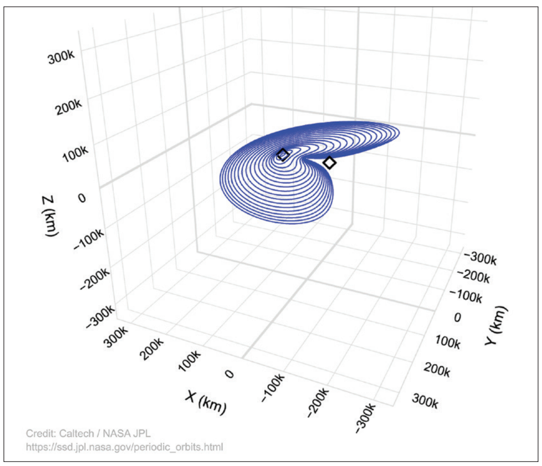
Source: George E. Pollock IV and James A. Vedda, *Cislunar Stewardship: Planning for Sustainability and International Cooperation* (Arlington, VA: Center for Space Policy and Strategy, June 2020), 2, https://csps.aerospace.org/sites/default/files/2021-08/Pollock-Vedda_CislunarStewardship_20200601.pdf.

The Lagrange points of cislunar space maintain a constant position relative to Earth and the Moon throughout their revolution. Since the rotational period of Earth's tidally locked Moon is so long, there is no lunar equivalent to GEO.[60] Lunar missions requiring a GEO-like constant view of the same area of the lunar surface might be possible from Lagrange orbits.

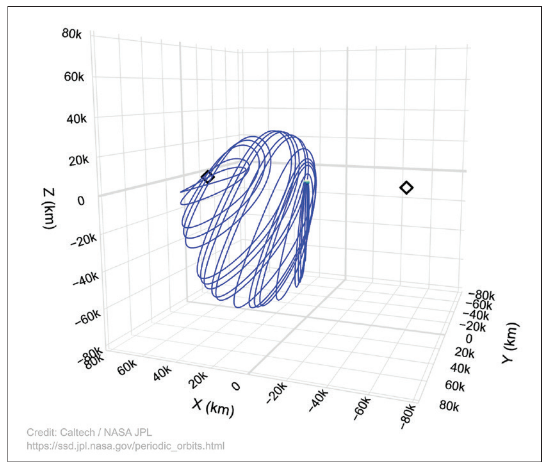
Objects in Earth orbit follow repeating, elliptical trajectories in a single plane. However, three-body problem orbits and trajectories in Space Frontier Areas are not always elliptical, and not always planar. These orbits may be near-elliptical, "kidney-bean" shaped, or follow "resonant" trajectories around multiple gravitational features. In the Earth-Moon system they may curve north or south (or both) from the ecliptic plane of the system's orbit around the Sun. The combination of vast distances and frequent, small spacecraft maneuvers in three-body problem motion could make patrols traversing Space Frontier Areas in nonrepeating trajectories as feasible as sustained orbit around gravitational features.

The variety of orbital trajectories that propagate around the Lagrange points of the Earth-Moon system is vast; see figure 12 for a very small sample of the multitude of orbits possible in the three-body problem. Lyapunov orbits propagate as elliptical or (as distance increases from the Lagrange point) kidney-shaped orbits, within the ecliptical plane of the Earth-Moon system's rotation. Axial orbits propagate north and south of the ecliptical plane, becoming more eccentric in their shape as distance from the Lagrange point increases. Halo orbits propagate from the co-linear Lagrange points (L1, L2, or L3), in nonplanar elliptical orbits north or south of the ecliptical plane (figure 12).

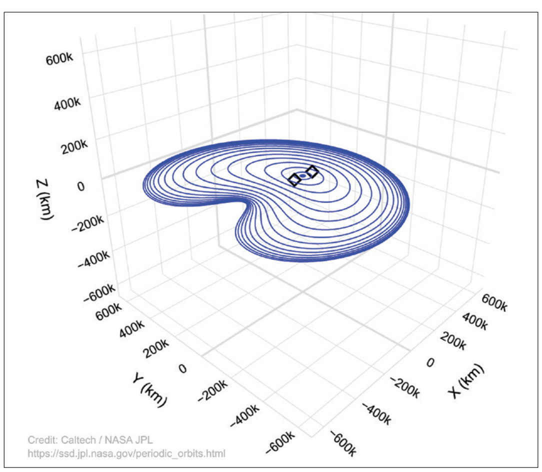
Figure 12. Very small sample of orbit types in vicinity of Earth-Moon L1 and L2. In each image, the two diamonds represent Earth-Moon L1 and L2; the Moon is immediately between them; Earth is in the direction of negative-X.



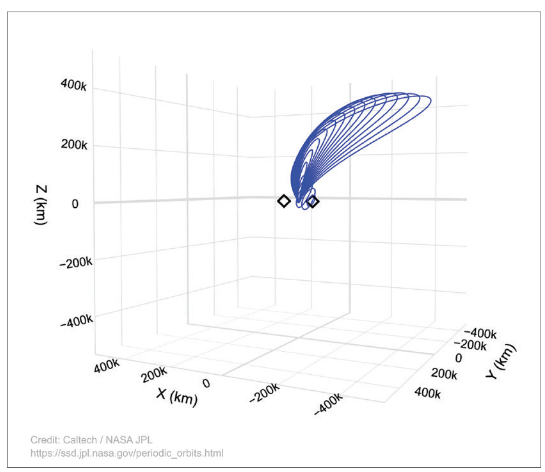
Sample Family of L1 Lyapunov Orbits.



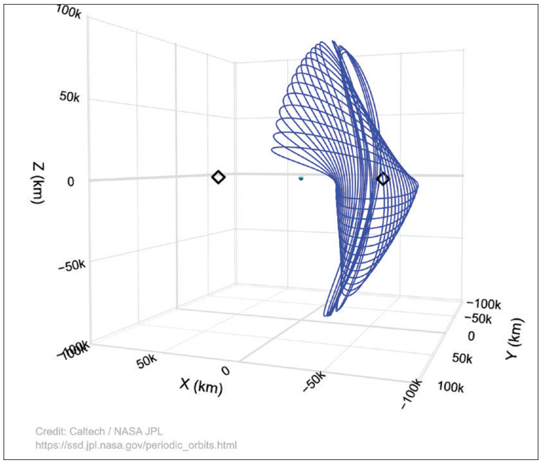
Sample Family of L1 Southern Halo Orbits.



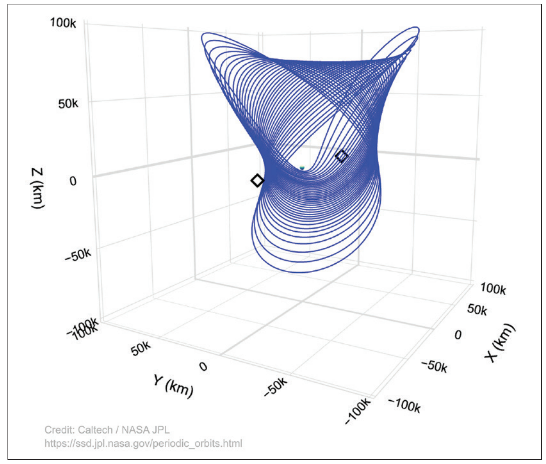
Sample Family of Distant Retrograde Orbits.



Sample Family of L1 Northern Halo Orbits.



Sample Family of L1 Axial Orbits



Sample Family of Northern Dragonfly Orbits.

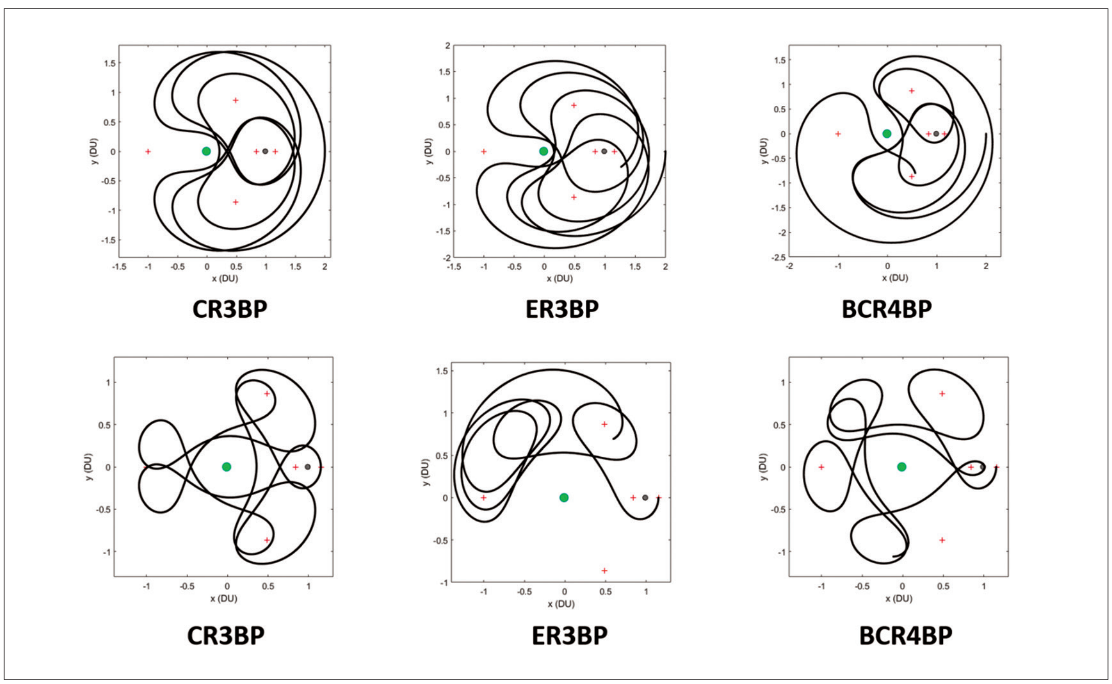
Source: "Three-Body Periodic Orbits," NASA Jet Propulsion Laboratory, California Institute of Technology, n.d., https://ssd.jpl.nasa.gov/tools/periodic_orbits.html.

Near the smaller body in a two-body celestial system, the halo orbits propagating from L1 and L2 form a near-rectilinear halo orbit (NRHO) that enables frequent close approach to the Moon. In the rotating frame of reference, in which the Moon rotates around the Earth, the NRHO orbital path makes a wave-like pattern keeping a satellite near the Moon throughout its orbit. In the inertial frame of reference (holding the Moon at a fixed position in order to understand the orbit), NRHO resembles an elliptical orbit around space near but slightly offset from the Moon itself. NASA is currently operating its Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) orbit demonstrator in NRHO near the Moon; this is the orbit projected for Gateway, NASA's crewed lunar orbiter.[61]

As distance from Lagrange points L1 and L2 increases, orbits around them in the ecliptical plane of the system merge into a single retrograde orbital trajectory (that is, the trajectory is in the opposite direction of the system's overall rotation) that interacts with both L1 and L2. As distance from the smaller of the central bodies increases, this distant retrograde orbit (DRO) may become non-elliptical. China recently launched two technology demonstrators into distant retrograde orbit: DRO A and B, so named by Western observers for the orbit they follow. Although the orbital path of distant retrograde orbit encircles the Moon, it is a three-body problem orbit, not a two-body problem frozen lunar orbit.

Multilobal orbits traverse multiple gravitational features, and (as the system rotates around its barycenter) create complex patterns of motion in highly idealized orbit design models; these orbital patterns become more chaotic as increasingly more realistic models are applied to them (figure 13).[62]

Figure 13. Two cislunar periodic orbits, illustrating complexity. The chaotic propagation of trajectories becomes more apparent as increasingly more realistic models are applied. In each image, the green dot at center represents Earth, the small blue dot represents the Moon, and the plus signs indicate Lagrange Points of the Earth-Moon system. The "CR3BP" model depicts an orbit in the Circular-Restricted 3-Body Problem, in which the orbits of the Earth and Moon are assumed to be perfectly circular. The "ER3BP" model depicts the same orbit, but in the Elliptical-Restricted 3-Body Problem, which assumes a more realistic elliptical orbit of the Moon around Earth. The "BCR4BP" model depicts the same orbit, but in the Bi-Circular Restricted 4-Body Problem. The BCR4BP expands on simpler models by accounting for the Sun's gravity but assumes the orbit of the Moon around Earth (the first circle) and the orbit of the Earth-Moon system around the Sun (the second circle) are perfectly circular. Dozens of such orbits were identified in the thesis from which these are derived; an infinite number are possible.



Source: Adam P. Wilmer, "Space Domain Awareness Assessment of Cislunar Periodic Orbits for Lagrange Point Surveillance for Lagrange Point Surveillance" (Master's thesis, Air Force Institute of Technology, 2021), 1, https://apps.dtic.mil/sti/pdfs/AD1166533.pdf.

In the vast volume of space in the Earth-Moon system, objects may dwell for long periods of time in regions of space where optical or infrared sensors on Earth (or in Earth orbit) cannot easily detect them due to illumination from the Sun or Moon: this phenomenon is referred to as solar exclusion (or lunar exclusion). Other detection and tracking phenomenologies do not fully mitigate solar or lunar exclusion from optical sensor view: radar detection of small objects is impractical at vast distances, and radiofrequency spectrum detection is only possible if the object is actively transmitting a detectable signal.

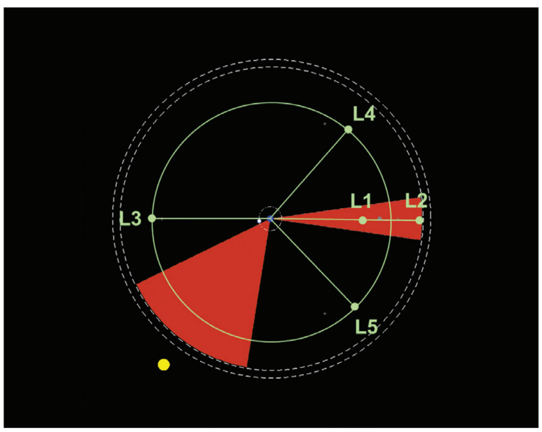
Exclusion Zones in Cislunar Space

In the contemporary Earth orbital regimes, it is possible for sensors on Earth or in Earth orbit to see almost any spacecraft in Earth orbit for most of any given day. However, in space beyond GEO, spacecraft may dwell for days or weeks in a zone of solar or lunar exclusion. An "exclusion zone" as used here refers to a volume of space in which optical sensors cannot detect a spacecraft because the illumination of the Sun or the Moon is brighter than the spacecraft to be detected. Exclusion in this sense is specific to a particular observer and depends on the location and capability of the sensors available to that observer. Today, most optical sensors are either on the surface of the Earth or in near-Earth orbit. Thus, spacecraft positioned between Earth and the Sun, or between Earth and a fully illuminated Moon, are in solar or lunar exclusion.

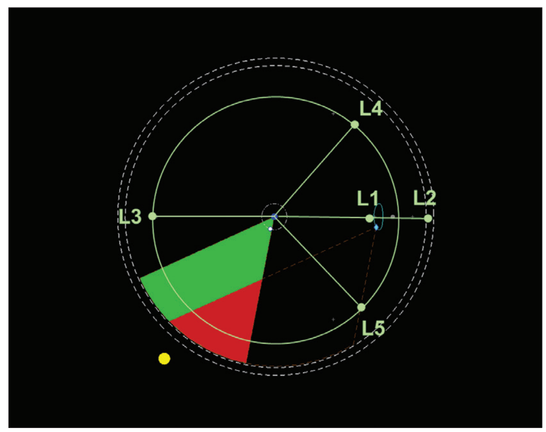
Some scholars speculate about the potential for an adversary to conceal space-based weapons in the vast volumes of cislunar space where they would be difficult to detect or track. Others question the practical utility of such a tactic (finding "little or no advantage over assets launched from the surface or already in orbit around the Earth to begin with").[63] However, the potential impracticality of concealing an attack within an exclusion zone may not deter an adversary from making such an attempt. The deployment of sensors throughout Space Frontier Areas in the Earth-Moon system could mitigate solar and lunar exclusion by providing additional fields of regard unobscured by solar or lunar illumination, thereby reducing the total areas of space in solar or lunar exclusion at any given time (see figure 14).

In addition to gravitational influences, other forces in the Earth-Moon system may impact space objects. Meteoroids tend to cluster at the most stable Lagrange points of any system (L4 and L5), forming a naturally occurring debris hazard.[64] Variable factors such as radiation pressure from solar activity, or long-duration heating-cooling cycles experienced during transit of vast areas of space, also influence the motion and performance of spacecraft. The gravity of Earth and the Moon predominate in the Earth-Moon System, but the gravity of the Sun also influences the motion of objects to some degree, contributing to the chaotic propagation of trajectories in Space Frontier Areas. Even concepts as fundamental as "time" change in Space Frontier Areas: time passes at different rates for objects moving at differing speeds, consistent with Einstein's theory of special relativity.[65] Each of these nongravitational influences grows in significance with distance from the central masses of a planetary system.

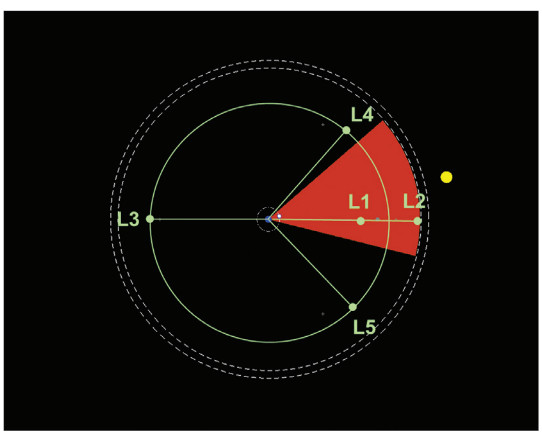
Figure 14. Potential reduction in solar exclusion from notional deployment of a space situational awareness sensor at Earth-Moon Lagrange Point 1. The red cones in the two images at left depict unmitigated areas of solar exclusion at two different epochs. The images on the right depict potential mitigation of solar exclusion, with the green area depicting gain in observability from the deployment of a sensor at Earth-Moon L1. In each image, the yellow dot indicates the direction of the Sun.



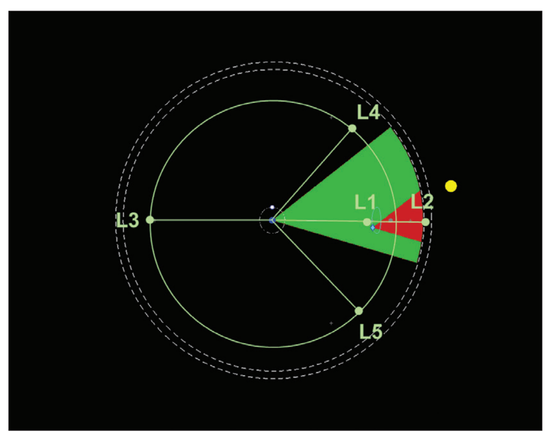
Exclusion 1



Exclusion 1 mitigated



Exclusion 2



Exclusion 2 mitigated

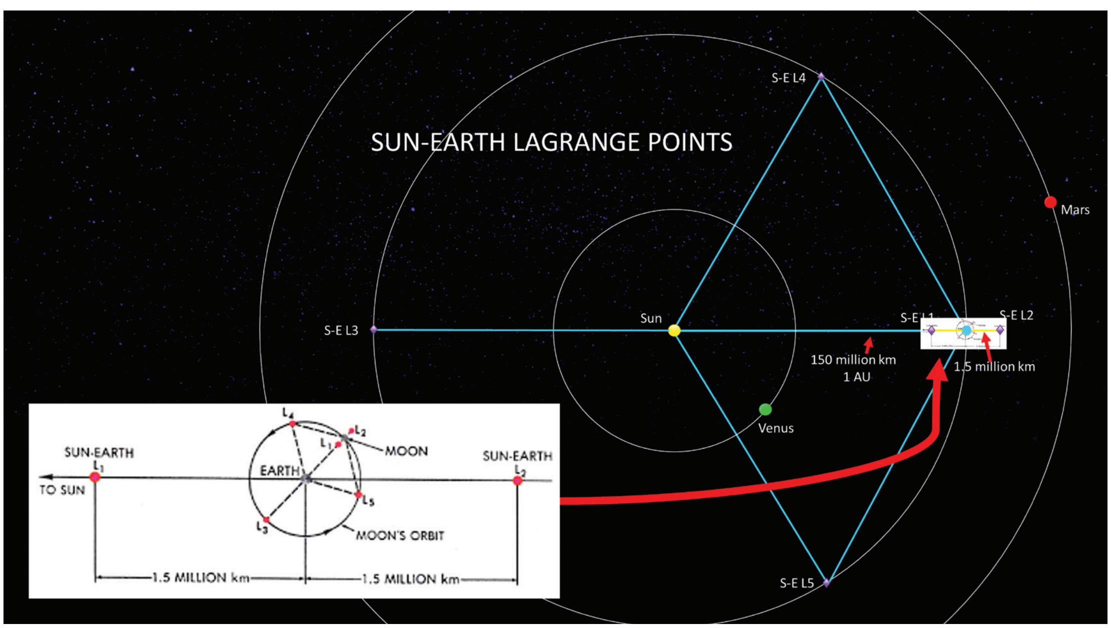
Source: Images derived from Jaime A. Stearns et al., AFRL Perspectives on Space Situational Awareness and Apophis (Kirtland Air Force Base, NM: Air Force Research Laboratory Space Vehicles Directorate, 2023). The author made further edits.

Space Frontier Areas in the Earth-Sun System

The entire Earth-Moon system orbits the Sun, moving in a band of solar system space within an even more vast Space Frontier Area. The limits of Space Frontier Areas on any relatively near-future time horizon almost certainly fall within our solar system. Like the Earth-Moon system, there are five Lagrange points in the Sun-Earth system. The distances to the Sun-Earth Lagrange points are orders of magnitude greater than any distances in cislunar space (see figure 15).

The nearest Sun-Earth Lagrange point (S-E L1) is 1.5 million km from Earth: a distance twice the entirety of cislunar space. Sun-Earth Lagrange points 4 and 5 are as far from Earth as the Sun (1.5 million km, a distance also known as one astronomical unit). During portions of their heliocentric orbit, Mars, Venus, and Mercury each come closer to Earth than Sun-Earth Lagrange points 4 and 5. However, at present no reasonably foreseeable strategic use is contemplated for Mercury, Venus, or Sun-Earth Lagrange point 3 (located on the far side of the Sun from Earth). The most distant areas of sufficient strategic interest to treat as Space Frontier Areas today are Mars,[66] our solar system's asteroid belt, and the areas of space in the vicinity the Sun-Earth Lagrange points on the Earth side of the Sun (that is, Sun-Earth L1, L2, L4, and L5).

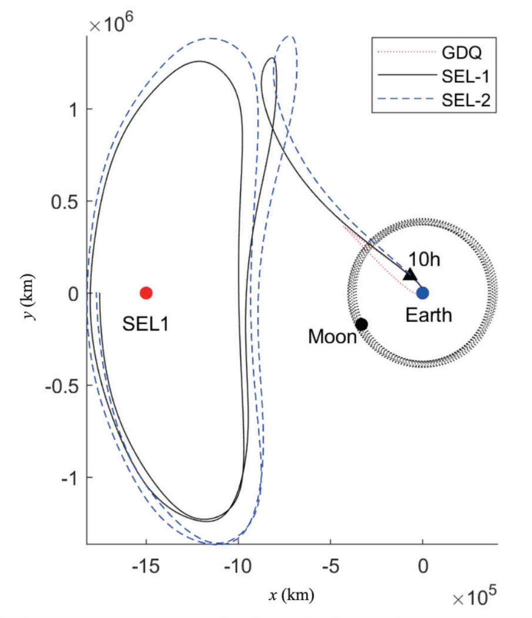
Figure 15. Lagrange points of the Sun-Earth system



Note: Celestial bodies are not depicted to scale, and the orbital paths of celestial bodies are depicted as more circular and more concentric than they are. Figure 7, depicting the Earth-Moon system and its Lagrange Points, is embedded to illustrate the scale of cislunar space within our solar system.

Source: Author.

Figure 16. Candidate orbits for the Chang'e-5 orbiter's mission to Lissajous orbit around Sun-Earth Lagrange Point 1. The approximate orbital trajectory actually followed by Chang'e-5 is depicted here as "SEL-2."



Source: Lei Liu et al., "Design and Implementation of Chinese Libration Point Missions," *Science China Information Sciences* 66, no. 9 (2023), 5–6, https://doi.org/10.1007/s11432-022-3716-9.

Space in vicinity of the Sun-Earth Lagrange points have, so far, mainly been used for missions of science observation. NASA's SOHO[67] and DSCOVR[68] spacecraft conduct solar and climate science observation from Sun-Earth L1, enjoying a continuously illuminated view of Earth and a field of solar regard unobscured by illumination or radiofrequency interference from Earth. NASA's James Webb Space Telescope[69] operates at Sun-Earth L2, from which it has a field of regard of deep space unimpeded by solar or lunar illumination or radiofrequency interference from Earth. Around Sun-Earth Lagrange point 1, an object can dwell in perpetual solar exclusion with respect to most sensors in Earth-Moon space. Deploying sensors able to detect and track non-cooperative objects at Sun-Earth L1 may require novel orbits incorporating other Sun-Earth Lagrange points.

The United States is not alone in exploring the farthest reaches of Space Frontier Areas. China's Chang'e-5 mission made headlines in 2020 when it reached lunar orbit, deployed a specimen collection lander to the lunar surface, recovered specimens of lunar material to the

Chang'e-5 orbiter, and then delivered the specimens back to Earth. The mission marked the first return of lunar material to Earth since the Soviet Union's Luna 24 mission in 1976. After delivering the lunar specimens to Earth, the Chang'e-5 orbiter went on to explore Sun-Earth Lagrange point 1 (see figure 16).[70]

Beyond Sun-Earth Space

Only a handful of human-launched space probes have ventured beyond our solar system. All have been missions of science and exploration. Although human imagination extends to the farthest reaches of space, strategic considerations beyond our solar system's asteroid belt are the province of a distant future.[71] For purposes of this paper, space and celestial bodies beyond our solar system's asteroid belt are considered of scientific interest, but not (yet) relevant for national security strategy.

Part II: Existing Literature on Space Frontier Areas

How do activities in Space Frontier Areas matter for the strategic interests of the United States? The literature about Space Frontier Areas, normally framed in terms of *xGEO space* or *cislunar space*, reveals two prevailing approaches. For purposes of this paper, I refer to them as *littoralist* and *lunarist* approaches.

The Littoralist Approach

The littoralist approach to Space Frontier Areas borrows from naval traditions emphasizing the strategic significance of littoral seas (that is, the maritime region immediately adjacent to land). A leading proponent of the littoralist perspective regarding Space Frontier Areas is Bleddyn Bowen. He refers to Earth orbit as our "cosmic coastline," and argues that "grand strategy in the Space Age must embrace the terrestrial origins and ends of spacepower."[72]

The projection of power inland from the maritime littorals is often described as "brown water" naval power, as distinguished from "blue water" naval power more concerned with control of lines of communication on the high seas. Many spacepower theorists borrow from these naval perspectives, describing emphasis on space support to terrestrial operations as a brown water view of spacepower, and an emphasis on space-to-space activities as a blue water view of spacepower.[73] The littoralist perspective regarding Space Frontier Areas embraces this brown water view of spacepower in emphasizing the nexus between space missions and their terrestrial purposes. This approach treats the terrestrial nexus to spacepower as more important than the physical distance between Earth and a spacecraft.

Writers expressing littoralist views generally embrace this perspective for its harmony with the current limits of space technology. Bowen dismisses most military purposes of missions to cislunar space as premature, "based on hopes rather than empirical evidence."[74] Scott Pace (a former National Space Council Executive Director) also concludes that large-scale operations beyond Earth orbit are "not today's reality," and urges U.S. Space Command to "remain focused on space operations from geosynchronous orbit to low Earth orbit, and delivering support to other combatant commands."[75] Others conclude that "the current rhetoric regarding the motivations for and value of cislunar exploration extends beyond what the evidence supports, particularly with respect to economic and national security arguments."[76]

However, the most common expression of the littoralist approach as applied to Space Frontier Areas is the unremarked omission (or mere passing mention) of Space Frontier Area activities in many works on spacepower. The U.S. Space Force's capstone doctrine publication *Spacepower* hints at a fundamentally littoralist orientation, stating "Today, the entirety of economic and military space activities is confined to the geocentric regime; however, commercial investments and new technologies have the potential to expand the reach of vital National space interests to the cislunar regime and beyond in the near future."[77] Of course, this begs a fundamental question: how soon is "near"? In the time horizon of current government budget processes, missions into Space Frontier Areas are likely to stay exceptional and mostly government-funded: every "commercial" mission to the Moon has received major funding from a national space agency.[78]

The littoralist perspective emphasizes the criticality of space support to terrestrial activities and the scarcity of resources for activities in Space Frontier Areas. Almost all of the Department of Defense (DOD)'s current space operations priorities concern Earth-focused space missions such as missile warning; nuclear command and control; position, navigation, and timing; intelligence collection; and satellite communications (or foundational space infrastructure activities common to all military space activities: command and control, space domain awareness, intelligence, and space launch).

Even "blue water" space missions such as the GEO Space Situational Awareness Program (GSSAP) ultimately matter for the terrestrial ends they serve: GSSAP provides space domain awareness in GEO to ensure the safety of space operations in that orbital regime, where many important missile warning and satellite communications spacecraft reside. Such capabilities are integral to the way the U.S. Armed Forces operate. General Stephen Whiting, Commander, U.S. Space Command has emphasized this point, noting that "for the last 35 years, our military Services have been sized around the assumption they will have access to space and space-enabled effects—and frankly they don't have the force structure to fight without space capabilities."[79]

The Lunarist Approach

The lunarist approach anticipates the future importance of Space Frontier Areas to be sufficiently substantial to justify present-day and near-term efforts to master access to and use of distant volumes of space, Earth's Moon, and other celestial bodies. Sources expressing the lunarist approach to Space Frontier Area activities anticipate a time when national and commercial efforts to reach, develop, and utilize the energy, mineral, and real estate resources of the Moon and other celestial bodies will transform some regions of celestial bodies (and free space beyond Earth orbit) into key nodes of economic activity, and some regions of space into key celestial lines of communication between and among these new nodes of economic activity and Earth.[80]

Unsurprisingly, the lunarist approach predominates in works on spacepower that are focused on xGEO space, cislunar space, or the Moon. Two leading proponents of the lunarist perspective are Namrata Goswami and Peter Garretson, whose book *Scramble for the Skies* concludes that we are in the early days of national space programs reorienting to the development and exploitation of space resources (most notably, as the lunarist moniker suggests, those of Earth's Moon).[81] This future-oriented approach embraces informed imagination regarding the future. Goswami and Garretson point to the thought of writer and futurist Arthur C. Clarke in this regard: "Space-travel is a sufficiently sensational subject to require no additional embellishment, and in the long run we can be sure that our wildest flights of fancy will fall short of the facts—as has always happened in the past history of scientific prediction."[82]

Lunarist sources look with concern at China's sustained interest and methodical approach to activities in cislunar space and beyond. They suggest that China fears repeating prior strategic mistakes by not betting on a future that includes access to and use of Space Frontier Areas. In Chinese political narratives, the memory of the burning or abandonment (depending on the source) of Admiral Zheng He's treasure ships still stings. In 1525, a newly enthroned emperor viewed Zheng's treasure ships as an unsustainably expensive venture; the ship's voyages were ended, and most maritime trade was outlawed. Military priorities shifted to land defenses. These decisions came to be widely perceived as setting conditions for the later Century of Humiliation. China hopes the "treasure ships" of the space age may regain what was lost after Zheng He.[83]

Poles Apart

Proponents of both littoralist and lunarist approaches of Space Frontier Areas agree on several matters. There is broad agreement that the most important technologies to deploy beyond the contemporary near-Earth orbits are those comprising the basic infrastructure of space activities: space situational awareness; position, navigation, and timing; and communications.[84] These foundational capabilities are necessary to scale up any missions in Space Frontier Areas beyond bespoke spacecraft for scientific or exploratory activities. However, littoralist and lunarist approaches diverge in their perspective on the optimal level of effort in Space Frontier Area activities in the near future. They also diverge with respect to the strategic interests served by Space Frontier Area activities.

In the littoralist perspective, meaningful expansion of space activities into Space Frontier Areas is a very long-term proposition. Any near-term strategic interest is probably limited to the avoidance of surprise by adversary activity in cislunar space. This approach does not deny the basic strategic logic of potential missions in Space Frontier Areas, but views them as too distant in the future to merit substantial near-term effort beyond civil space programs of scientific exploration.[85]

The lunarist perspective concedes the lengthy expected time before any economically viable use of the resources of Space Frontier Areas is likely. One assessment of the expected time to realize economic return on investments from lunar Helium-3 mining concluded it would take at least 44 years of mining operations on the Moon to pay off the initial capital investment for the mining activity.[86] That is probably a conservative estimate. Even zealous advocates for the future importance of space-based resources accept that the time to realize return on investment for space resources could be measured in centuries rather than decades . . . though they argue the eventual return on investment could rival that of Spain's investment in Columbus's voyages: a return on investment of 100,000 to 1.[87] The enormous potential long-term value of such resources, the extensive research and development investments required to reach and utilize them, and the fact that China—the pacing threat on which DOD is oriented[88]—has made exploitation of lunar resources a prominent line of effort in its space programs[89] motivates lunarist adherents to advocate for significant near-term growth in U.S. space operations focused on Space Frontier Areas.

In short, in the literature on Space Frontier Areas we see general acceptance of General Cartwright's framing of patterns of expansion into new domains: exploration is followed by normalized transit and communications, which paves the way for conflict and competition, with commercial interests following national security activities into the new domain.[90] The literature describes security and economic interests (arising in that sequence) as predominant interests in Space Frontier Areas. Sources expressing the littoralist and lunarist approaches to Space Frontier Areas cluster at distant poles of a very long timeline, with the littoralist perspective emphasizing present-day and near-term security concerns, and the lunarist perspective emphasizing long-term economic potential.

There is a logic to each perspective. The urgency and enormity of current near-Earth national security space operations is clear. Similarly, the potential for important future uses of Space Frontier Areas is well-appreciated—if not well-understood in its particulars. The existing literature offers compelling arguments for each of the contending views, but does little to harmonize and integrate the most salient points of each in time horizons relevant to contemporary decisionmakers. This paper seeks to develop the literature through a research-informed approach to understanding how activities in Space Frontier Areas have strategic significance, in a time frame relevant to contemporary decisionmakers.

Part III: Space Frontier Areas: In Search of Strategic Coherence

This paper documents a study undertaken to propose and test a framework for understanding the ways in which activities in Space Frontier Areas have strategic significance. A valid framework for evaluating Space Frontier Area activities could clarify the relative significance of various strategic purposes such activities serve. This framework could enable a more coherent approach to evaluating, characterizing, prioritizing, executing, or responding to missions in Space Frontier Areas.

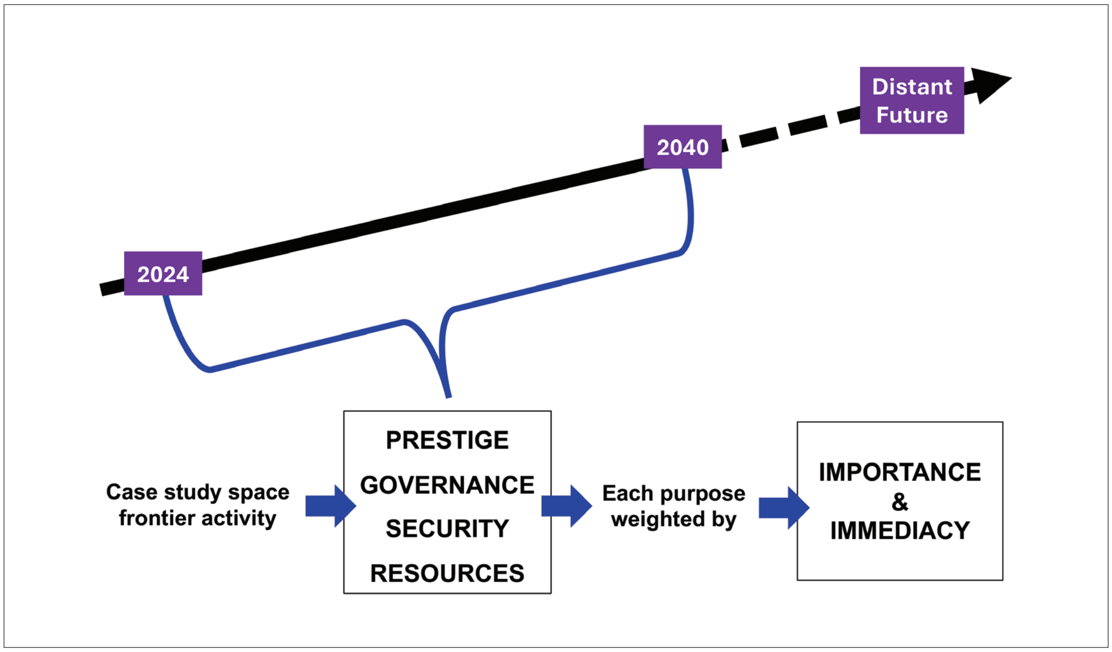
This study hypothesizes that the coherence of strategic thought about activities in Space Frontier Areas activities can be improved (relative to the binary perspective found in the literature) through a more fulsome framework for assessment. It proposes a model for evaluating near-future (through 2040) Space Frontier Activities based on the importance and immediacy of the prestige, governance, security, and resource purposes they serve (figure 17).

Three case studies of current and projected Space Frontier Area activities were selected to test this hypothesis, using a qualitative assessment tool tested and validated through a focus group process. The tool was used in research interviews with experts in space operations from military, intelligence, civil, and commercial space sectors to quantify each expert's assessment of the importance and immediacy of each strategic purpose (prestige, governance, security, and resources) for each case study.[91]

The study hypothesized that expert strategic perspectives on case studies of Space Frontier Area activities would tend to converge in a manner that highlighted the most significant near-term strategic purposes that such activities might serve. Such a convergence of strategic understanding could be useful when making funding decisions, evaluating risk, and establishing space mission priorities for DOD and the U.S. space enterprise more broadly.

Key Finding: The study found moderate convergence in strategic perspectives through use of this framework.

Figure 17. Concept for Understanding the Strategic Significance of Space Frontier Area Activities



Strategic Purposes

The study first assessed the categories of strategic purposes that Space Frontier Area activities serve. A region or position does not have strategic value itself, "it is the specific use of an area by a certain belligerent, and not the general value of the geographic position itself, that gives us its high strategic value."[92] While the key propositions and findings in the literature on Space Frontier Area activities tend to center on security and resources considerations, two other strategic purposes are also frequently discussed: prestige and governance. The research interviews conducted in the course of this study validated these four categories of strategic interest (prestige, governance, security, and resources) as sufficient and useful to describe the strategic purposes served by activities in Space Frontier Areas.[93] Each of these categories bear, to varying degrees, on most Space Frontier Area activities.

Prestige as a Strategic Purpose

Prestige as a strategic purpose is a function of perception and influence. Accomplishments that are noteworthy because they are novel, difficult, or unexpected demonstrate national will and capability. Will and capability enhance prestige by making one appear more attractive as a leader or partner (or more formidable as an adversary).[94] Prestige is a strategic interest not because it satisfies petty ambitions or confers bragging rights, but because the perception of capability, capacity, and will is a powerful source of soft power: the ability to influence outcomes by attraction rather than coercion or payment.[95]

Prestige was the central strategic purpose served by the U.S. Apollo program of lunar missions. Wrestling with the massive budget implications of the program prior to committing to Apollo, President John F. Kennedy stated, "We're talking about these fantastic expenditures which wreck our budget and all these other domestic programs and the only justification for it, in my opinion, to do it in this time or fashion, is because we hope to beat [the Soviet Union] and demonstrate that starting behind, as we did by a couple years, by God, we passed them."[96] Prestige remains an animating strategic purpose for major spacefaring powers.[97]

Prestige can result in influence directly (as with the Apollo landings) or indirectly. An indirect dividend of prestige could be the sense of obligation an emerging spacepower may feel toward a major power that enables the emerging power's access to space.[98] Prestige is also perishable. Author Mark Whittington argues, "If China is the first country back to the moon in this century, it will not matter that America landed a man on the moon 50 years ago. The world will see that the country that landed there no longer exists and that the future belongs to China . . . ."[99] This suggests that the prestige value of accomplishment may vary among actors: new human Moon landings by the United States may at best sustain preexisting U.S. leadership in space, whereas China could receive more prestige value for the same accomplishment.

Some experts interviewed in the course of this study (principally from the military space sector) suggested that scientific discovery for its own sake should be considered a separate strategic interest. Others (principally from the civil space sector) viewed science and exploration as principally of strategic value for prestige purposes, or else instrumental for the other strategic purposes postulated here.[100] This paper treats missions primarily designed for science and exploration as of strategic interest principally for their prestige value, recognizing that such missions may also have instrumental or collateral value for governance, resources, or security purposes.

Governance as a Strategic Purpose

Governance as the term is used in this study refers to the formal and informal structures that influence the behavior of spacefaring actors and shape perceptions about the legitimacy of actions in space. Both littoralist and lunarist sources agree that Space Frontier Area activities have significance for governance purposes.[101] Expressions of governance—"rules," in a broad sense—may be legal obligations, treaty commitments, or organizational forums. However, governance also includes less formal understandings such as norms, guidelines, technical standards, naming conventions, informal arrangements, or best practices.

Customary international law is formed by the general and continuing practice of states from a sense of legal obligation.[102] Thus, state practice not only provides evidence of what states believe the law is, but what they believe the law should be. State practice can take many forms, but "it is a longstanding truism that the rules of international relations in new domains are created by those who show up and not by those who stay home."[103] Chinese officials such as Ye Peijian, a senior official in China's lunar exploration program, have expressed similar views: "If we don't go there now even if we're capable of doing so, then we will be blamed by our descendants. If others go there, they will take over, and you won't be able to go even if you want to. This is reason enough."[104]

Novel space activities that tend to establish or crystallize a rule, or which require new interpretation or understanding of a rule, are important for governance purposes. Activities that challenge a proposed or putative rule also have significance for governance. The United States conducts freedom of navigation operations at sea and in international airspace to challenge excessive maritime claims.[105] Space missions similar to naval and air freedom of navigation operations may become important in Space Frontier Areas.[106] Under the Outer Space Treaty, states are internationally responsible for their national space activities, whether undertaken by the government itself or by a nongovernmental entity.[107] Thus, both government and commercial space activities matter for governance purposes in Space Frontier Areas.

Security as a Strategic Purpose

Security as used in this study refers to activities undertaken for the protection and defense of a state's national interests. This can include military and intelligence activities, as well as constabulary functions such as law enforcement and search and rescue functions.[108]

The threshold security interest in Space Frontier Areas is extending space domain awareness beyond near-Earth orbits. The potential exists for an adversary to use the vast distances, solar exclusion zones, or complex trajectories of cislunar space to project effects from Space Frontier Areas to spacecraft in Earth orbit, or to Earth itself. Thus, there is a growing security interest in detecting and characterizing activities in Space Frontier Areas in order to understand and mitigate such risks.[109] The relatively obscure insight into Space Frontier Areas provided by current space domain awareness architectures sows the seeds of a security dilemma: spacecraft deployed by one state to Space Frontier Areas to track and support activities there risk being perceived by others as offensive capabilities.[110]

Notwithstanding their great distance from Earth, security uses of Space Frontier Areas may serve conceptually brown water strategic purposes such as defending against distant orbital bombardment (or attack of spacecraft in Earth orbit from solar exclusion).[111] Some sources treat the prospect of sneak attack from beyond near-Earth orbit as "strategically absurd," arguing that the long transit of spacecraft or projectiles deployed from there would provide significant warning time.[112] However, the extent of advance warning does not depend solely on the threat vector's transit time: time required to detect and characterize the threat may delay effective early warning. Detecting objects in the vast expanse of Space Frontier Areas is a substantial technical challenge. Once an object is detected, characterizing it and predicting its trajectory requires observations over longer periods of time compared to threats in Earth orbit. Further, warning does not automatically mitigate risk: one may or may not have options to address a threat vector originating a Space Frontier Area, from which it may enjoy kinetic and maneuver advantage.

Security uses of Space Frontier Areas may also serve blue water strategic purposes, such as the deployment to relative safety (compared to near-Earth orbit, within the range of ground-launched or Earth-orbit antisatellite weapons) of a "space force in being,"[113] able to maneuver down the gravity well into Earth orbit to replenish space systems that may be attritted during conflict.[114] Additionally, maturation of technology capable of extracting and utilizing space resources will create new nodes of economic activity, and produce new celestial lines of communication between and among Earth and these nodes of economic activity. Defending these may become an important security interest. Many anticipate a future U.S. Space Force role in ensuring free access to and through outer space akin to the Navy's role protecting commerce on the high seas.[115]

Resources as a Strategic Purpose

Resources as used in this study refers to the energy, mineral, and real estate resources of Space Frontier Areas.[116] Economically viable use of space-based resources for financial or operational purposes is probably the strategic interest most distant in the future; however, it looms as the most consequential for those willing to imagine that far ahead. Mineral resources on celestial bodies (both planetary bodies and asteroids) may exist in quantities or concentrations not available on Earth. In the future, they may be more economical for *in situ* utilization in space than supplies launched from Earth. Some energy resources, such as solar radiation, are abundant throughout Space Frontier Areas. Others, such as water ice that can be converted to spacecraft propellant, may only exist in usable quantities in small areas of some celestial bodies. Economic use of these resources may prove elusive for many years, as has been the case with deep seabed mining and the economic use of Antarctica.[117] Recent trends would suggest this is the case. However, a "significant or unexpected technological breakthrough" could change everything,[118] and even incremental steps toward a distant or speculative future source of national wealth can be sufficiently attractive to invite some level of investment and effort.[119]

The Moon's peaks of eternal light (providing refuge from the long lunar night) and craters in perpetual darkness (believed to hold the greatest concentrations of water ice) are found only in small areas near the lunar poles.[120] Some orbits, trajectories, or other conceptions of celestial lines of communication through which data, spacecraft, and objects transit may also become important "terrain" for strategic purposes. Resources are of strategic interest when they can be exploited for their economic value, whether that value is in the form of commercial profit, national wealth, or enabling some other activity that would otherwise require the use of terrestrial resources launched from Earth to a Space Frontier Area.[121]

Chinese officials have framed their interest in Space Frontier Area activities in terms of the importance of space resources. According to Lieutenant General Zhang Yulin, deputy director of the People's Liberation Army General Armaments Division, "The limited capacity of Earth resources is the root cause of global problems"; cislunar space "will become another broad field for the expansion of human living space."[122] Chinese strategists not only seek economic advantages that may be found in Space Frontier Areas, they also fear that the United States intends to control access to cislunar space and the Moon in order to limit Chinese access.[123] For its part, U.S. space program leaders have expressed similar fears about China.[124]

Time Horizons

Most studies of "space futures" seek to bound the many unknowable variables of a future-oriented assessment to a defined time horizon. The littoralist perspective largely emphasizes present-day or near-term time horizons. A milestone prominently featured in recent spacepower and national security scholarship is Xi Jinping's mandate that the People's Liberation Army attain the capability to conduct a military invasion of Taiwan by 2027.[125] This very near-term milestone is within a time frame that drives many operational and strategic decisions in DOD's 5-year Future Years Defense Program, the planning process for the U.S. defense budget.

By contrast, studies informing the lunarist perspective look much farther into the future. However, even the most forward-looking studies tend to bound their time horizon of interest to two, three, or four decades.[126] This study sought a balance between the expected importance of Space Frontier Areas in distant futures, the uncertainty of future technological and geopolitical developments, the reality of DOD's 5-year defense budget planning process, and the urgency of currently underresourced space requirements in near-Earth space.

Based on these factors, a 15-year time horizon (2025 through 2040) was selected for this study because it is within the expected professional career of today's mid- and senior-level space enterprise leaders. The author judged this time horizon near enough that many of today's current space enterprise leaders will live to realize outcomes occurring between now and then. However, 2040 looks farther ahead than the next few Program Objective Memorandum cycles, the benchmark on which many defense initiatives anchor due to the critical importance of the budget process. In addition, 2040 is at or near the temporal benchmark for several U.S. and China space program initiatives.[127] Experts interviewed in the course of this study indicated that 2040 was a reasonable time horizon for this analysis.

Evaluating Strategic Purposes

With the independent variables of strategic purposes (prestige, governance, security, and resources) thus established, and a time frame for analysis specified (present through 2040), analysis next turned to the dependent variables that could give form to a framework for assessing the strategic significance of activities in Space Frontier Areas. Researcher judgment suggested two dependent variables: importance and immediacy.

"Importance" here is the degree to which a Space Frontier Area activity serves a particular strategic purpose. The importance variable does not compare the importance of one category of strategic purposes against any other category of strategic purposes. Rather, it seeks to characterize the extent to which the activity in question is likely to result in effects advancing that strategic purpose. Some amount of importance is expected for most strategic purposes, in any given case study. An activity that has direct and consequential implications for a strategic purpose has a high importance value. An activity with only incremental or collateral implications for a strategic purpose has a low importance value.

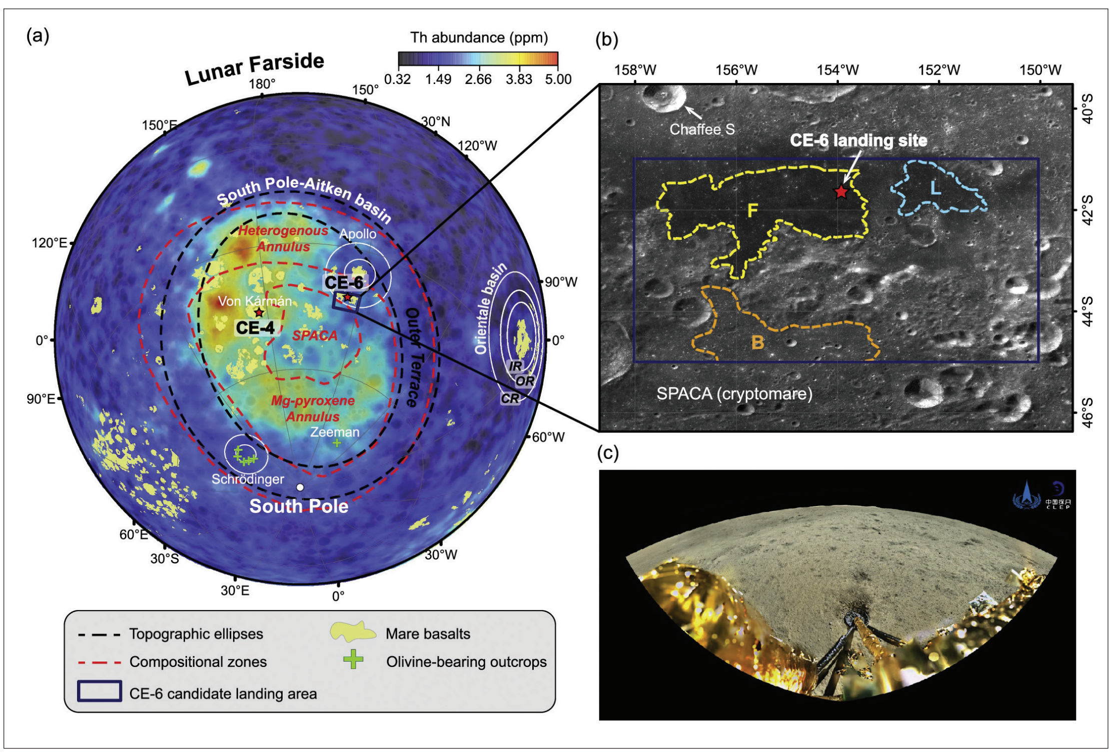
"Immediacy" is the expected time within the study's temporal horizon by which effects related to the strategic purpose in question will be realized. An effect or outcome related to that strategic purpose that is expected immediately or shortly after an activity would have a high immediacy value. The further in the future an effect or outcome is expected, the lower its immediacy value.

Importance and immediacy are qualitative judgments. To gather this qualitative data in a quantifiable form for analysis, the author conducted research interviews with 18 U.S.-based space operations subject matter experts (17 of these experts completed the qualitative assessment). The qualitative assessment included three case studies. For each case study, the expert was asked to score, on a scale of 1 to 10, the importance and immediacy of each strategic purpose (prestige, governance, security, resources) with respect to that case study.

Case Studies Overview

The first case study is "China's Lunar Far Side Activities." These activities include several Chinese missions to cislunar space culminating in the first-ever return of lunar regolith from the far side of the Moon to Earth. The case study is a contemporary example of incremental technological advances enabling new milestones in the use and exploration of the far side of the Moon as a Space Frontier Area. China began lunar missions in 2007 with the Chang'e-1 orbiter, followed by the Chang'e-2 orbiter 3 years later. In 2013, the Chang'e-3 mission delivered the Yutu robotic rover in China's first successful controlled landing on the Moon. These missions paved the way for the more challenging task of operating on the far side of the Moon. In 2018, China launched the Quequiao-1 communications relay satellite to orbit in the vicinity of Earth-Moon Lagrange point 2; from the vantage of E-M L2 orbit, Quequiao-1 serves as a communications relay between ground stations on Earth and the Moon's far side. Quequiao-1 provided the communications necessary for China to make the first successful controlled landing on the far side

Figure 18. Chang'e-6 Landing Site, Near Lunar South Pole on Moon's Far Side



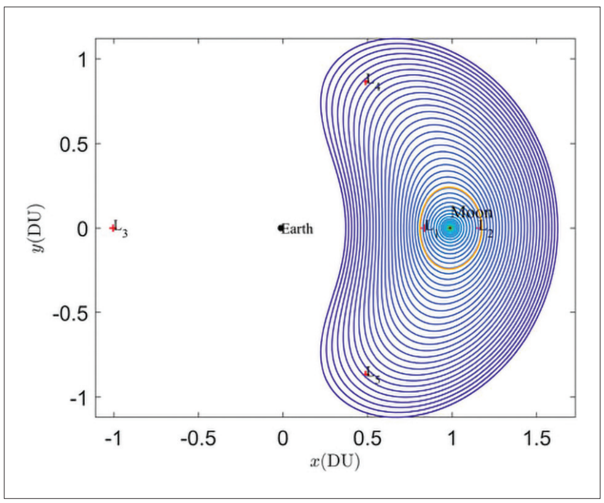
Source: Xing Wang et al., "Lunar Farside Samples Returned by Chang'E-6 Mission: Significance for Understanding the South Pole-Aitken Basin Stratigraphic History," *The Astronomical Journal* 168, no. 6 (2024), 1–11, https://doi.org/10.3847/1538-3881/ad7fce.

of the Moon in 2018 during the Chang'e-4 mission. This was the first time China had achieved a global first in space operations, rather than repeating a U.S. or Soviet Union accomplishment.[128] Two years later, it enabled the Chang'e-5 mission to deliver a lander and ascent module to the lunar surface, and to return specimens of lunar materials to Earth (making China the third nation—after the United States and Soviet Union—to do so).[129] In 2024, China's Chang'e-6 mission accomplished another global first, becoming the first nation to collect lunar specimens from the far side of the Moon (more specifically, the Aitken basin near the lunar South Pole, a suspected area of concentrated lunar resources), and return those specimens to Earth.[130]

The second case study is "Cislunar Infrastructure Demonstrators." Missions in this case study demonstrate "infrastructure" functions such as orbit maintenance, space domain awareness, and navigation in Space Frontier Areas of cislunar space. It is a state-agnostic case study, focusing on applied technology as such rather than on the state actor conducting the mission. Examples of activities in this case study were China's DRO A and B mission, the planned Air Force Research Laboratory Oracle mission, and NASA's CAPSTONE.

DRO A and B was a mission of the China Academy of Sciences involving two satellites in distant retrograde orbit around the Moon apparently demonstrating the utility of the orbit for navigation and communications payloads[131] (figure 19). Oracle is a series of missions planned by the Air Force Research Laboratory's Space Vehicles Directorate to conduct experiments on maneuver and space situational awareness capabilities in cislunar space.[132] CAPSTONE is a NASA-funded mission currently operating in near-rectilinear halo orbit (governed by interaction with Earth-Moon L1 and L2) in the vicinity of the Moon. CAPSTONE is demonstrating the feasibility of the lunar near-rectilinear halo orbit, of interest to NASA as a possible staging orbit for future lunar missions.[133]

Figure 19. Objects in lunar Distant Retrograde Orbit travel in the opposite direction of the Moon's orbit around Earth, interacting with the gravity of both Earth-Moon Lagrange Points 1 and 2.



Source: Ming Wang et al., "Family of 2:1 Resonant Quasi-Periodic Distant Retrograde Orbits in Cislunar Space," *Frontiers in Astronomy and Space Sciences* 11 (September 2024), figure 2, https://doi.org/10.3389/fspas.2024.1352489.

The third and final case study is "First Declaration of a Lunar Safety Zone." It is an expected future scenario, and selected because it represents an important future "first" in Space Frontier Area activities, is probable before 2040, and (as an expected future event) is state-unknown. The concept of a "safety zone," a designated area in which lunar surface activities are coordinated to prevent harmful interference with space resource extraction and utilization activities on the Moon or other celestial bodies, is proposed in the United States–led Artemis Accords. The Accords are not a legally binding treaty, but rather "establish a political understanding regarding mutually beneficial practices for the future exploration and use of outer space."[134] The Accords describe a *safety zone* as an "area wherein . . . notification and coordination will be implemented to avoid harmful interference," within some broadly described parameters of reasonableness.[135] However, the case study is not limited to a safety zone as described in the Artemis Accords: it refers to the first zone around lunar surface activities declared to prevent harmful interference, by any state, regardless of the particulars of implementation.

These case studies represent recent, planned, or expected Space Frontier Area activities. The case studies reflect a range of state attribution characteristics. They represent state-specific (China's Lunar Far Side Activities), state-agnostic (Cislunar Infrastructure Demonstrators), and state-unknown (First Declaration of a Lunar Safety Zone) examples. This range of state attribution characteristics was judged useful for this study, which is designed to test the framework for analysis more than the underlying activities represented in the case studies. The activities selected as case studies are not principally devoted to missions of basic scientific discovery, but rather to space missions with more or less immediate application to a wide range of future activities in Space Frontier Areas.

Qualitative Assessment Methodology

Seventeen participating experts completed qualitative assessments of each case study during research interviews conducted by the author. All experts were United States persons, selected for their experience in space operations in various space sectors. The experts averaged 23.3 years of space operations experience. The expert with the least space experience was a senior military officer with 6 years supporting space missions; the expert with the most experience had worked in space programs in three different sectors for 41 years. Six of the experts had worked in civil space programs. Nine had worked on space programs at a commercial company. Two experts had prior full-time experience at an academic institution. Most of the experts (14) had current or former experience in military or intelligence community space programs. Most (10) had experience in two or more space sectors. Eleven of the experts had, at some point in their professional career, worked on a mission involving xGEO or cislunar space.

Each expert provided their evaluation, on a scale of 1 to 10, of the importance and immediacy of each strategic quality (prestige, governance, security, and resources), within the time frame of present day through 2040, with respect to each case study.[136] To standardize data for comparative analysis, each expert's scores within each case study were normalized to a scale of 1 to 10. The normalized importance and immediacy scores for each strategic purpose were then multiplied together, to produce a "relative significance" value for each strategic quality within that case study.

These relative significance values were then visually depicted on both a color-coded score card and on a radar chart. On the score card, each column provides one expert's "relative significance" score for the strategic purpose reflected on that row. That expert's highest score (indicating the strategic purpose they found most significant for the activity described in that case study) is coded green; that expert's lowest score (indicating the strategic purpose they found least significant for the activity described in that case study) is coded red. Scores in between are indicated with gold or intermediate shades; assessments resulting in a tie in scoring were not discounted since a score suggesting equal relative significance of two or more strategic qualities was not treated as inherently invalid.

Because this research and assessment was exploratory in nature, criteria for assessing the degree of convergence of expert views were not postulated in advance. Rather, factors indicating more or less convergence in expert views were identified once a data set was available for review. Further research testing this framework would be useful in validating the criteria for convergence proposed here. From the research data, three indicators of convergence emerged:

- Majority or plurality consensus: Among four independent variables, none of the strategic qualities will necessarily emerge as a majority consensus view of "most significant" in each case study; however, a plurality consensus emerged in each case study here.

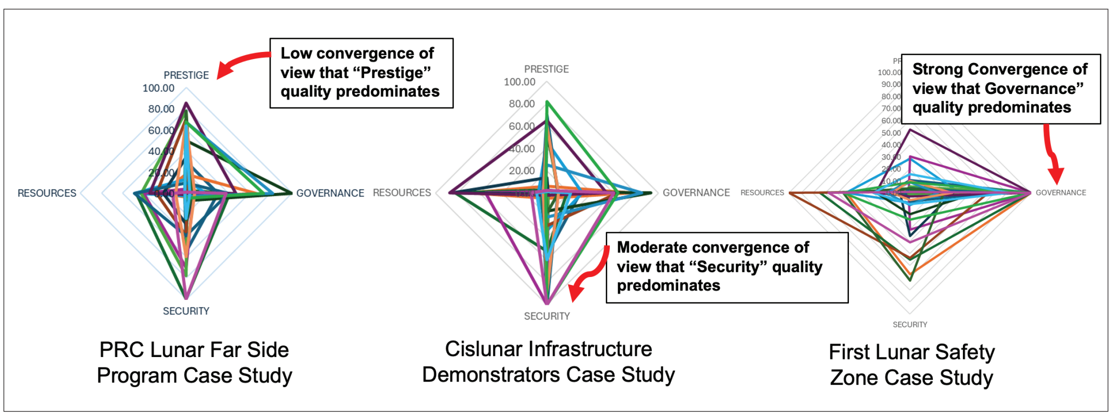
- Consensus margin: The difference in the number of experts assessing a strategic category as "most significant" versus the number of experts assessing the next-highest ranked strategic quality as "most significant." As the value of this margin increases, it suggests a stronger degree of convergence.

- Internal assessment margin: The difference in the number of experts assessing a strategic category as "most significant" and "least significant." The greater the value of this difference, the more it suggests greater levels of converging views (with positive values indicating convergence of views regarding the "most significant" strategic quality, and negative values indicating convergence of views regarding the "least significant" strategic quality, for each case study).

Findings

Moderate or high convergence of expert views was observed in 2 of 3 cases. This suggests with overall moderate confidence that a framework accounting for the importance and immediacy of prestige, governance, security, and resource aspects of strategic purpose, in a defined time horizon, increases the coherence of strategic views of Space Frontier Area activities. The outcomes of this analysis are summarized at figure 20 and discussed more fully below.

Figure 20. Summary of Study Findings



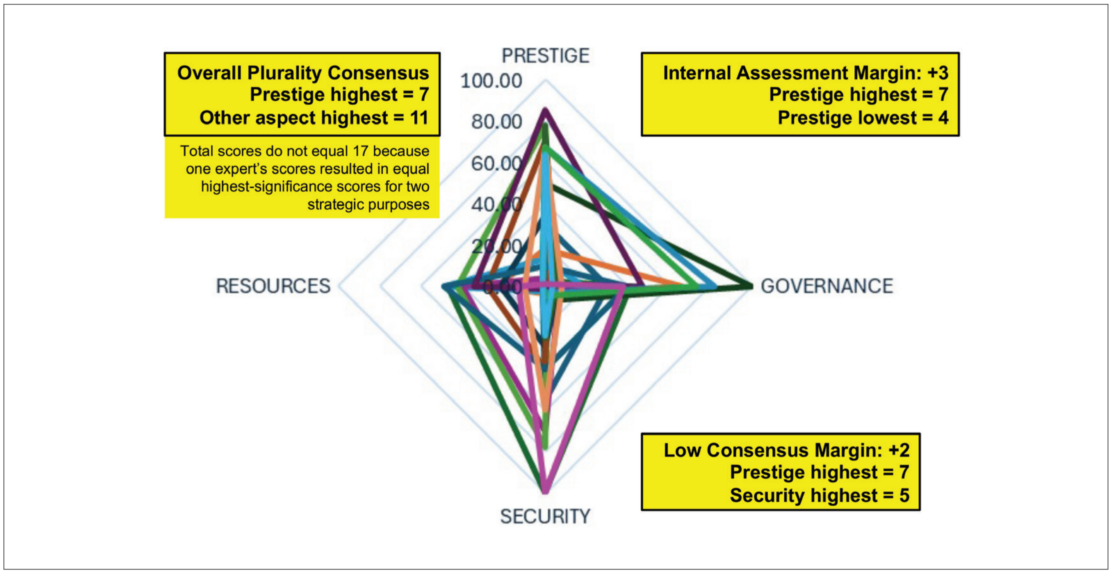
China's Lunar Far Side Activities

There was relatively low convergence of expert views in the first case study. A plurality of relative significance scores (7 of 17) identified prestige as the predominant strategic quality of these Space Frontier Activities. The internal assessment margin of relative significance scores for prestige as the predominant strategic quality (compared to relative significance scores viewing prestige as the least strategic quality) is relatively low but is greater than for any other strategic quality within this case study. In a framework with four strategic qualities, a plurality view will usually emerge; it is only the internal assessment margin of the plurality view that suggests any measure of convergence in the views observed here.

Figure 21. Relative Significance Scores for This Case Study (Each Column Represents One Expert's Scores).

PRESTIGE	30.25	17.88	2.80	13.26	4.00	77.50	33.91	70.00	49.61	10.00	85.00	77.50	67.24	67.24	67.24	64.00	1.00
GOVERNANCE	30.25	66.25	40.96	18.45	7.00	1.00	6.63	1.00	100.00	40.00	46.75	5.50	82.00	7.84	73.00	3.70	37.73
SECURITY	55.00	3.25	100.00	2.29	70.00	77.50	28.84	40.00	7.20	40.00	1.00	25.19	2.80	59.86	4.60	23.68	100.00
RESOURCES	1.00	24.06	46.72	48.57	40.00	42.63	21.25	28.00	1.00	49.00	34.00	1.00	1.00	10.00	1.00	1.00	12.76

Figure 22.



- PRESTIGE: Seven experts (a plurality consensus) scored prestige as the most significant strategic interest; four scored prestige as the least significant strategic interest; internal assessment margin of +3.

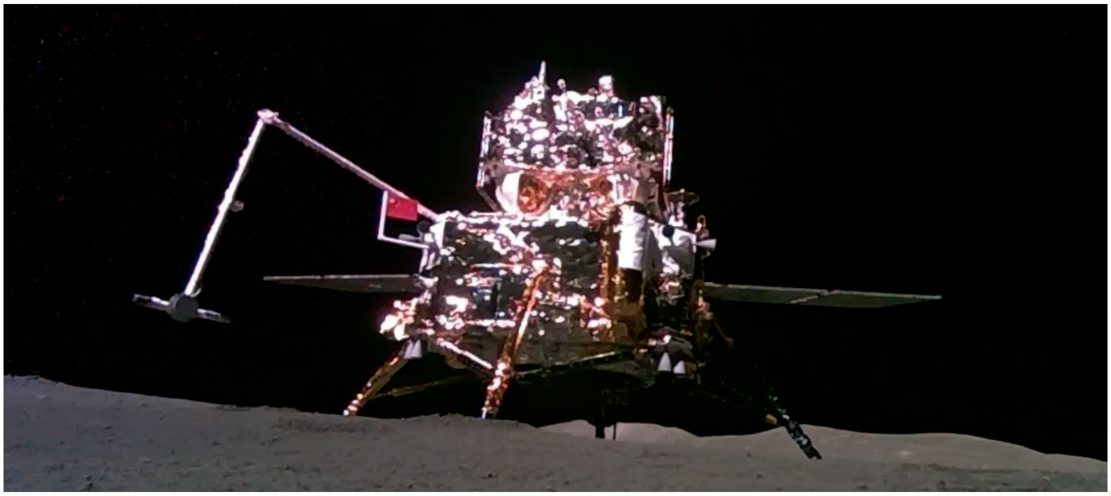
- SECURITY: Five scored security as most significant; three scored it as least significant; internal assessment margin of +2.

- GOVERNANCE: Four scored governance as most significant; four scored it as least significant; internal assessment margin of 0.

- RESOURCES: Two scored resources as the most significant strategic interest; six scored it as least significant; internal assessment margin of -4.

While expert views about the most important strategic purpose served by China's lunar far side program showed relatively low convergence, there was greater convergence regarding

Figure 23. Chang'e 6 Lander at Far Side Region of the Lunar South Pole



Source: Image by China National Space Agency, reprinted in Martijn Luinstra, "NASA's CLPS Program Accelerates as Two Landers Head for the Moon," NASA Space Flight, January 26, 2025, https://www.nasaspaceflight.com/2025/01/lunar-missions-roundup/.

views on the least important strategic purpose: six experts assessed resources as the least important strategic purpose, for an internal assessment margin of -4. This outcome is somewhat counterintuitive given the apparent nexus between exploration of lunar polar regions and intent to exploit lunar resources. The low relative significance score for resources in this case study is attributable to the consistently low expert assessment of the "immediacy" of China's lunar far side program to realizing resource-related effects. The data suggests that although resources may be an important long-term strategic aim of China's lunar far side program, the lengthy expected time before the economic benefits of lunar resources could be realized limit the strategic significance of this aspect of Space Frontier Area activity, at least through 2040.

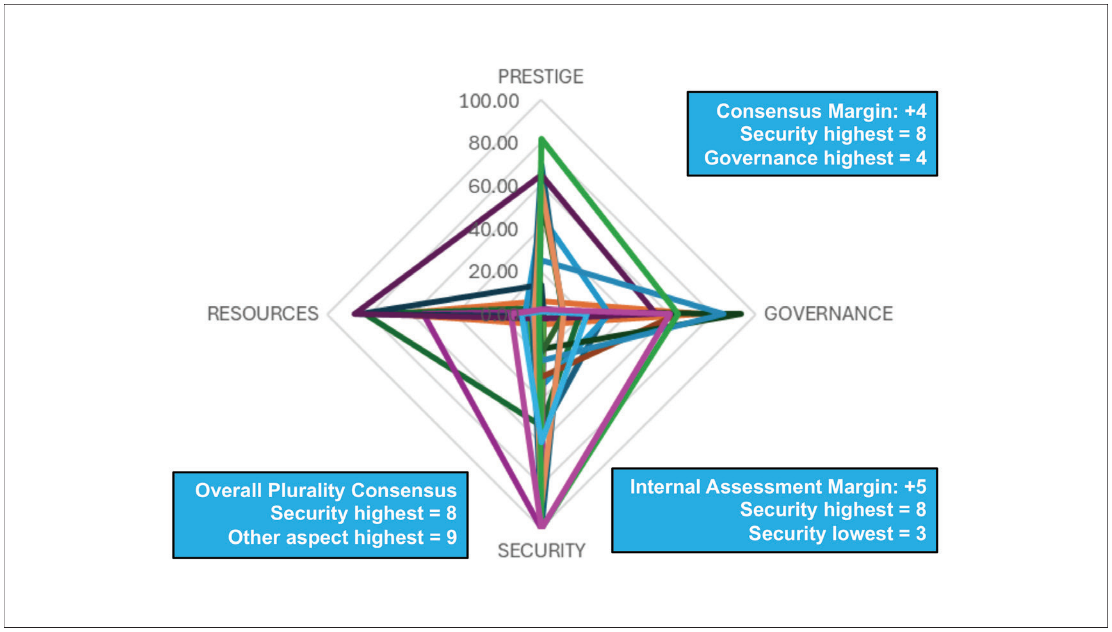
Cislunar Technology Demonstrators

There was a moderate convergence of expert views that security was the most significant strategic purpose in the second case study, Cislunar Technology Demonstrators. The total weight of this plurality view was greater than in the first case study, as were both the consensus margin and the internal assessment margin. Although the degree of consensus and internal assessment margins converge to a greater degree here than in the first case study, expert views here continue to reflect a wide range of perspectives regarding the strategic qualities of this type of Space Frontier Area activity. It is only the relatively more substantial assessment margins that suggest a moderate degree of convergence in the experts' strategic perspective.

Figure 24. Relative Significance Scores for This Case Study (Each Column Represents One Expert's Scores).

PRESTIGE	1.00	5.91	2.80	46.00	1.00	1.00	13.75	1.00	1.00	70.00	64.73	55.00	25.00	60.06	82.00	1.00	2.13
GOVERNANCE	30.25	75.45	17.92	31.96	1.00	1.00	1.00	64.00	93.57	10.00	53.53	10.56	85.00	10.56	64.00	21.25	60.06
SECURITY	55.00	4.79	52.48	33.64	100.00	55.00	1.00	29.44	16.11	100.00	2.29	17.88	22.00	88.75	100.00	60.06	100.00
RESOURCES	1.00	69.28	82.00	7.60	55.00	5.50	85.00	4.60	2.70	4.00	87.14	1.00	4.00	3.25	1.00	8.88	14.22

Figure 25.



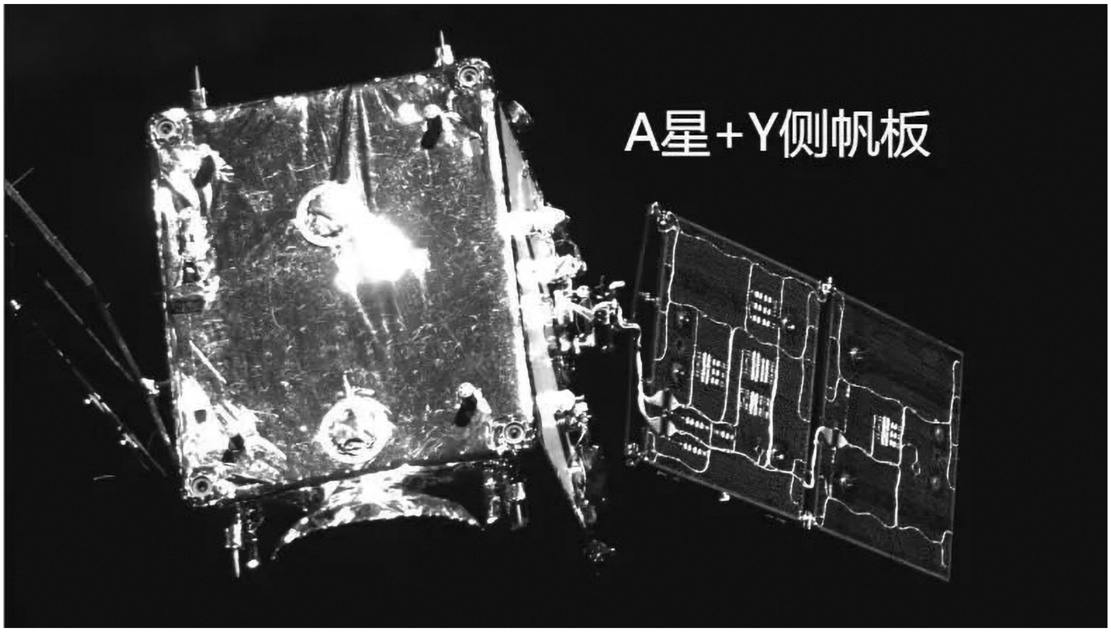
- SECURITY: Eight experts assessed security as the most significant strategic quality; this was twice the number of assessments for the next-highest scoring strategic quality governance, according to four experts), and was one score short of a majority; three experts assessed security as the least significant purpose; internal assessment margin of +5.

- GOVERNANCE: Four experts scored governance as most significant; three scored it as least significant; internal assessment margin of +1.

- RESOURCES: Three experts scored resources as most significant; seven scored it as least significant; internal assessment margin of -4.

- PRESTIGE: Two experts scored prestige as the most significant strategic purpose; eight scored it as least significant; internal assessment margin of -6.

Figure 26. One of China's DRO Satellites (With Damaged Solar Array), Imaged by Other DRO Satellite



Source: Image by China National Space Agency, reprinted in Martijn Luinstra, "NASA's CLPS Program Accelerates as Two Landers Head for the Moon," NASA Space Flight, January 26, 2025, https://www.nasaspaceflight.com/2025/01/lunar-missions-roundup/.

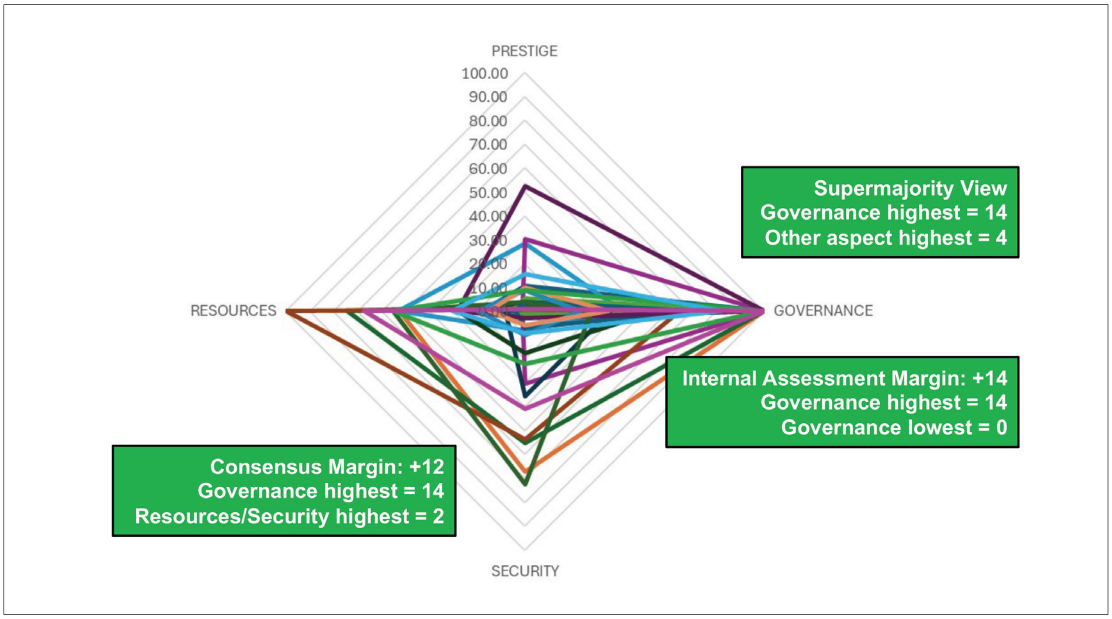
First Declaration of a Lunar Safety Zone

There was high convergence of expert views for the third case study, First Declaration of a Lunar Safety Zone. A supermajority (14 of 17) of experts assessed governance as the most significant purpose this activity would serve. No expert assessed governance as the least important strategic quality, resulting in an internal assessment margin of +14. The next-highest-scoring strategic qualities were resources and security, with two experts each scoring these highest (for a comparative margin assessment of +12). Expert views also showed high convergence regarding the least significant strategic quality of this activity: no expert assessed prestige as the most important quality, and 10 experts assessed it as least important. The clear majority view and high margin assessments indicate high convergence of expert views in this case study.

Figure 27. Relative Significance Scores for This Case Study (Each Column Represents One Expert's Scores).

PRESTIGE	10.56	2.80	2.29	28.41	30.25	5.50	1.00	1.00	4.00	4.00	52.48	4.00	8.71	10.00	8.71	15.40	1.00
GOVERNANCE	100.00	100.00	100.00	40.96	100.00	100.00	35.71	64.73	55.00	70.00	100.00	28.00	22.86	35.00	100.00	82.00	100.00
SECURITY	1.00	67.24	55.18	7.95	30.25	1.00	35.71	53.53	17.50	7.00	2.80	72.25	10.00	6.00	21.94	9.10	40.96
RESOURCES	17.88	52.48	74.29	53.05	1.00	5.50	8.16	100.00	28.00	4.00	28.00	55.00	19.92	15.00	55.18	30.25	67.24

Figure 28.



■ GOVERNANCE: Fourteen scored governance as the most significant strategic quality (seven times the next highest "most significant" assessment); 0 scored governance as least significant; internal assessment margin of +14.

■ RESOURCES: Two scored security as most significant; two scored it as least significant; internal assessment margin of 0.

■ SECURITY: Two scored security as most significant; six scored it as least significant; internal assessment margin of -4.

■ PRESTIGE: No expert scored prestige as the most significant aspect of this Space Frontier Area activity; 10 scored it as least significant; internal assessment margin of -10.

Conclusions

The findings suggest, with overall moderate confidence, that the framework tested here is useful for improving the coherence of strategic perspectives about activities in Space Frontier Areas. Further research would be required to validate this framework to a higher level of confidence. However, the general proposition that the strategic significance of activities in Space Frontier Areas includes aspects of prestige, governance, security, and resources appears sound.

Experts interviewed for this study generally expressed satisfaction with this four-axis framing of strategic purposes served by activities in Space Frontier Areas. Views did not diverge along the poles-apart axes of "high-immediacy security purposes" and "low-immediacy resource purposes," as the literature might suggest. Similarly, views about the strategic qualities of Space Frontier Activities had little to no correlation with experts' space sector experience, years of total space experience, or experience with xGEO/cislunar-specific activities. Rather, the wide range of expert views suggests a probable degree of interrelated qualities among the strategic purposes and high levels of uncertainty inherent in any future-oriented assessment of complex activities. This observation should caution against the dogmatic or colloquial focus on any single aspect of strategic significance for Space Frontier Area activities.

The framework suggested here may be useful when conducting formal assessments of observed, planned, or proposed activities in Space Frontier Areas. It may be useful as a mechanism to enhance consistency in analytical approach for a wide range of activities in dynamically diverse regions of space. It may also be useful as a planning guideline for wargames or exercises, to determine if event participants employing this framework achieve better outcomes than other participants.

The most important dynamic qualities of Space Frontier Areas are the vast distances and complex gravitational phenomena spacecraft encounter getting there or being there. States that master the science and technology necessary to reach and operate there, and build the infrastructure necessary to scale their use and exploration of Space Frontier Areas, will enjoy the fullest range of strategic advantages these new areas of space will offer. Today's Space Frontier Areas will be some future era's key orbital trajectories, conventional orbit families, or valuable celestial body resources. Every decision about how much attention, effort, money, and risk should be put toward Space Frontier Area programs is a bet on what that future looks like. Bets on that future should be made with a disciplined, clear-eyed understanding of what we hope to gain. The framework proposed here offers clarity about the relative significance of each strategic purpose served by specific Space Frontier Area programs or activities in a given time horizon. This strategic clarity will be important for establishing priorities, evaluating risk, and protecting national interests in space beyond near-Earth orbits.

Notes

[1] James Cartwright, *Hearing on China in Space: A Strategic Competition?* Hearing Before the U.S.-China Economic and Security Review Commission, 116th Cong., 1st sess., 2019, 15, https://www.uscc.gov/sites/default/files/2019-10/April%2025%202019%20Hearing%20Transcript.pdf.

[2] From 1958 through 1979, the United States and the Soviet Union attempted 119 total missions to lunar space or the Moon, of which only 49 were partially or fully successful. During the 1980s and 1990s, only three missions (all successful) attempted to reach lunar space: two orbiters from the United States and one orbiter from Japan. Since 2000, only 30 missions (6 conducted by commercial space companies) have attempted to reach lunar space or the Moon. The United States and China made the most attempts (8 missions each); 6 other states have also attempted to reach the Moon in the current millennium. "Moon Missions," National Aeronautics and Space Administration (NASA), April 4, 2025, https://science.nasa.gov/moon/missions/.

[3] *Spacepower: Doctrine for Space Forces* (Washington, DC: Headquarters U.S. Space Force, June 2020), 24, https://apps.dtic.mil/sti/trecms/pdf/AD1129735.pdf.

[4] *Spacepower*.

[5] The discussion here is informed by the author's review of several still-draft concepts for further delineation of cislunar space, in development at several military commands and nongovernmental organizations. See also Scott Pace, "A U.S. Perspective on Deterrence and Geopolitics in Space," *Space Policy* 66 (2023), 6.

[6] For example, spacepower theorist Everett Dolman divides space into four geopolitical regions: Terra (Earth), Earth Space (LEO to GEO), Lunar Space (GEO to the Moon's orbit), and Solar Space (the solar system beyond the Moon's orbit). Everett C. Dolman, *Astropolitik: Classical Geopolitics in the Space Age* (London: Frank Cass, 2002), 69.

[7] One perspective on cislunar space delineates it into spherical zones around the Earth-Moon system, though this approach is more useful for "discussion, intuition building, and some feature classification applications" than for strategic thought or spacecraft trajectory planning. M.J. Holzinger, C.C. Chow, and P. Garretson, *A Primer on Cislunar Space* (Wright-Patterson Air Force Base, OH: Air Force Research Laboratory, 2021), 7–8, https://www.afrl.af.mil/Portals/90/Documents/RV/A%20Primer%20on%20Cislunar%20Space_Dist%20A_PA2021-1271.pdf.

[8] For example, Fahrner, Correa, and Wysack describe an "Earth-Moon corridor," generally the volume of encompassing space between Earth, the Moon, and 10,000 kilometers beyond Earth-Moon Lagrange point 2; this conception of a region of space is of interest because from there, "objects in the Earth-Moon system . . . could pose a threat to Earth-orbiting spacecraft." Naomi Owens Fahrner, Jeremy Correa, and Joshua Wysack, "Capacity-Based Cislunar Space Domain Awareness Architecture Optimization," technical paper from the Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference 2022, 3, https://amostech.com/TechnicalPapers/2022/Cislunar-SSA/Fahrner.pdf.

[9] George E. Pollock IV and James A. Vedda, *Cislunar Stewardship: Planning for Sustainability and International Cooperation* (Chantilly, VA: Center for Space Policy and Strategy, The Aerospace Corporation, June 2020), 1–3, https://csps.aerospace.org/sites/default/files/2021-08/Pollock-Vedda_CislunarStewardship_20200601.pdf; Phillip M. Cunio, Marcus J. Bever, and Brien R. Flewelling, "Payload

and Constellation Design for a Solar Exclusion-Avoiding Cislunar SSA Fleet," technical paper from the AMOS Conference, 2020, 3, https://amostech.com/TechnicalPapers/2020/Cislunar-SSA/Cunio.pdf.

[10] "I think the emphasis on distance from Earth may not be right: I'm more interested in energy—not joules, but effort to maneuver. You could draw a line by distance, but technology can shift that line." Author interview with an expert in space operations, with military and civil space sector experience. "A strictly spatial definition is probably inadequate." Author interview with an expert in space operations, with civil and commercial space sector experience. All research interviews cited in this study were conducted between October 2024 and January 2025. All interviews were conducted in confidentiality; the names of interviewees are withheld by mutual agreement, and the views expressed are those of the interviewees and not any organization with which they are or have been affiliated.

[11] David Christian, "Silk Roads or Steppe Roads? The Silk Roads in World History," *Journal of World History* 11, no. 1 (2000), 7, https://www.jstor.org/stable/20078816.

[12] Joint Publication (JP) 3-14, *Joint Space Operations* (Washington, DC: The Joint Staff, August 23, 2023), sec. 2.c.(1).

[13] "Applications of a LEO Satellite," Dragonfly Aerospace, April 19, 2022, https://dragonflyaerospace.com/what-are-some-applications-of-a-leo-satellite/.

[14] James A. Van Allen, "Radiation Belts Around the Earth," *Scientific American* 200, no. 3 (1959), 46.

[15] Nicholas L. Johnson, "A New Look at the GEO and Near-GEO Regimes: Operations, Disposals, and Debris," *Acta Astronautica* 80 (November–December 2012), 82, https://doi.org/10.1016/j.actaastro.2012.05.024. The concept of a satellite orbit over the equator with its orbital period matching the Earth's rotation, thereby seeming to be "stationary above the same spot on the planet," and the utility of such a satellite for communications relay, was understood and popularized by Arthur C. Clarke even before Sputnik. See Arthur C. Clarke, "Extra-Terrestrial Relays; Can Rocket Stations Give World-Wide Radio Coverage?" *Wireless World*, October 1945, 305, http://clarkeinstitute.org/wp-content/uploads/2010/04/ClarkeWirelessWorldArticle.pdf. "GEO" can also refer to the broader category of geosynchronous Earth orbit; this refers to any satellite orbital period matching Earth's rotational period. To distinguish the two, the acronym GSO is often used to refer to geosynchronous Earth orbit. Geostationary Earth orbit is one type of geosynchronous orbit. However, satellite orbital periods can match Earth's rotational period at any inclination, in orbits often forming a figure-8 shaped ground track on the surface of Earth.

[16] This description is somewhat idealized. In actual spaceflight, satellites in a generally geostationary orbit are often slightly inclined above 0°. As a result, a satellite in GEO often seems (to an observer on Earth) to move slightly up and down with each orbital period. Likewise, slight eccentricity of the orbit, small changes in altitude, variations in distribution of the Earth's mass, and other minor perturbing forces can contribute to satellites in GEO tending to "drift" east or west. Occasional stationkeeping maneuvers are usually required for a satellite in GEO to hold a relatively fixed position relative to Earth. See Jacob Decoto and Patrick Loerch, "Technique for GEO RSO Station Keeping Characterization and Maneuver Detection," technical paper from the AMOS Conference, 2015, https://amostech.com/TechnicalPapers/2015/SSA/Decoto.pdf.

[17] *Space Force Doctrine Document 3-0 (SFDD_3-0), Operations Doctrine for Space Forces* (July 19, 2023), 15, https://www.starcom.spaceforce.mil/Portals/2/SDP%203-0%20Operations%20%2819%20July%202023%29_1.pdf.

[18] "Global Navigation Satellite System (GNSS) and Satellite Navigation Explained," Inertial Labs, November 2024, https://inertiallabs.com/gnss-and-satellite-navigation-explained.

[19] Pace, "A U.S. Perspective on Deterrence and Geopolitics in Space," 6.

[20] "We need to get DOD space-thinking about space beyond just four orbits." Author interview with a space operations expert with military and civil space sector experience.

[21] JP 3-14, figure I-1.

[22] Malcolm Davis, "Space Operations in the Deep Black of xGEO," *The Strategist*, July 3, 2024, https://www.aspistrategist.org.au/space-operations-in-the-deep-black-of-xgeo/.

[23] John J. Klein, *Space Warfare: Strategy, Principles and Policy*, 2nd ed. (New York: Routledge, 2025), 227.

[24] Between 1957 and 2024, 6,285 spacecraft successfully reached Earth orbit or beyond. Of these, only 272 (less than 4.5 percent) ventured beyond Earth orbit. Between 2020 and 2024, a mere 27 spacecraft launched beyond Earth orbit, almost all on missions of scientific discovery. Data derived from "Orbital Launches by Year," Space Stats, accessed March 31, 2025, https://spacestatsonline.com.

[25] David Buehler et al., "Posturing Space Forces for Operations Beyond GEO," *The Space Force Journal* 1, no. 1 (2021). In a research interview with the author, an expert in space operations with civil and military space sector experience clarified that above the Worden Line, changes in inclination (the degree of an orbit's "tilt" above the equator) become as "cheap"—in terms of energy required for the maneuver—as changes in altitude (the overall distance from Earth). There is not a single, agreed definition of the Worden Line, and its qualities become apparent gradually. Based on the author's conversations with space operations experts, changes in maneuver options become apparent at distances between approximately 90,000 and 100,000 kilometers from Earth.

[26] Dolman, *Astropolitik*, 66–67.

[27] Two of the space operations experts interviewed for this study suggested this potential use of Earth orbit beyond GEO.

[28] Fahrner, Correa, and Wysack, "Capacity-Based Cislunar Space Domain Awareness Architecture Optimization," 3; Dolman, *Astropolitik*, 75. According to Dolman (discussing the earlier work of G.H. Stine), the gravitational advantage of space near the top of the gravity well has energy and maneuver aspects. "The first, energy advantage, is a firepower benefit because weapons placed higher in the gravity well gain the downward momentum—velocity in the power equation, velocity times mass—while kinetic energy weapons firing up the gravity well lose momentum. The maneuver advantage comes because spacecraft higher up in the gravity well have more time to observe and react to attacks than those at lower positions."

[29] More correctly, both Earth and the Moon orbit the barycenter of the Earth-Moon system. The Earth-Moon barycenter is a point approximately 5,000 kilometers from the center of the Earth (about 75 percent of the distance from the center of the Earth to its surface) along the line formed between the centers of Earth and the Moon. If the Earth-Moon system were viewed in a frame of reference holding the barycenter at a fixed position, Earth would seem to "wobble" as the Moon orbited around it. Nicholas Connors, "Barycenter of the Earth-Moon System," in *Encyclopedia of Lunar Science*, ed. Brian Cudnik (Cham: Springer, 2022), https://doi.org/10.1007/978-3-319-05546-6_151-1.

[30] "Tidal Locking," NASA, n.d., https://science.nasa.gov/moon/tidal-locking/. "There is no dark side [of] the Moon," observed Gerry O'Driscoll, doorman for Abbey Road Studios, during the recording of Pink Floyd's 1973 album *The Dark Side of the Moon*. He is heard saying these words at the end of the album's closing song "Eclipse." Mr. O'Driscoll's observation is correct only in that no hemisphere of the Moon is in perpetual darkness. While the match of the lunar rotation on its axis and lunar orbit of Earth (about 27.3 days) causes the "near side" hemisphere of the Moon to always face Earth, most regions of the lunar surface experience a lunar day and lunar night each lasting for approximately 14 days, in Earth time. Some high-altitude areas near the lunar poles experience perpetual day, while craters at the poles experience perpetual night.

[31] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies [Outer Space Treaty], signed at Washington, London, and Moscow, January 27, 1967, 18 U.S.T. 2410, 610 U.N.T.S. 205, https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html.

[32] A notable exception to the general proposition that the Moon and other celestial bodies are treated as legally equivalent portions of of "outer space" is found at Outer Space Treaty, Article IV, which reserves use of the Moon and other celestial bodies for "exclusively peaceful purposes." Article IV specifically prohibits the building of military fortifications, the conduct of military maneuvers, or the testing of weapons of any kind on the Moon or any other celestial body.

[33] For example, the National Cislunar Science and Technology Strategy defines "cislunar space" as "the three-dimensional volume of space beyond Earth's geosynchronous orbit that is mainly under the gravitational influence of the Earth and/or the Moon. Cislunar space includes the Earth-Moon Lagrange point regions . . . , trajectories utilizing those regions, and the Lunar surface." National Science and Technology Council, *National Cislunar Science and Technology Strategy*, 3.

[34] A "planetary-mass object" is a celestial body massive enough to achieve a roughly spherical shape, but not massive enough to sustain core fusion like a star. Gibor Basri and Michael E. Brown, "Planetesimals to Brown Dwarfs: What Is a Planet?" Annual Review of Earth and Planetary Science 34 (2006), https://doi.org/10.1146/annurev.earth.34.031405.125058.

[35] "Cislunar is distinct from lunar." Author interview with an expert in space operations, with military and commercial space sector experience.

[36] Pace, "A U.S. Perspective on Deterrence and Geopolitics in Space," 9.

[37] "Moon Missions."

[38] Martin Elvis, Alanna Krolikowski, and Tony Milligan, "Concentrated Lunar Resources: Imminent Implications for Governance and Justice," *Philosophical Transactions of the Royal Society A* 379, no. 2188 (November 2020), 2, https://doi.org/10.1098/rsta.2019.0563.

[39] Shuai Li et al., "Direct Evidence of Surface Exposed Water Ice in the Lunar Polar Regions," *Proceedings of the National Academy of Sciences* 115, no. 36 (2018), http://www.pnas.org/cgi/doi/10.1073/pnas.1802345115.

[40] Elvis, Krolikowski, and Milligan, "Concentrated Lunar Resources," 4.

[41] See generally James Clay Moltz, "Toward Cooperation or Conflict on the Moon? Considering Lunar Governance in Historical Perspective," *Strategic Studies Quarterly* 3, no. 3 (Fall 2009), 82–103, https://www.jstor.org/stable/26268666.

[42] Andrea Farkasvölgyi, László Csurgai-Horváth, and Petr Boháček, "The Evolution of Lunar Communication—From the Beginning to the Present," *International Journal of Satellite Communications and Networking* 42, no. 3 (2024), sec. 3.5.1., https://doi.org/10.1002/sat.1507.

[43] I. Bernard Cohen, "Newton's Concepts of Force and Mass, With Notes on the Laws of Motion," in *The Cambridge Companion to Newton*, ed. I. Bernard Cohen and George E. Smith (Cambridge: Cambridge University Press, 2002), 58. The text referenced here is the modern expression of Newton's Universal Law of Gravitation; Newton's original description of his discovery comes from his *Principia*, book 1, section 11 (propositions 57 through 69). Isaac Newton, *The Principia: The Authoritative Translation and Guide: Mathematical Principles of Natural Philosophy*, 1st ed., trans. I Bernard Cohen, Anne Whitman, and Julia Budenz (Berkeley: University of California Press, 1999).

[44] Dolman, *Astropolitik*, 65.

[45] Victor Szebehely, *Theory of Orbits: The Restricted Problem of Three Bodies* (New York: Academic Press, 1967), 8.

[46] Zi Chong Kao, *Classical Mechanics: The Three-Body Problem* (Chicago: Vertical Integration of Research and Education, University of Chicago, August 2011), 17, https://www.math.uchicago.edu/~may/VIGRE/VIGRE2011/REUPapers/KaoZ.pdf.

[47] Szebehely, *Theory of Orbits*, 5. Explanation of this concept is also based on the author's participation in the Cislunar Space Executive Workshop conducted by the Whiting School of Engineering at Johns Hopkins University, December 2024.

[48] Holzinger, Chow, and Garretson, *A Primer on Cislunar Space*, 21. The number of bodies at work in any particular case is enormous; conceptually all motion in the universe is an "n-body problem" encompassing every particle in the universe. However, practical necessity requires simplifying the description of any particular instance of motion to a small number of gravitational influences.

[49] Wilmer, "Space Domain Awareness Assessment of Cislunar Periodic Orbits for Lagrange Point Surveillance for Lagrange Point Surveillance," 5.

[50] Explanation of this concept is based on the author's participation in the Cislunar Space Executive Workshop conducted by the Whiting School of Engineering at Johns Hopkins University, December 2024.

[51] Holzinger, Chow, and Garretson, *A Primer on Cislunar Space*, 16.

[52] "Orbits in cislunar are less permanent, and more transitory." Author interview with an expert in space operations, with military space sector experience.

[53] The discussion of stable, unstable, and center manifolds is derived from the Cislunar Space Executive Workshop conducted by the Whiting School of Engineering at Johns Hopkins University, December 2024.

[54] Holzinger, Chow, and Garretson, *A Primer on Cislunar Space*, 20.

[55] "Our [space domain awareness] is tuned to predictable orbits," and motion in Space Frontier Areas is far less predictable than in Earth orbit. Author interview with an expert in space operations, with military and commercial space sector experience.

[56] Dolman, *Astropolitik*, 71–72.

[57] See, generally, Ryan J. Whitley et al., "Earth-Moon Near Rectilinear Halo and Butterfly Orbits for Lunar Surface Exploration," paper from AAS/AIAA Astrodynamics Specialists Conference,

Snowbird, Utah, August 2018, https://www.researchgate.net/publication/339028625_Earth-Moon_Near_Rectilinear_Halo_ and_Butterfly_Orbits_for_Lunar_Surface_Exploration. Whitley et al. discuss several possible near-lunar halo orbits lasting almost a week; Lissajous and Lyapunov orbits around the more stable Lagrange points 4 and 5 can be much larger, with correspondingly longer orbital periods.

[58] Although he disputes the strategic importance of space beyond GEO on any foreseeable time horizon, Professor Bleddyn Bowen agrees that "going into cislunar (between Earth and the Moon) or interplanetary space, space may become more akin to the high seas where spacecraft may enjoy relative safety and obscurity away from the Earth." Bleddyn E. Bowen, *Original Sin: Power, Technology and War in Outer Space* (New York: Oxford University Press, 2023), 113.

[59] Holzinger, Chow, and Garretson, *A Primer on Cislunar Space*, 10.

[60] "Tidal Locking," NASA, n.d., https://science.nasa.gov/moon/tidal-locking/.

[61] "What Is CAPSTONE?" NASA, February 7, 2025, https://www.nasa.gov/smallspacecraft/capstone/.

[62] See, generally, Wilmer, "Space Domain Awareness Assessment of Cislunar Periodic Orbits for Lagrange Point Surveillance for Lagrange Point Surveillance."

[63] Mariel Borowitz, Althea Noonan, and Reem El Ghazal, "U.S. Strategic Interest in the Moon: An Assessment of Economic, National Security, and Geopolitical Drivers," *Space Policy* 69 (August 2024), 6–7.

[64] "Lucy: The First Mission to Explore the Jupiter Trojan Asteroids," NASA, n.d., https://science.nasa.gov/mission/lucy/.

[65] Author interview with an expert in space operations, with intelligence space sector experience.

[66] *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; C. Todd Lopez, "Defense Intelligence Agency Report Details Space-Based Threats From Competitors," *DOD News*, April 12, 2022; Presidential Memorandum, *National Space Policy*, 85 Federal Register 81755, December 16, 2020, https://www.federalregister.gov/documents/2020/12/16/2020-27892/the-national-space-policy. The Defense Intelligence Agency report mentions Mars 16 times; Mars is mentioned 4 times in the *National Space Policy*.

[67] "SOHO: Solar and Heliospheric Observatory," NASA, n.d., https://soho.nascom.nasa.gov/.

[68] "DSCOVR: Deep Space Climate Observatory," NASA, n.d., https://science.nasa.gov/mission/dscovr/.

[69] "James Webb Space Telescope," NASA, n.d., https://science.nasa.gov/mission/webb/.

[70] Lei Liu, Wei-Ren Wu, and Yong Li, "Design and Implementation of Chinese Libration Point Missions," *Science China Information Sciences* 66, no. 191201 (2023), 5–6, https://doi:10.1007/s11432-022-3716-9.

[71] "You get so far out in space, it stops becoming useful to be there." Todd Harrison, *Hearing on China in Space: A Strategic Competition?* Hearing Before the U.S.-China Economic and Security Review Commission, Panel 1 Question and Answer, 116th Cong., 1st sess., 2019, 122.

[72] Bleddyn E. Bowen, *War in Space: Strategy, Spacepower, Geopolitics* (Edinburgh: Edinburgh University Press, 2020), 112–113.

[73] Peter Garretson, "Bluewater and Brownwater Space Strategies and Their Budgetary Profiles," in *Space: America's New Strategic Front Line*, ed. Henry D. Sokolski (Arlington, VA: Nonproliferation

Policy Education Center, 2023), 89–112, https://npolicy.org/wp-content/uploads/2023/08/Bluewater-and-Brownwater-Space-Strategies-and-Their-Budgetary-Profiles.pdf.

[74] Namrata Goswami and Bleddyn Bowen, *High Ground or High Fantasy: Defense Utility of Cislunar Space* (Chantilly, VA: Center for Space Policy and Strategy, The Aerospace Corporation, May 2024), 6, https://csps.aerospace.org/sites/default/files/2024-05/Wilson_HighGround_20240416.pdf.

[75] Pace, "A U.S. Perspective on Deterrence and Geopolitics in Space," 9.

[76] Borowitz, Noonan, and El Ghazal, "U.S. Strategic Interest in the Moon," 13–14.

[77] *Spacepower*, 14.

[78] Both U.S. companies that have reached the Moon, Intelligent Machines and Firefly Aerospace, did so with funding from NASA's Commercial Lunar Payload Services program. William Harwood, "Intuitive Machines Lunar Lander Healthy, but Apparently on Its Side," *Spaceflight Now*, March 7, 2025, https://spaceflightnow.com/2025/03/07/intuitive-machines-lunar-lander-healthy-but-apparently-on-its-side/. The lunar missions by Japan's iSpace are principally funded by Japan and U.S. national space programs. Jeff Foust, "Resilience Lunar Lander Enters Orbit Around the Moon," *SpaceNews*, May 7, 2025, https://spacenews.com/resilience-lunar-lander-enters-orbit-around-the-moon/. India's lunar landings (like those of Russia and China) have been missions of their respective national space programs. Shobhit Gupta, "'India Is on the Moon': ISRO Chief S. Somanath on Chandrayaan-3's Successful Lunar Landing," *Hindustan Times*, August 23, 2023, https://www.hindustantimes.com/india-news/india-is-on-the-moon-isro-chief-s-somanath-on-chandrayaan-3s-successful-lunar-landing-101692794452005.html.

[79] "Remarks by the Commander, U.S. Space Command, General Stephen Whiting," Air and Space Power Association, Defence Space Conference 2024, London, September 25, 2024, https://air-spacepower.com/wp-content/uploads/2024/09/Defence-Space-24-CDR-USSC-Keynote.pdf.

[80] Namrata Goswami and Peter A. Garretson, *Scramble for the Skies: The Great Power Competition to Control the Resources of Outer Space* (Lanham, MD: Lexington Books, 2020), 12.

[81] Goswami and Garretson, *Scramble for the Skies*.

[82] Goswami and Garretson. Clarke's quote is from Arthur C. Clarke, *The Exploration of Space* (London: Temple Press, 1951), xii.

[83] Joshua P. Carlson, *Spacepower Ascendant: Space Development Theory and a New Space Strategy* (Independently published, 2020), 83.

[84] National Science and Technology Council, *National Cislunar Science and Technology Strategy*; Pollock and Vedda, *Cislunar Stewardship*, 2; Carlson, *Spacepower Ascendant*, 2; Clayton Swope and Louis Gleason, *Salmon Swimming Upstream: Charting a Course in Cislunar Space* (Washington, DC: Center for Strategic and International Studies, October 2024), 2, https://www.csis.org/analysis/salmon-swimming-upstream-charting-course-cislunar-space; Mengfei Yang et al., "Architecture and Development Envision of Cislunar Space Infrastructure," *Chinese Space Science and Technology* 44, no. 3 (2024), 12.

[85] National Science and Technology Council, *National Cislunar Science and Technology Strategy*; Goswami and Bowen, *High Ground or High Fantasy*; "Debating National Security Space," with Namrata Goswami and Bleddyn Bowen, Space Policy Institute, The George Washington University, Elliott School of International Affairs, August 29, 2024, video 2:22:00, https://youtu.be/7SlwMnZIsNs, mark 32:45.

[86] Borowitz, Noonan, and El Ghazal, "U.S. Strategic Interest in the Moon," 3–4.

[87] Goswami and Garretson, *Scramble for the Skies*, 10–16.

[88] Pete Hegseth, "Secretary of Defense Pete Hegseth Delivers Keynote Address at Special Operations Forces Week 2025," Department of Defense, May 6, 2025, https://www.defense.gov/News/Transcripts/Transcript/article/4176603/secretary-of-defense-pete-hegseth-delivers-keynote-address-at-special-operation/.

[89] Kelsey L. Schoeman and Irina Liu, *People's Republic of China in Cislunar Space: Activities, Motivations, and Implications* (Alexandria, VA: Institute for Defense Analyses, April 2024), 18–19, https://www.ida.org/-/media/feature/publications/p/pe/peoples-republic-of-china-in-cislunar-space-activities-motivations-and-implications/3002255.ashx.

[90] James Cartwright, *Hearing on China in Space: A Strategic Competition?* Hearing Before the U.S.-China Economic and Security Review Commission, Opening Statement.

[91] The qualitative assessments described here were obtained during the research interviews conducted by the author between October 2024 and January 2025. All interviews were conducted in confidentiality; the names of interviewees are withheld by mutual agreement, and the views expressed are those of the interviewees and not any organization with which they are or have been affiliated.

[92] Bowen, *War in Space*, 90.

[93] One expert interviewed during this study suggested that the strategic purposes of "prestige, governance, security, and resources" are "basically DIME" (an acronym often used to describe the instruments of national power as diplomatic, informational, military, and economic). While conceptually related, the strategic purposes discussed in this study describe purposes, interests, or goals, whereas DIME describes the tools available to accomplish those goals. For a description and critique of the DIME model, see Matthew O'Connor, "The Problem With Thinking in DIME," *War Room*, Army War College, April 10, 2025, https://warroom.armywarcollege.edu/articles/problem-with-dime/.

[94] "Space achievements demonstrate American leadership. U.S. human and robotic accomplishments in space unlock the mysteries of the universe and provide tangible measures of American technological capacity and our national ability to execute large-scale, complex projects. Our successes in space bolster our credibility and influence worldwide." *United States Space Priorities Framework* (Washington, DC: The White House, December 2021), https://bidenwhitehouse.archives.gov/briefing-room/statements-releases/2021/12/01/united-states-space-priorities-framework/.

[95] Borowitz, Noonan, and El Ghazal, "U.S. Strategic Interest in the Moon," 10. In a research interview with the author, a space operations expert with military space sector experience said, "The [People's Republic of China]'s space missions motivate their science and technology base. That is a strategic interest: you get operational smarts from inspiring your science and technology base. It's how you win."

[96] "Supplemental Appropriations for the National Aeronautics and Space Administration," transcript of Presidential meeting in the Cabinet Room of the White House, John F. Kennedy Presidential Library and Museum, Recordings Collection Tape #63, November 21, 1962, https://www.nasa.gov/wp-content/uploads/static/history/jfk-webbconv/pages/transcript.pdf.

[97] U.S. National Space Policy calls for "a program to land the next American man and the first American woman on the Moon by 2024, followed by a sustained presence on the Moon by 2028, and the subsequent landing of the first human on Mars." The first goal date has passed, but the overall goals remain. *National Space Policy*, sec. 5. China has also made its lunar ambitions part and parcel of its national space program. *China's Space Program: A 2021 Perspective* (Beijing: The State Council Informa-

tion Office of the People's Republic of China, January 2022), https://english.www.gov.cn/archive/whitepaper/202201/28/content_WS61f35b3dc6d09c94e48a467a.html. See also David Christopher Arnold, *"We Choose to Go to the Moon": An Analysis of a Cold War Means-Developing Strategy* (Washington, DC: NDU Press, January 2022), https://digitalcommons.ndu.edu/nwc-case-studies/3/.

[98] Carlson, *Spacepower Ascendant*, 49; Todd Harrison, *Hearing on China in Space: A Strategic Competition?* Hearing Before the U.S.-China Economic and Security Review Commission, 44.

[99] Mark R. Whittington, "Returning to the Moon to Gain Soft Political Power," *The Hill*, April 27, 2019, https://thehill.com/opinion/technology/440751-returning-to-the-moon-to-gain-soft-political-power/.

[100] Carlson, *Spacepower Ascendant*, 59. Carlson argues that "There is no reason for a nation to spend billions of dollars developing space technology and then expend production to go to space for the weak reason of 'scientific curiosity.'"

[101] "If China can sustain a long-term program for lunar exploration, it will give Beijing leverage in any future discussions and negotiations on the governance of the Moon and in particular on the management and deconfliction of lunar operations." Bleddyn Bowen, quoted in Andrew Jones, "Chinese Scientists Outline Major Cislunar Space Infrastructure Project," *SpaceNews*, July 30, 2024, https://spacenews.com/chinese-scientists-outline-major-cislunar-space-infrastructure-project/; "The United States needs to lead in utilizing space and space resources, in order to establish common international operating principles based on Western values and law. . . . It is in the national security interests of the United States to establish the Western principles of free trade and commerce, including free enterprise development and use of space resources, in international common law." *Fast Space: Leveraging Ultra Low-Cost Space Access for 21st Century Challenges* (Maxwell Air Force Base, AL: Air University, January 2017), sec. C2, F.3.3., https://www.govinfo.gov/content/pkg/GOVPUB-D301-PURL-gpo131929/pdf/GOVPUB-D301-PURL-gpo131929.pdf.

[102] "Customary International Law," in *Restatement (Third) of Foreign Relations Law of the United States* (Philadelphia, PA: American Law Institute, 1987), sec. 102(2). See also *Draft Conclusions on Identification of Customary International Law, With Commentaries* (Geneva: United Nations, International Law Commission, 2018), https://legal.un.org/ilc/texts/instruments/english/commentaries/1_13_2018.pdf.

[103] Scott Pace, "How Far—If at All—Should the USA Cooperate With China in Space?" *Space Policy* 27, no. 3 (2011), 130.

[104] 热血院士叶培建：面向未来 探索星辰大海 [Enthusiastic Academician Ye Peijian: Exploring the Stars and the Sea in the Future], *CCTV News*, September 18, 2019, https://news.cctv.com/2019/09/18/ARTI40ad9pLx5jBrz8rnohTS190918.shtml. Dr. Andrew Taffer of the Center for the Study of Chinese Military Affairs assisted with locating and translating the original source for Ye Peijian's quoted remarks. Interestingly, in a research interview with the author, a space operations expert with military sector experience offered an almost identical thought. He said, "The space system's goal matters first; it tells you which orbit makes it matter. But for all, access and presence matter. *That's important enough until more use cases emerge*."

[105] *John S. McCain National Defense Authorization Act for Fiscal Year 2019*, Pub. L. No. 115-232, 132 Stat. 1992, 115th Cong., 2nd sess., 2018, § 1086.

[106] Klein, *Space Warfare*, 220.

[107] Outer Space Treaty, art. VI.

[108] Klein, *Space Warfare*, 208; Thomas J. Fay, Adam P. Wilmer, and Robert A. Bettinger, "Investigation of Near-Rectilinear Halo Orbit Search and Rescue Using Staging L1/L2 Lyapunov and Distant Retrograde Orbit Families," *Journal of Space Safety Engineering* 11, no. 2 (June 2024), 2, https://doi.org/10.1016/j.jsse.2024.04.009. "The increase in both crewed and uncrewed missions to lunar and cislunar orbits . . . motivates the need for infrastructure to support search and rescue operations when mishaps inevitably occur." See also Jeff Foust, "Planning for Space Rescue," *The Space Review*, January 6, 2025, https://www.thespacereview.com/article/4914/1.

[109] Borowitz, Noonan, and El Ghazal, "U.S. Strategic Interest in the Moon," 8.

[110] Borowitz, Noonan, and El Ghazal, 8; Kevin Pollpeter et al., *China's Space Narrative: Examining the Portrayal of the U.S.-China Space Relationship in Chinese Sources and Its Implications for the United States* (Maxwell Air Force Base, AL: China Aerospace Studies Institute, 2020), 74, https://www.cna.org/analyses/2020/10/chinas-space-narrative.

[111] Carlson, *Spacepower Ascendant*, 199.

[112] Goswami and Bowen, *High Ground or High Fantasy*, 6.

[113] Klein, *Space Warfare*, 180. Forces held in reserve or for augmentation are not exactly how Klein describes his concept of "space force in being." Rather, his use of the phrase describes keeping "less capable space forces 'in being' through active utilization and operations until the situation develops in their favor." An example he cites would be deploying low-cost, expendable satellites in close proximity to an adversary's high-value asset. However, satellites—once launched—are conducting active operations, if only by virtue of expending operational service life, regardless of whether they are held in reserve or operationally employed. Klein's description of a "space force in being" is a nod to the naval strategy concept of a "fleet in being." Julian S. Corbett, *Some Principles of Maritime Strategy* (Annapolis, MD: Naval Institute Press, 1988), 211.

[114] Author interview with an expert in space operations, with military and commercial space sector experience.

[115] John E. Shaw, Jean Purgason, and Amy Soileau, "Sailing the Wine-Dark New Sea: Space as a Military Area of Responsibility," *Æther: A Journal of Strategic Airpower and Spacepower* 1, no. 1 (2022), 43, https://www.jstor.org/stable/48651805. Goswami and Garretson attribute to Dr. Fred Kennedy, first director of Space Development Agency, a similar view: "Defense follows where commercial goes." Goswami and Garretson, *Scramble for the Skies*, 151.

[116] Goswami and Garretson, *Scramble for the Skies*, 151.

[117] Bowen, *War in Space*, 5–6. In a research interview with the author, a space operations expert with military and civil space sector experience described an internal study on lunar mining: with every favorable assumption, including zero launch cost, the study found no business case where economics favored lunar resources over terrestrial resources.

[118] Borowitz, Noonan, and El Ghazal, "U.S. Strategic Interest in the Moon," 3–4.

[119] "Resources could be a motivating factor for an actor, uncorrelated from the probability of actually realizing value." Author interview with an expert in space operations, with military and civil space sector experience.

[120] See, generally, Elvis, Krolikowski, and Milligan, "Concentrated Lunar Resources."

[121] Water ice—from which rocket fuel can be derived—is an example. Space-based water ice could be of economic value regardless of whether it is the object of a commercial transaction, or is used *in situ*. “Mining lunar ice for rocket propellant is likely to be the first economic use of lunar resources.” Bernard F. Kutter and George F. Sowers, “Cislunar-1000: Transportation Supporting a Self-Sustaining Space Economy,” paper from the AIAA Space 2016 Conference, Long Beach, California, September 13–16, 2016, 3, https://doi.org/10.2514/6.2016-5491.

[122] Pollpeter et al., *China’s Space Narrative*, 47. The authors note that it is unclear to what extent China’s top leadership has accepted this vision of space; Zhang’s statements were reported in English sources as official positions, and in Chinese sources as his personal opinion.

[123] Kristin Burke, “Chinese Military Thinking on Orbits Beyond GEO,” *The Space Review*, May 16, 2022, https://www.thespacereview.com/article/4387/1.

[124] “We must be very concerned that China is landing on the Moon and saying, ‘It is ours now and you stay out.’” Former NASA Administrator Bill Nelson, quoted by Borowitz, Noonan, and El Ghazal, “U.S. Strategic Interest in the Moon,” 11.

[125] Ian M. Sullivan, “Three Dates, Three Windows, and all of DOTMLPF-P: How the People’s Liberation Army Poses an All-of-Army Challenge,” *Military Review* 104, no. 1 (January–February 2024), 17, https://www.armyupress.army.mil/Portals/7/military-review/Archives/English/JF-24/Sullivan/Sullivan-ua.pdf; Kyle Amonson and Dane Egli, “The Ambitious Dragon: Beijing’s Calculus for Invading Taiwan by 2030,” *Journal of Indo-Pacific Affairs* 6, no. 3 (March–April 2023), 37–53, https://media.defense.gov/2023/apr/24/2003205860/-1/-1/1/_jipa_march-april%202023.pdf/_jipa_march-april%202023.pdf.

[126] Goswami and Garretson, though they contemplate economic possibilities centuries in the future, limit the focus of their study to the next three decades (2020–2050). Goswami and Garretson, *Scramble for the Skies*, 10. One space futures study convened shortly before establishment of the U.S. Space Force in 2019 looked four decades ahead to 2060. *The Future of Space 2060 and Implications for U.S. Strategy: Report on the Space Futures Workshop* (Colorado Springs, CO: Air Force Space Command, September 5, 2019). Another strategic foresight initiative (in which the author is a participant) is currently underway within the U.S. Space Force; it looks two decades ahead to 2045.

[127] General Stephen Whiting, Commander, U.S. Space Command, has spoken of the command’s “pivot to 2040.” Greg Hadley, “Whiting Calls for ‘Space Fires’ in Rare Hint About Offensive Weapons,” *Air and Space Forces Magazine,* August 8, 2024, https://www.airandspaceforces.com/spacecom-boss-space-fires/. For China’s part, it has established a goal date of 2035 for initial operation of a moon base, the China-led International Lunar Research Station. Schoeman and Liu, *People’s Republic of China in Cislunar Space*, 9.

[128] Goswami and Garretson, *Scramble for the Skies*, 97.

[129] Schoeman and Liu, *People’s Republic of China in Cislunar Space*, 5–6.

[130] Xing Wang et al., “Lunar Farside Samples Returned by Chang’E-6 Mission: Significance for Understanding the South Pole–Aitken Basin Stratigraphic History,” *The Astronomical Journal* 168, no. 6 (2024), https://doi:10.3847/1538-3881/ad7fce.

[131] Andrew Jones, “Mission Team Details Complex Rescue of Chinese Lunar Spacecraft,” *SpaceNews*, April 17, 2025, https://spacenews.com/mission-team-details-complex-rescue-of-chinese-lunar-spacecraft/.

[132] "Oracle Family of Systems," Air Force Research Laboratory, n.d., Change HL: https://afresearchlab.com/cislunar-highway-patrol-system-chps/, accessed January 8, 2026.

[133] "What Is CAPSTONE?"

[134] "The Artemis Accords," NASA, n.d., https://www.nasa.gov/artemis-accords/.

[135] "The Artemis Accords."

[136] Raw data is on file with the author.

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