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**THE NEXT HIGH GROUND: AN INTEGRATED APPROACH TO U.S.  
LEADERSHIP IN CISLUNAR SPACE**

**SPACE INDUSTRY STUDY GROUP PAPER**

**INSTRUCTOR NAMES**

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## Executive Summary<sup>1</sup>

The United States faces a strategic inflection point: it must act decisively to secure the cislunar domain—the region of space between geosynchronous Earth orbit (GEO) and the Moon—or risk ceding this critical high ground to global competitors like China and Russia. As space becomes increasingly commercialized and contested, a deliberate U.S. strategy is essential to preserve freedom of maneuver, enable economic expansion, and set the normative foundations for responsible behavior beyond Earth orbit.

Drawing from field studies across the United States and Japan and incorporating insights from government, industry, and academic stakeholders, this analysis examines the current strategic environment, innovation trends, supply chain dynamics, and governance gaps shaping the Earth-Moon system. It identifies a growing risk from adversarial civil-military fusion efforts, ambiguous legal regimes, and a lack of cohesive U.S. infrastructure and investment coordination in the cislunar domain. Meanwhile, opportunities abound in infrastructure-first advantages, in-space servicing, assembly, and manufacturing (ISAM), lunar resource extraction, and public-private partnerships that can catalyze a projected over \$100 billion cislunar economy.

The paper recommends a comprehensive approach anchored by three integrated Lines of Effort:

1. **Consolidate U.S. Leadership:** Establish a U.S. Department of Space to centralize civil and commercial space governance, create an International Cislunar Infrastructure Bank (ICIB) to mobilize allied investment, and lead new global standard-setting organizations for cislunar operations.

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<sup>1</sup> ChatGPT, response to “Please create an executive summary for the attached group paper.” May 11, 2025, OpenAI, See Appendix D for additional information.

2. **Build and Secure Cislunar Infrastructure:** Invest in a domain awareness architecture, resilient communications and navigation systems, and in-space logistics platforms such as depots and reusable transport vehicles to anchor a durable American presence.
3. **Cultivate the Private-Sector Cislunar Economy:** Generate stable demand through long-term government contracts, pass a Space Resources Act to incentivize lunar extraction, expand innovation financing tools, and launch international innovation hubs to align global industry with U.S. standards.

The report also underscores the importance of educational wargaming and artificial intelligence in shaping future cislunar strategies, highlighting the need for scenario-driven learning and autonomous operational capabilities. The time to act is now. The cislunar domain will define the next era of strategic competition, and the United States must lead—or be led.

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CDR Steve Curtas, U.S. Navy  
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Col Laurel Walsh, U.S. Space Force  
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COL Jim Gifford, PhD, U.S. Army  
Co-Lead Space Industry Study

## In-Class Guest Speakers and Field Studies/Hosts

### *In-class Guest Speakers*

-Astrobotic -Besxar -Capella Space	-Carleton University -Cislunar Industries -Institute for National Strategic Studies	-Satellite Industry Association -Rocket Lab
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### *Washington, D.C. Metro Area Site Visits & Speakers*

-Department of Defense (Pentagon)  ○ DoD Leadership Panel ○ U.S. Space Force (USSF) S2 ○ Office of Net Assessment	-Department of State  -Iridium -Johns Hopkins Advanced Physics Laboratory -NASA Headquarters	-National Geospatial-Intelligence Agency (NGA) -Northrop Grumman -SES Space and Defense
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### *Florida Site Visits & Speakers*

-Airbus  -Blue Origin -Space Florida	-Space Launch Delta 45 (Patrick Space Force Base) -United Launch Alliance
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### *Colorado Site Visits & Speakers*

-Advanced Space -Astroscale -BAE Systems -BlueStaq -Buckley Space Force Base  ○ Space Base Delta 2 ○ Mission Delta 4 ○ Aerospace Data Facility -Colorado National Guard -Colorado School of Mines -Colorado Space Business Roundtable	-Lockheed Martin - Space -Lt. Gov. of Colorado -Orbital Mining Corporation -Sierra Space -Space Information Sharing & Analysis Center -Schriever Space Force Base ○ National Space Defense Center (NSDC) ○ NSDC-Joint Commercial Operations Cell ○ Delta 9 ○ Mission Delta 31 ○ Delta 8	-True Anomaly -USSPACECOM – Peterson SFB ○ USSC Chief of Staff ○ USSC J5 ○ USSC J8  ○ Space Operation CMD CDR ○ Space Warfighting Analysis Center
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### *Japan Site Visits & Speakers*

-Astroscale -Axelspace  -ispace -JPN Aerospace Exploration Agency (JAXA) -JAXA Tsukuba Space Center	-JPN Ministry of Defense -JPN National Space Policy Secretariat  -Mitsubishi Electric -Mitsubishi Heavy Industries  -Space BD	-Synspec -Toyota Museum of Industry & Technology -U.S. Embassy, Tokyo
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## Acronym List

AFRL	Air Force Research Lab
AI	artificial intelligence
API	application programming interface
APL	(Johns Hopkins) Applied Physics Laboratory
ASAT	anti-satellite
CLPS	(NASA's) Commercial Lunar Payload Services
COPUOS	(UN) Committee on the Peaceful Uses of Outer Space
DARPA	Defense Advanced Research Projects Agency
DLA	Defense Logistics Agency
DoC	U.S. Department of Commerce
DoD	U.S. Department of Defense
DRACO	Demonstration Rocket for Agile Cislunar Operations
E.O.	Executive Order
ESA	European Space Agency
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FFRDC	Federally Funded Research and Development Center
GDP	gross domestic product
GEO	geosynchronous Earth orbit
GNSS	global navigation satellite system
GPS	Global Positioning System
IC	Intelligence Community
ICAO	International Civil Aviation Organization
ICB	International Cislunar Bureau (notional)
ICIB	International Cislunar Infrastructure Bank (proposed)
ILRS	(China's) International Lunar Research Station
ISAM	in-space servicing, assembly, and manufacturing
ISR	intelligence, surveillance, and reconnaissance
ISRU	in-situ resource utilization
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunication Union
JAXA	Japan Aerospace Exploration Agency
JWST	James Webb Space Telescope
L1, L2	L1 and L2 Earth-Moon Lagrange points
LEO	low-Earth orbit
LLM	large language model
LOE	line of effort
ML	machine learning
MOU	memorandum of understanding
NASA	National Aeronautics and Space Administration
NDU	National Defense University
NGA	National Geospatial-Intelligence Agency
NRO	National Reconnaissance Office
NSDC	National Space Defense Center

NTP	nuclear thermal propulsion
OST	Outer Space Treaty
OSTP	Office of Science and Technology Policy
PESTL	political, economic, social, technological, and legal (factors)
PLA	People's Liberation Army
PNT	positioning, navigation, and timing
PRC	People's Republic of China
QZSS	(Japan's) Quasi-Zenith Satellite System
R&D	research and development
RL	reinforcement learning
SAP	special access program
SBIR	Small Business Innovation Research
SBSP	space-based solar power
SDA	space domain awareness
SLS	(NASA's) Space Launch System
SSA	space situational awareness
STRATFI	Strategic Funding Increase
STTR	Small Business Technology Transfer
TACFI	Tactical Funding Increase
UARC	university-affiliated research center
ULA	United Launch Alliance
USSC	United States Space Command
USSF	United States Space Force



## **Introduction**

Today, the United States stands at a strategic precipice: it must secure the emerging frontier between Earth and the Moon—the cislunar domain—or risk ceding this critical high ground to global competitors. Just as the transcontinental railroad linked a nation, the Panama Canal reshaped trade, and the Interstate Highway System propelled American power and prosperity, what may seem visionary now will soon define our national interests. These transformative achievements were never guaranteed; they resulted from deliberate strategy—built through steel, stone, and resolve—driven by foresight, bold investment, and a recognition that expansive, interconnected infrastructure shapes history. Cislunar space is the next strategic frontier—one that will determine not only the future of exploration, but the security, economic resilience, and global leadership of the United States.

A strong American presence in cislunar space – defined in U.S. code as beyond low Earth orbit (LEO) and encompassing the lunar surface<sup>2</sup> – should form the backbone of 21st-century U.S. influence: a region for economic vitality and freedom of movement, a strategic zone projecting deterrence, and a governance sphere strengthening allied ties. Beyond the U.S. Code, definitions vary across government, industry, and academia; this analysis uses the common industry definition: the space between geosynchronous Earth orbit (GEO) and the Moon. As China and Russia expand their presence across the Earth-Moon system, cislunar space becomes a contested domain – challenging global norms, economic advantage, and military capability. A U.S.-led cislunar architecture must connect allies, project deterrence, and preserve access and navigation.

Naval strategist Alfred Thayer Mahan argued that control of maritime commerce was foundational to national power and that investments in fleets and ports yielded lasting influence. As sea power defined great powers in the 19th and 20th centuries, space power will define the 21st century. As Mahan wrote in 1890, "unsettled political conditions ... when combined with great military or commercial importance... involve, now as always, dangerous germs of quarrel, against which it is at least prudent to be prepared."<sup>3</sup> The Earth-Moon system is becoming the new sea: a corridor for influence, deterrence, and commerce. And as with Mahan's vision of naval bases and coaling stations, the infrastructure America builds in cislunar space—depots, relays, and surveillance platforms—will determine whether it can sustain freedom of movement and global leadership in the decades ahead.

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<sup>2</sup> U.S. Code, Title 51, § 10101 (2025).  
<https://uscode.house.gov/view.xhtml?req=cislunar&f=treesort&fq=true&num=0&hl=true&edition=prelim&granuleId=USC-prelim-title51-section10101>. Accessed May 7, 2025.

<sup>3</sup> Alfred Thayer Mahan, "The United States Looking Outward," *Atlantic Monthly* 66 (December 1890): 816–24.  
<https://www.usmcu.edu/Portals/218/United%20States%20Looking%20Outward%2C%20Alfred%20Thayer%20Mahan.pdf>. Accessed May 7, 2025.

Landing on the Moon was not the end state – it was the opening chapter. Real, transformative American power comes not just from exploration, but from infrastructure that turns ambition into permanence. The transcontinental railway merged new frontiers into a national purpose. The Panama Canal reshaped global security. The interstate highway system enabled rapid military deployment and economic growth. Cislunar infrastructure must serve the same dual purpose: strategic resilience and economic opportunity. Time is limited. The decisions made today will shape 2055. China understands this. Its International Lunar Research Station (ILRS) and dual-use initiatives, which encompass both commercial and national security uses, aim to define the operational and legal environment to U.S. disadvantage.

Cislunar space is the new strategic high ground. Dominance here will determine who writes the rules for security, economy, and technology. This paper outlines a vision for U.S. leadership in cislunar space by 2055. It addresses key requirements: dual-use infrastructure, space domain awareness (SDA), resource access, governance, and innovation. These recommendations reflect an integrated view of national security imperatives and economic opportunity in cislunar space.

The FY26 President's Budget increases the Department of Defense (DoD) topline by \$113 billion<sup>4</sup> and explicitly prioritizes space-based national security, including investments in programs like the proposed "Golden Dome." Integrating cislunar space domain awareness (SDA) into Golden Dome would demonstrate strategic foresight—offering early warning of space-based threats beyond GEO, including long-loiter weapons, and tracking maneuvering foreign spacecraft that may pose dual-use risks.

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<sup>4</sup> Office of Management and Budget, Fiscal Year 2026 Discretionary Budget Request, May 2, 2025. <https://www.whitehouse.gov/wp-content/uploads/2025/05/Fiscal-Year-2026-Discretionary-Budget-Request.pdf>. Accessed May 7, 2025.

Meanwhile, private firms compete for government contracts amid inconsistent demand. Still, many invest heavily in space technologies, betting on the lunar economy's long-term returns. Without a unifying strategy, however, the United States and its allies will fall behind in the race to shape this new domain. As Mahan wrote, "Whether they will or no, Americans must now begin to look outward. The growing production of the country demands it."<sup>5</sup> Securing cislunar dominance by 2055 is not optional; it is imperative. The United States must act boldly, unify our allies and industries, and pave the way for a space domain rooted in American values – free, open, and prosperous for future generations.

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<sup>5</sup> Mahan, "The United States Looking Outward."

## Strategic Environment

General John W. Raymond, the first Chief of Space Operations, warned, "space superiority is a condition, not a permanent state. It must be gained and maintained through active measures."<sup>6</sup> Cislunar space is no longer a benign frontier and is emerging as a critical domain of strategic competition, economic opportunity, and national security concern. As such, U.S. leadership in cislunar space is a *sine qua non* to U.S. space superiority.

**Problem Statement.** Failure to assert sustained U.S. leadership in cislunar space—the strategic “high ground”—puts the United States at risk of forfeiting freedom of action in space and on Earth to the People’s Republic of China (PRC). Beijing’s lunar presence threatens to undermine U.S. security, ceding control of key Lagrange points and access to resources that will anchor future space logistics nodes and weakening emerging international norms embodied in the Artemis Accords.<sup>7</sup> Adversarial leadership in cislunar also puts at risk the terrestrial systems that rely on space capabilities to ensure America’s security, prosperity, and welfare.

The environment shaping U.S. interests in the cislunar domain is defined by several interrelated trends: the drivers of strategic competition, the threat environment, the opportunity environment, industry and innovation trends, and supply chain issues. Each of these trends exhibits the challenges to U.S. leadership in cislunar, including: (1) the growing lunar presence of U.S. adversaries, (2) competing U.S. priorities to secure existing space assets and support missile defense; (3) the current lack of a viable business model for lunar development; and (4) the increasing number of partner nations seeking an active role in the cislunar domain.

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<sup>6</sup> John W. Raymond, *Spacepower: Doctrine for Space Forces* (U.S. Space Force, 2020), 12.

<sup>7</sup> The Artemis Accords are a set of non-binding agreements between the United States and 53 foreign governments outlining principles for responsible and sustainable exploration of outer space, including the Moon and other celestial bodies. <sup>6</sup> NASA, “The Artemis Accords,” accessed May 6, 2025. <https://www.nasa.gov/artemis-accords/>.

## Strategic Drivers of Cislunar Competition

China views cislunar space as a strategic priority. The PRC's advantage is its civil-military fusion model which integrates commercial, academic, and defense sectors to accelerate innovation.<sup>8</sup> Civil-military fusion enables the People's Liberation Army (PLA) to leverage civilian advances for strategic gains in space, including cislunar. Through its International Lunar Research Station (ILRS) program, the PRC seeks not merely scientific advancement but strategic positioning. The ILRS aims to establish dual-use infrastructure projects at the Moon's south pole and in cislunar space by 2040, providing Beijing with control over lunar resources and key Earth-Moon transfer points.<sup>9, 10</sup> The PRC's goal is to achieve "comprehensive national power" superiority by mid-century, including dominance of space.<sup>11</sup>

### *Great Power Competition*

China treats space as an extension of terrestrial strategic competition. In 2024, the PRC reaffirmed the inclusion of cislunar development as part of its "civil-military fusion" doctrine, ensuring cislunar projects contribute to military advantage.<sup>12</sup> China's ILRS architecture—including resource extraction, communications, and intelligence, surveillance, and reconnaissance (ISR) platforms—could allow it to monitor, interfere with, or exclude rivals from key regions of cislunar space.<sup>13</sup> China's robust investment in dual-use technologies, such as autonomous servicing vehicles and advanced positioning, navigation, and timing (PNT) systems

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8 U.S. Department of State, *The Chinese Communist Party's Military-Civil Fusion Policy* (2020). <https://2017-2021.state.gov/military-civil-fusion/>.

9 "China Forges Ahead with Ambitious Plans for International Lunar Research Station," *New Space Economy*, accessed May 5, 2025. <https://newspaceconomy.ca/2024/09/16/china-forges-ahead-with-ambitious-plans-for-international-lunar-research-station/>.

10 *The Diplomat*, "China's Military-Civil Fusion Space Program," April 2024. <https://thediplomat.com/2024/04/chinas-military-civil-fusion-space-program/>.

11 U.S. Department of Defense, *Annual Report to Congress: Military and Security Developments Involving the People's Republic of China 2024* (Washington, DC: Office of the Secretary of Defense, 2024), 58–60.

12 *The Diplomat*, "China's Military-Civil Fusion Space Program."

13 U.S. Department of Defense, *Military and Security Developments Involving the PRC 2024*, 61–62.

for lunar operations, suggests preparation for contested scenarios. The PLA views the Earth-Moon system as a domain of decisive maneuver, where dominance could allow it to control access to critical terrestrial and orbital infrastructure.<sup>14</sup>

By honing advanced on-orbit maneuvering with satellites such as TJS-4, which slipped behind a U.S. surveillance craft in GEO to degrade its view, Beijing is rehearsing for control of cislunar space as the next strategic high ground.<sup>15</sup> The same propulsion, navigation, and proximity-operations techniques could allow Chinese spacecraft to shadow, refuel, or even neutralize U.S. assets from cislunar space, while staking out vantage points from which to monitor lunar traffic and defend infrastructure. China's GEO maneuvers are proof-of-concept demonstrations for holding and denying command of the cislunar domain. Strategic cislunar competition thus is more than symbolic milestones like lunar landings. It encompasses control of orbits, resources, and strategic positions that enable—or prevent—freedom of action.

### *Economic Competition*

Economic competition in space is focused on commercial satellite services in LEO and GEO, including new constellations like SpaceX's Starlink and Amazon's Project Kuiper. China also deploys mega-constellations, but its behavior poses significant economic and operational challenges. The country's Long March rockets often leave upper stages at altitudes around 800 km, which can persist in orbit for over a century, creating long-term risks to space infrastructure and collision hazards.<sup>16</sup> This self-interested behavior is a dangerous harbinger of how the PRC may act in cislunar space.

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<sup>14</sup> Ibid, 63–64.

<sup>15</sup> Clayton Swope et al., *Space Threat Assessment 2025* (Washington, DC: Center for Strategic and International Studies, Aerospace Security Project, April 2025), 6–8. TJS-4 is a classified Chinese geostationary satellite from the Tongxin Jishu Shiyao ("Communications Technology Experiment") series. TJS-4, launched in 2019, is believed to be a "Qianshao-3" signals-intelligence spacecraft that has already conducted notable proximity maneuvers in GEO.

<sup>16</sup> Ibid, 29–30.

The cislunar domain presents unprecedented commercial opportunities. Water ice deposits at the lunar poles can be processed for use as propellant for space operations.<sup>17</sup> Helium-3 offers the possibility of future fusion energy applications.<sup>18</sup> Rare earth elements on the Moon could provide an alternative source of minerals whose production China now dominates.<sup>19</sup> The Moon's lower gravity also presents a logistics advantage: it takes just one fifth the energy to launch an object into orbit from the Moon than from the Earth.<sup>20</sup> Control over cislunar resources and positions thus offers not just economic advantage, but enduring geostrategic leverage.

Private industry is starting to mobilize. Astrobotic, Intuitive Machines, and SpaceX are developing landers, cargo vehicles, and in-space servicing, assembly, and manufacturing (ISAM) platforms with dual-use applications for commercial and government customers.<sup>21</sup> However, the absence of explicit international norms for lunar resource rights poses risks. Without U.S.-led frameworks, commercial actors face legal uncertainty, deterring investment or driving firms to operate under more permissive or even adversarial regulatory regimes.<sup>22</sup> If the United States does not secure a first-mover advantage, adversaries could lock in dominant positions across the cislunar economy, undermining U.S. economic interests and autonomy.

### *Governance Gaps*

Existing space governance regimes—primarily the Outer Space Treaty (OST) of 1967

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17 Clayton Swope et al., *Space Threat Assessment 2025* (Washington, DC: Center for Strategic and International Studies, Aerospace Security Project, April 2025), 6–8.

18 Aaron D. S. Olson, “Lunar Helium-3: Mining Concepts, Extraction Research, and Potential ISRU Synergies,” November 3, 2021, 1. [https://ntrs.nasa.gov/api/citations/20210022801/downloads/AIAA%20ASCEND%202021%20Paper\\_211018.pdf](https://ntrs.nasa.gov/api/citations/20210022801/downloads/AIAA%20ASCEND%202021%20Paper_211018.pdf).

19 Peng Zhang et al., “Overview of the Lunar In Situ Resource Utilization Techniques for Future Lunar Missions,” *Space: Science & Technology* 3 (June 2023): 2. <https://doi.org/10.34133/space.0037>.

20 Julia Seibert, “Moon vs Mars Exploration: The Big Space Debate of 2025,” *Space Insider*, February 18, 2025. <https://spaceinsider.tech/2025/02/18/moon-vs-mars-exploration-the-big-space-debate-of-2025/>.

21 NASA, “Artemis Partners,” accessed April 30, 2025. <https://www.nasa.gov/artemis-partners/>; and NASA, “Commercial Lunar Payload Services,” June 15, 2023. <https://www.nasa.gov/reference/commercial-lunar-payload-services/>.

22 James E. Dunstan, “Who Wants to Step Up to a \$10 Billion Risk?” *SpaceNews*, June 25, 2021. <https://spacenews.com/op-ed-who-wants-to-step-up-to-a-10-billion-risk/>.

and related conventions—are ill-equipped to manage the realities of modern space operations. The OST touches on cislunar development by addressing non-appropriation, militarization, and international responsibilities. However its prohibition on sovereign territorial claims leaves critical ambiguities regarding the extraction and ownership of resources.<sup>23</sup> Such ambiguities might provide room for innovation to shape the regulatory environment as new capabilities emerge.<sup>24</sup> Efforts to clarify these issues, including via the Artemis Accords, have attracted a growing coalition but face opposition from China and Russia.<sup>25</sup> An updated OST could clarify conditions and promote emerging technologies and space commerce, but would require time-consuming negotiations and compromises, and may create new obstacles to cislunar development.

In cislunar space, where orbital dynamics differ significantly from Earth orbits, the lack of standard practices for space traffic management—collision avoidance, servicing, or debris mitigation—creates heightened risks of miscalculation, accident, or interference.<sup>26</sup> China and Russia have signaled their willingness to operate outside global norms, rejecting the U.S.-led Artemis Accords and pursuing parallel governance architectures through the ILRS.<sup>27</sup> Absent U.S. leadership, the cislunar environment risks becoming a fragmented and contested domain, dominated by rules set by authoritarian powers.

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<sup>23</sup> *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”), 1967.

<sup>24</sup> George Nield, “Op-Ed: FAA Overregulation Threatens America’s Future in Commercial Space,” *SpaceNews*, March 28, 2024. <https://spacenews.com/op-ed-faa-overregulation-threatens-americas-future-in-commercial-space/>.

<sup>25</sup> National Science and Technology Council, *National Cislunar Science & Technology Action Plan* (Washington, DC: Executive Office of the President, December 2024), 20.

<sup>26</sup> Mir Sadat and Julia Siegel, *Space Traffic Management: Time for Action* (Washington, DC: Atlantic Council, Forward Defense Issue Brief, August 2, 2022). <https://www.atlanticcouncil.org/in-depth-research-reports/issue-brief/space-traffic-management-time-for-action/>. Accessed April 30, 2025.

<sup>27</sup> National Science and Technology Council, *National Cislunar Science & Technology Action Plan* (Washington, DC: Executive Office of the President, December 2024).

## Threat Environment

The cislunar domain is steadily becoming a new strategic high ground. Beijing's ILRS signals China's ambition to shape infrastructure and operating norms around the Moon.<sup>28</sup> The PRC is field-testing the comprehensive logistics framework required for sustained presence: fluid-transfer demonstrations, robotic tug operations, and sample-return missions intended to scout and exploit lunar ice deposits.<sup>29, 30, 31</sup> These dual-use technologies could help refuel a friendly spacecraft or disable an adversarial one. China frames the U.S.-led Artemis Accords as exclusionary, using diplomatic pressure to steer undecided states toward ILRS.<sup>32, 33</sup> Table 1 shows how China and other U.S. adversaries field a wide range of counterspace weapons, eroding long-standing norms and any illusion of a permissive space environment.

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28 Alexander S. Ermakov, "The Sino-American Battle for the Moon," *Primakov National Research Institute of World Economy and International Relations* 23, no. 1 (January–March 2025): 203.

29 Alexander S. Ermakov, "The Sino-American Battle for the Moon," *Primakov National Research Institute of World Economy and International Relations* 23, no. 1 (January–March 2025): 203

30 Kristin Burke, China's SJ-21 Framed as Demonstrating Growing On-Orbit Servicing, Assembly, and Manufacturing (OSAM) Capabilities (Maxwell AFB, AL: USAF China Aerospace Studies Institute, December 9, 2021), 1–2. <https://www.airuniversity.af.edu/Portals/10/CASI/documents/Research/Space/2021-12-09%20SJ-21%20and%20China%27s%20OSAM%20Capabilities.pdf>.

31 Kristin Burke, PLA On-Orbit Satellite Logistics (China Aerospace Studies Institute, 2024), 1–6. <https://www.airuniversity.af.edu/Portals/10/CASI/documents/Research/Space/2024-03-18%20PLA%20On-Orbit%20Satellite%20Logistics.pdf>.

32 "China Forges Ahead with Ambitious Plans for International Lunar Research Station," *New Space Economy*, accessed April 30, 2025. <https://newspaceconomy.ca/2024/09/16/china-forges-ahead-with-ambitious-plans-for-international-lunar-research-station/>.

33 Andrew Jones, "Egypt Joins China's ILRS Moon Base Initiative," *SpaceNews*, December 7, 2023. <https://spacenews.com/egypt-joins-chinas-ilrs-moon-base-initiative/>. China leverages the ILRS "global partnership" to increase its technical knowledge in areas where it is not the leader, such as Russian nuclear space technology. Similarly, China understands that creating a cislunar infrastructure requires long-term patient capital and is willing to let other nations invest. This initiative is unlike its BRI, where international infrastructure investment increases jobs and manufacturing for Chinese citizens.

## COUNTERSPACE WEAPONS OF CHINA, RUSSIA, IRAN, AND NORTH KOREA AS OF MARCH 2025

	Kinetic Weapons			Non-Kinetic Weapons		Electronic Weapons		Cyber Operations
	Terrestrial Infrastructure Attack	Direct-Ascent ASAT	Orbital ASAT	Nuclear Detonation	Directed Energy	Jamming	Spoofing	
China	Yes	Yes	Maybe	Yes	Yes	Yes	Yes	Yes
Russia	Yes	Yes	Probably	Yes	Yes	Yes	Yes	Yes
Iran	Yes	No	No	No	No	Yes	Yes	Yes
North Korea	Yes	No	No	Yes	No	Yes	Yes	Yes

CSIS AEROSPACE SECURITY PROJECT RESEARCH AND ANALYSIS

**Table 1:** Counterspace Capabilities of U.S. Adversaries<sup>34</sup>

Russia also possesses a potent space toolkit. Table 2 shows that Beijing *and* Moscow are deploying a full spectrum of cislunar infrastructure, maneuver, and counterspace systems—positioning them to dominate resources, disrupt U.S. space domain awareness, and coerce allied spacecraft. Through ILRS, Moscow has leveraged its experience in rendezvous, docking, and nuclear propulsion to gain a stake in any future lunar base camp. Russian spacecraft show a willingness to conduct risky proximity maneuvers in GEO, and a proposed nuclear-electric tug could reposition heavy payloads—or weapons—anywhere in cislunar space. Moscow's anti-satellite (ASAT) tests and plasma-rocket prototypes keep pressure on the United States and allow a Sino-Russian coalition to contest freedom of maneuver in cislunar orbits.<sup>35</sup> A coherent U.S. cislunar strategy must treat China's integrated civil–military build-out and Russia's counterspace portfolio as a combined, layered challenge that leverages legal gray zones and proximity operations to impose costs on U.S. freedom of action around the Moon.

<sup>34</sup> Clayton Swope et al., *Space Threat Assessment 2025* (Washington, DC: Center for Strategic and International Studies, Aerospace Security Project, April 2025).

<sup>35</sup> “Mars in 30 Days: Russia Unveils Prototype of Plasma Rocket Engine,” *World Nuclear News*, March 1, 2024. <https://www.world-nuclear-news.org/articles/mars-in-30-days-russia-unveils-prototype-of-plasma-rocket-engine>.

Capability Area	People’s Republic of China	Russian Federation	Strategic Impact on U.S./Allies
<b>Lunar Infrastructure</b>	ILRS (Shackleton Crater, 2030s); Chang’e 7/8 precursor landers; plans for nuclear surface power. <sup>36</sup>	ILRS co-partner; Luna 25–27 landers (renewed after Luna 25 crash). <sup>37</sup>	Creates de facto control of water-ice regions; potential exclusion of rival landers <sup>38</sup>
<b>Proximity &amp; Tug Operations</b>	Shijian-21 removed defunct GEO satellite (2022); Tianyuan-1 on-orbit fluid transfer. <sup>39</sup>	Luch/Olymp 2 and Cosmos 2576 GEO shadowing; history of “nesting-doll” satellites. <sup>40</sup>	Enables refuel/repair—or hostile grappling—of U.S./commercial assets.
<b>Logistics &amp; Propulsion</b>	Tested green-propellant refueling; planning reusable lunar ferry stages derived from LM-10. <sup>41</sup>	Prototype 1-MW “Zeus” nuclear-electric tug (payload relocation across cislunar). <sup>42</sup>	Greater maneuver reach, complicating space domain awareness (SDA).
<b>Counterspace Weapons</b>	Co-orbital inspector sats; 2015 DN-3 direct-ascent ASAT; doctrinal writings on cislunar denial. <sup>43, 44</sup>	2021 direct-ascent ASAT test created >1,500 LEO debris; plasma rocket R&D aimed at fast-intercept. <sup>45</sup>	Heightened threat of kinetic or non-kinetic attacks beyond GEO.
<b>Norms &amp; Diplomacy</b>	Rejects Artemis Accords; promotes UN COPUOS consensus; aligns Belt & Road partners via ILRS MOU. <sup>46</sup>	Supports Chinese stance; leverages UN veto; portrays U.S. export rules as “containment.”	Seeks rule-sets that slow commercial growth and justify gray-zone maneuvers.

**Table 2:** Impact of Adversarial Cislunar Capabilities on the United States and Allies

### *Normative Erosion*

Some commercial space firms are beginning to circumvent national regulations. U.S.-

36 Eduardo Baptista, “China, Russia May Build Nuclear Plant on Moon to Power Lunar Station, Official Says,” *Reuters*, April 23, 2025. <https://www.reuters.com/business/energy/china-led-lunar-base-include-nuclear-power-plant-moons-surface-space-official-2025-04-23/>. Accessed April 30, 2025.

37 Ibid.

38 Alexander S. Ermakov, “The Sino-American Battle for the Moon,” *Primakov National Research Institute of World Economy and International Relations* 23, no. 1 (January–March 2025): 203.

39 Kristin Burke, China’s SJ-21 Framed as Demonstrating Growing On-Orbit Servicing, Assembly, and Manufacturing (OSAM) Capabilities (Maxwell AFB, AL: USAF China Aerospace Studies Institute, December 9, 2021), 1–2. <https://www.airuniversity.af.edu/Portals/10/CASI/documents/Research/Space/2021-12-09%20SJ-21%20and%20China%27s%20OSAM%20Capabilities.pdf>; Kristin Burke, PLA On-Orbit Satellite Logistics (China Aerospace Studies Institute, 2024), 1–6.

<https://www.airuniversity.af.edu/Portals/10/CASI/documents/Research/Space/2024-03-18%20PLA%20On-Orbit%20Satellite%20Logistics.pdf>.

40 Swope et al., *Space Threat Assessment* 2025, 10–11.

41 Zhao Lei, “In-orbit Refueling Test Proves a Success,” *China Daily*, July 4, 2016. [https://english.www.gov.cn/news/top\\_news/2016/07/04/content\\_281475385733686.htm](https://english.www.gov.cn/news/top_news/2016/07/04/content_281475385733686.htm). Accessed April 30, 2025.

42 Swope et al., *Space Threat Assessment* 2025, 10–11.

43 Zhao Lei, “In-orbit Refueling Test Proves a Success.”

44 Andrew Jones, “China Outlines Pathway for Lunar and Deep Space Exploration,” *SpaceNews*, November 28, 2022. <https://spacenews.com/china-outlines-pathway-for-lunar-and-deep-space-exploration/>. Accessed April 30, 2025.

45 Swope et al., *Space Threat Assessment* 2025, 10–11.

46 Ermakov, “The Sino-American Battle for the Moon,” 203.

based E-Space and AST SpaceMobile filed their satellite applications in Rwanda and Papua New Guinea.<sup>47</sup> This regulatory forum shopping may enable faster approvals, but undermines accountability and transparency, eroding efforts to promote sustainable and responsible behavior in orbit. In cislunar space, companies might pursue resource extraction or infrastructure placement outside U.S. authority or Artemis Accord principles.<sup>48</sup> This could result in fragmented oversight, weakened enforcement, and heightened diplomatic tensions.

Adversarial states could exploit loopholes by using proxy firms to pursue strategic objectives under the guise of commercial activity. PRC and Russian actors might use legal ambiguity to justify de facto appropriation, coercive presence, or denial of access. China is a vocal critic of U.S. space activities, accusing Washington of double standards concerning satellite proximity operations and working to dilute consensus around Western-led space norms.<sup>49</sup> The PRC's strategy seeks to reshape the cislunar legal and diplomatic terrain, weakening the foundation of responsible space conduct.

### *Environmental and Operational Risks*

Cislunar space presents operational complexities that elevate strategic risk, particularly near the Earth–Moon Lagrange Points, where gravitational dynamics are nonlinear and orbital stability is fragile. Slight deviations in trajectory can result in cascading collisions or mission failure.<sup>50</sup> These unstable conditions differ from more predictable Earth orbits and require advanced planning and precision maneuvering.

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<sup>47</sup> Matt Daneman, "E-Space's Rwandan Roots Seen Evading Regulation," *Communications Daily*, Mar. 2, 2022.

<sup>48</sup> Swope et al., *Space Threat Assessment 2025*.

<sup>49</sup> *Ibid.*

<sup>50</sup> Michael J. Holzinger, Charles C. Chow, and Peter Garretson, *A Primer on Cislunar Space* (Kirtland AFB, NM: Air Force Research Laboratory, Space Vehicles Directorate, May 3, 2021), 10–11. [https://www.afrl.af.mil/Portals/90/Documents/RV/A%20Primer%20on%20Cislunar%20Space\\_Dist%20A\\_PA2021-1271.pdf](https://www.afrl.af.mil/Portals/90/Documents/RV/A%20Primer%20on%20Cislunar%20Space_Dist%20A_PA2021-1271.pdf).

Absent coordinated traffic management, the growth of cislunar missions increases the likelihood of collisions, debris generation, and disruption of space-based services.<sup>51</sup> This is exacerbated by the lack of persistent SDA architecture beyond GEO.<sup>52</sup> Without robust cislunar tracking systems, adversaries could exploit detection gaps to reposition assets, conduct surveillance, or interfere with U.S. space infrastructure undetected, posing serious gray zone threats. The recent breakup and explosion of Russian and Chinese satellites in Earth orbits highlight the growing debris hazard and the challenge of delayed tracking and cataloging.<sup>53</sup> In cislunar space, these risks could create serious operational instability. Without timely investment in cislunar space domain awareness (SDA) and regulatory coordination, adversarial cislunar activity could undermine safety, stability, and strategic predictability.

### Opportunity Environment

The cislunar environment also offers opportunities to expand U.S. commercial presence and define the norms for a cislunar economy projected to exceed \$100 billion annually by the 2040s.<sup>54</sup> Space industry representatives stress the importance of early-stage government investment as a catalyst to develop cislunar business. By securing the first-mover advantage in cislunar commerce, the United States can lead the emerging cislunar economic order.

### *Infrastructure First-Mover Advantage*

A cislunar infrastructure network might include communications relays, navigation

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51 Clayton Swope et al., *Space Threat Assessment 2025* (Washington, DC: Center for Strategic and International Studies, Aerospace Security Project, April 2025), 22–23.

52 U.S. Space Force, *Space Force Doctrine Document 1*, April 4, 2025, 23. [https://www.starcom.spaceforce.mil/Portals/2/Space%20Force%20Doctrine%20Document%201%20FINAL\\_4Apr25.pdf](https://www.starcom.spaceforce.mil/Portals/2/Space%20Force%20Doctrine%20Document%201%20FINAL_4Apr25.pdf).

53 Swope et al., *Space Threat Assessment 2025*.

54 Deloitte, “Exploring the Future of Space: The Lunar Economy Takes Shape,” *Deloitte Insights*, April 2023. <https://www2.deloitte.com/insights/us/en/industry/public-sector/lunar-economy.html>.

systems, refueling depots, and ISAM platforms to sustain operations beyond GEO.<sup>55</sup> Building this infrastructure before rivals do offers logistical, economic, and security advantages. A U.S.-led logistics network, with propellant depots, could reduce mission costs and extend the reach of government and commercial actors. Control over the Lagrange Points L1 and L2 – much like the Panama or Suez canals a century earlier – would allow the United States to both facilitate and regulate transit to and from the lunar surface.<sup>56</sup>

Early establishment of cislunar PNT systems would reinforce operational freedom, support precision operations, and deny adversaries an easy path to disrupt navigation.<sup>57</sup> The Global Positioning System (GPS) was initially a defense technology, later adopted for commerce and now essential to life on earth. Cislunar PNT could have a similar transformative impact. By investing in dual-use infrastructure, the U.S. can entrench itself as the enabler of cislunar operations, incentivizing allies and even competitors to use U.S.-operated and controlled systems.

### *Industrial Leadership and Economic Expansion*

The economic value of cislunar space will accelerate as technology matures. Research suggests lunar water ice mining, ISAM capabilities, cislunar transportation, and microgravity manufacturing could drive a multibillion-dollar cislunar economy.<sup>58</sup> Companies capable of servicing, assembling, and extending the lifespan of space assets will create new value chains in

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55 Henry Swope, *Swimming Upstream: Aligning Commercial Space Launch Regulation with National Objectives* (Center for Strategic and International Studies, October 21, 2024), 32. [https://aerospace.csis.org/wp-content/uploads/2024/10/241021\\_Swope\\_Swimming\\_Upstream\\_0-compressed.pdf](https://aerospace.csis.org/wp-content/uploads/2024/10/241021_Swope_Swimming_Upstream_0-compressed.pdf).

56 National Space Society, “An Integrated Cislunar Space Transportation and Logistics System,” accessed April 30, 2025. <https://nss.org/space-settlement-roadmap-14-cislunar-infrastructure/>.

57 Executive Office of the President, “National Cislunar Science & Technology Action Plan,” 2024, 11–12. <https://bidenwhitehouse.archives.gov/wp-content/uploads/2024/12/Cislunar-Implementation-Plan-Final.pdf>.

58 Luigi Scatteia and Yann Perrot, “Lunar Market Assessment 2021: Market Trends and Challenges in the Development of a Lunar Economy,” PwC, 33. Accessed April 30, 2025. <https://www.pwc.com.au/industry/space-industry/lunar-market-assessment-2021.pdf>.

cislunar space.<sup>59</sup> The United States, through public-private partnerships and models like NASA’s Commercial Lunar Payload Services (CLPS), can stimulate these sectors and establish U.S. firms as leaders.<sup>60</sup> A dynamic industrial base will advance economic interests and reinforce strategic resilience by ensuring critical space capabilities are sourced from secure supply chains. U.S. competitiveness in the cislunar domain can be a pillar of America’s future prosperity.

### *Norms and Governance Leadership*

The most durable opportunity lies in defining the norms and rules governing cislunar activities. By expanding the Artemis Accords and embedding principles of transparency, sustainability, and non-interference into multilateral agreements, the United States can shape expectations for behavior in cislunar space, reducing the risk of conflict and fostering a stable operating environment.<sup>61</sup> Internationally recognized best practices—responsible resource extraction, registration of space objects, debris mitigation, and servicing standards—can be advanced through U.S. leadership at forums like the UN Committee on the Peaceful Uses of Outer Space (COPUOS) and agreements with allies.<sup>62</sup>

If U.S.-led norms are perceived as hegemonic, foreign states may reject models like the Artemis Accords. This could fragment international consensus, accelerate parallel rulemaking by China or Russia, and lead to competing legal regimes that undermine cislunar governance. A U.S. effort to update the OST would demonstrate a U.S. commitment to a balanced, multilateral, rules-based order for cislunar space. If adversaries oppose such an initiative, the United States

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<sup>59</sup> Markets and Markets Research, “On-Orbit Satellite Servicing Market Size, Share & Growth 2030,” MarketsandMarkets, accessed April 18, 2025. <https://www.marketsandmarkets.com/Market-Reports/on-orbit-satellite-servicing-market-206789424.html>.

<sup>60</sup> NASA, “Commercial Lunar Payload Services,” June 15, 2023. <https://www.nasa.gov/reference/commercial-lunar-payload-services/>.

<sup>61</sup> National Science and Technology Council, National Cislunar Science & Technology Action Plan (Washington, DC: Executive Office of the President), December 2024, 3–7.

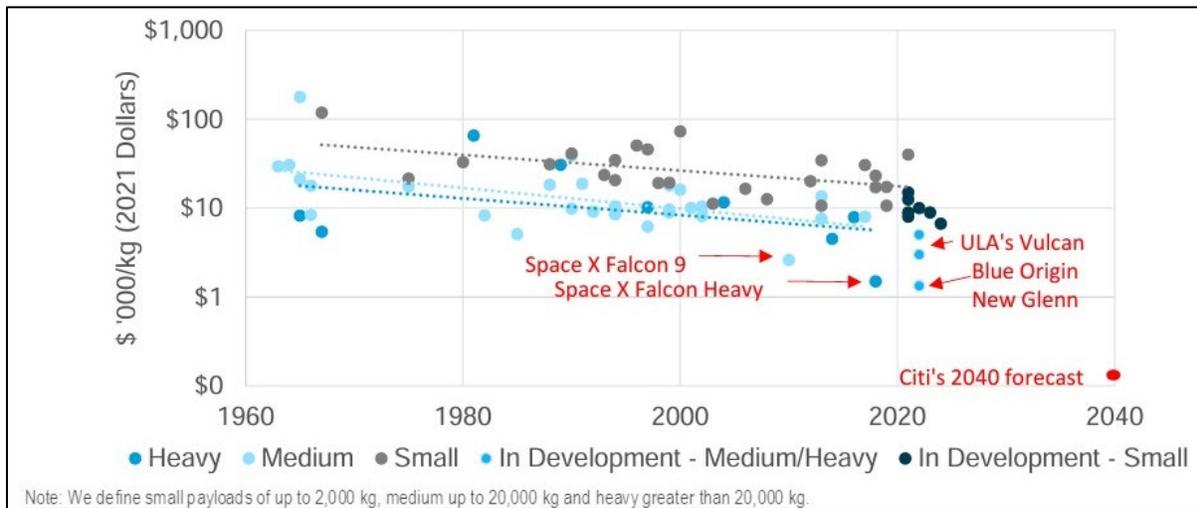
<sup>62</sup> National Science and Technology Council, National Cislunar Science & Technology Strategy (Washington, DC: Executive Office of the President), November 2022, 6–9.

can then consider a plurilateral approach with the most cooperative space-faring partners. Robust legal and regulatory structures aligned with international law will provide industry with the certainty to invest in cislunar development.

### Industry and Innovation Trends

#### Launch

The United States dominates the global launch market and sets the price of access to orbit. Figure 1 shows how launch costs have dropped more than 90 percent since the 1960s, a decline driven by SpaceX’s reusable rocket breakthroughs and the diffusion of new composite materials and additive manufacturing. New Blue Origin and Rocket Lab platforms promise to widen access further. Together, these trends position the United States to retain leadership in an increasingly contested and congested space domain and promise greater access to cislunar space. Rising demand to put mega-constellations into LEO is also driving dramatic increases in launch capacity, which will grow from 2 kilotons in 2024 to up to 40 kilotons by 2030.<sup>63</sup>



**Figure 1: Launch Costs to Low-Earth Orbit (\$1,000s/kg, 2021 inflation adjusted dollars)<sup>64</sup>**

63 Chris Daehnick, John Gang, and Ilan Rozenkopf, “Space Launch: Are We Heading for Oversupply or a Shortfall?” McKinsey & Company, April 2023, 6. <https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/space-launch-are-we-heading-for-oversupply-or-a-shortfall>.

64 Citi Global Perspectives & Solutions (Citi GPS), Space: The Dawn of a New Age (New York: Citigroup, May 9, 2022), fig. 1. [https://icg.citi.com/icghome/what-we-think/citigps/insights/space\\_20220509](https://icg.citi.com/icghome/what-we-think/citigps/insights/space_20220509). Accessed May 6, 2025.

## *Satellite Manufacturing*

U.S. satellite production follows a dual-track model shaped by defense priorities. Over 90 percent of payloads and two-thirds of bus production serve DoD missions.<sup>65</sup> Legacy prime contractors like Lockheed Martin and Northrop Grumman deliver long-life, radiation-hardened satellites for SDA and missile warning. New venture firms such as Planet and Terran Orbital mass-produce small satellites in rapid, six-week cycles, and SpaceX Starlink and Amazon Kuiper are deploying mega-constellations in LEO. These proliferated constellations have transformed the satellite industry. This shift to low-cost satellite production allows for rapid and distributed deployments, such as the U.S. Space Force’s Proliferated Warfighter Architecture, which seeks to outpace adversarial ASAT countermeasures.

## *In-Space Servicing, Assembly, and Manufacturing (ISAM)*

ISAM is key to resilience in cislunar space, where hardware must be refueled, repaired, reconfigured, or even manufactured in situ. New propellant depots and satellites can be assembled from modular components rather than launched as monolithic payloads. ISAM can shorten resupply timelines, slash launch needs, and enable a self-sustaining industrial cycle to exploit lunar resources for construction feedstock, propellant, and spare parts.<sup>66</sup> ISAM demonstrations have shown their potential. Northrop Grumman’s MEV-2 performed a life-extension docking to an Intelsat satellite in GEO in 2020.<sup>67</sup> In 2027, Astroscale’s LEXI servicer will combine magnetic-capture plates with Orbit Fab’s RAFTI refueling port—an open standard

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65 Evan Jozkowski, “Performance - 33641B Space Vehicle & Missile Manufacturing in the US,” IBISWorld. <https://my-ibisworld-com.nduezproxy.idm.oclc.org/us/en/industry/33641b/performance>.

66 NASA, *ISAM State of Play 2023: In Space Servicing, Assembly, and Manufacturing Report* (Washington, DC: NASA, October 2023), 8–10.

67 Dale Arney et al., *In-Space Servicing, Assembly, and Manufacturing (ISAM) State of Play: 2023 Edition*, NASA Langley Research Center, October 2023, 14–16. <https://www.nasa.gov/wp-content/uploads/2023/10/isam-state-of-play-2023.pdf>.

used on eight DoD and NASA buses.<sup>68</sup> DARPA’s NOM4D program seeks to demonstrate assembly processes in space.<sup>69</sup> By being the first to deploy and field-test hardware and interfaces, these pioneers can set de facto standards and reap the economic benefits of a developing cislunar architecture.

### *Energy Systems*

Today’s space energy systems will require advances and adaptations to power missions in cislunar space. On the Moon, power systems must survive 14 days of continuous sunlight followed by an equally long night, endure surface temperatures ranging from +120 °C to –130 °C, and operate in permanently shadowed craters. Space-based solar power (SBSP) could remain in near-constant light and beam power to the Moon’s surface. In 2023, Caltech beamed a tiny amount of space-collected solar energy to the Earth using microwaves. Aetherflux is planning an SBSP demonstration in 2026 using infrared lasers, while Space Solar hopes to realize a large 30-megawatt (MW) SBSP demo in Iceland by 2030. Advances in small modular reactors suggest that nuclear energy can power cislunar activities. NASA and the Department of Energy are working to develop a Moon-based nuclear power system that could provide 40 kilowatts (kW) of power, enough to power a small lunar station for 10 years. A solicitation is planned in 2025 to launch a demonstration lunar reactor in the early 2030s.<sup>70</sup>

### *Propulsion Systems*

Evidence of ice on the Moon and methane on Mars offers the potential to manufacture

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68 SatNews, “Astroscale U.S. + Orbit Fab Sign the First On-Orbit Satellite Fuel Sale Agreement,” April 13, 2022. <https://news.satnews.com/2022/04/13/astroscale-u-s-orbit-fab-sign-the-first-on-orbit-satellite-fuel-sale-agreement/>; Douglas Gorman, “Astroscale, Orbit Fab Pair to Gas Up DoD,” Payload, April 9, 2025. <https://payloadspace.com/astroscale-orbit-fab-team-up-on-first-in-space-refueling-flight/>.

69 Defense Advanced Research Projects Agency, “DARPA Demos Will Test Novel Tech for Building Future Large Structures in Space,” February 10, 2025. <https://www.darpa.mil/news/2025/novel-tech-space-structures>.

70 NASA, “Fission Surface Power,” accessed April 30, 2025. <https://www.nasa.gov/space-technology-mission-directorate/tdm/fission-surface-power/>.

propellants in space. These require cryogenic environments to keep them in liquid form and face transportation challenges. Nuclear thermal propulsion (NTP) provides thrust levels comparable to chemical rockets but is two to five times more efficient, enabling multiple movements within cislunar space. In 2023, Lockheed Martin and BWX Technologies were awarded contracts under a DARPA and NASA program – Demonstration Rocket for Agile Cislunar Operations (DRACO) – to build an NTP system for a demonstration by 2027.<sup>71</sup> NTP could provide maneuver advantages to defend space assets in cislunar and Earth orbits.<sup>72</sup>

### Supply-Chain Issues and Factor Conditions

Cislunar space activity is currently focused on scientific and exploratory missions, rather than commercial applications. One can examine the supply chain issues affecting today’s space industry to gain insight into future cislunar supply chains.

The opening of federal facilities to commercial launch firms helped make the United States the world's premier launch country. Figure 2 shows the order of magnitude growth in U.S. commercial launches over the past decade, after stagnating for 30 years. U.S. government facilities, however, struggle to keep up with the growing volume of launches and required maintenance or capital improvements. SpaceX and Rocket Lab have opened private launch facilities to increase capacity.<sup>73</sup> Another constraint is the availability of payload processing facilities, including those for processing national security payloads. Rocket Lab built a dedicated integration facility at its Wallops Island launch facility, but smaller firms may find such

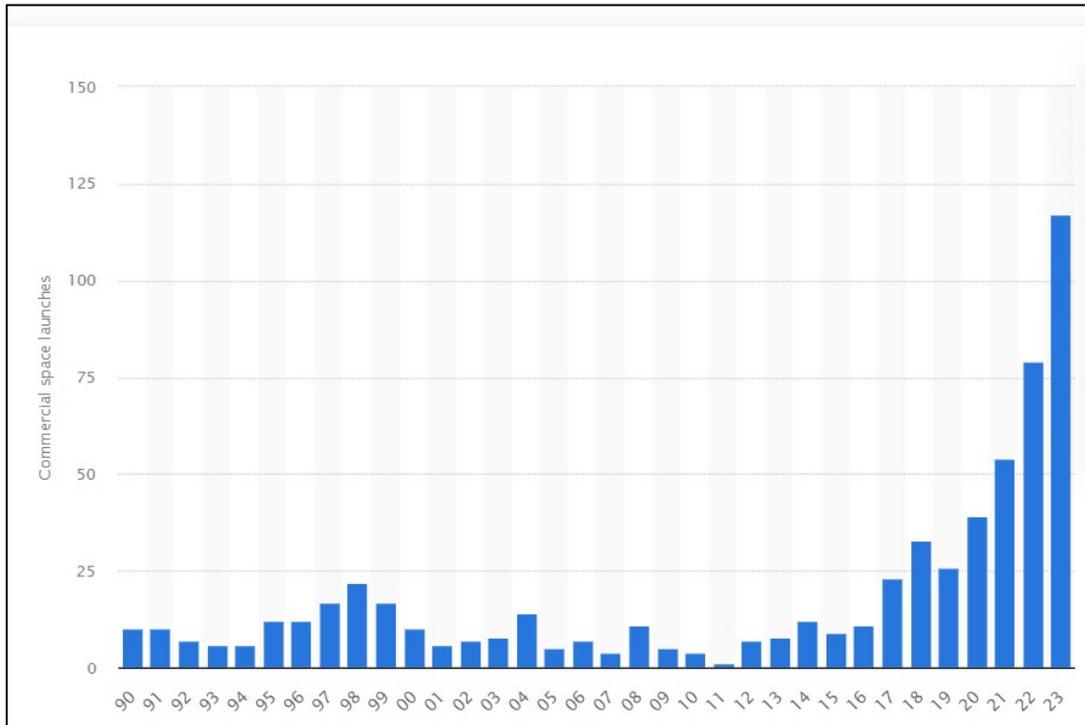
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71 Bill Emrich, “Promises and Challenges of Nuclear Propulsion for Space Travel,” International Atomic Energy Agency, February 21, 2022. [https://nucleus.iaea.org/sites/fusionportal/Atoms%20for%20Space/04\\_Emrich%20Promises%20and%20Challenges%20of%20Nuclear%20Propulsion%20for%20Space%20Travel.pdf](https://nucleus.iaea.org/sites/fusionportal/Atoms%20for%20Space/04_Emrich%20Promises%20and%20Challenges%20of%20Nuclear%20Propulsion%20for%20Space%20Travel.pdf).

72 Chris Young, “New Nuclear Fuel Withstands 4220 deg F Heat, Will Fly Rockets to Mars in Just 45 Days,” Interesting Engineering, January 21, 2025. <https://interestingengineering.com/innovation/nuclear-fuel-power-rockets-to-mars>.

73 BryceTech, "Orbital and Suborbital Launch Sites of the World 2025," revised April 18, 2025. <https://brycetek.com/reports>.

investments challenging.<sup>74</sup>



**Figure 2:** U.S. Commercial Space Launches from 1990 to 2023<sup>75</sup>

As satellite manufacturers move to volume production, firms use more off-the-shelf components and fewer customized parts, reducing costs and increasing supplier diversity. Key technical components, however, still face bottlenecks. Some firms have sought vertical integration to overcome shortages of traveling-wave-tube amplifiers, star trackers, and reaction wheels.<sup>76</sup> Rocket Lab purchased Sinclair Interplanetary in 2020 to secure a steady flow of reaction wheels and star trackers, while Sierra Space acquired SpaceDev for the firm’s spacecraft

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74 Rocket Lab USA, Inc., Annual Report - U.S. Securities and Exchange Commission Form 10-K for Fiscal Year Ended December 31, 2024, February 27, 2025, 12. <https://d18rn0p25nwr6d.cloudfront.net/CIK-0001819994/c5d1fba9-6e22-42ae-8e23-a15229a11f4d.pdf>.

75 Statista, “U.S. Commercial Space Launches from 1990 to 2023,” 2025. Accessed May 7, 2025. <https://www.statista.com/statistics/185464/total-us-commercial-space-launches-since-1990/>.

76 Traveling-wave-tube amplifiers are specialized vacuum tubes that amplify radio frequency signals and are essential for many communications satellites. Star trackers are optical sensors that measure the position of stars using a camera and can assist navigation. Reaction wheels help control a satellite’s three-axis attitude, adjusting orientation without requiring the use of propellant.

subsystems.<sup>77, 78</sup> Some analysts recommend space firms modify supply chain management by rebalancing power between engineering and other functions, increasing supply chain transparency, and establishing criteria on which components to outsource.<sup>79</sup>

Compliance with the U.S. International Traffic in Arms Regulations (ITAR) presents a regulatory burden, particularly for the small, innovative space firms. U.S. reciprocal tariff proposals could hinder trade that might otherwise favor U.S. suppliers. Trade distortions caused by tariffs could lead to shortages, disrupting production. Other key supply conditions include the availability of a trained workforce and financing for the cislunar space industry.

### Summary

Given the evolving dynamics of the cislunar space domain—defined by intensifying strategic competition, emerging economic opportunities, and fragile governance—the United States must act decisively. Achieving enduring U.S. leadership in cislunar space will require more than infrastructure or doctrine alone. It demands a coordinated effort across government, industry, allies, and partners. Understanding each stakeholder's interests and capabilities is essential to crafting an effective national strategy.

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<sup>77</sup> Rocket Lab USA, Inc., "Rocket Lab Closes Acquisition of Satellite Hardware Manufacturer Sinclair Interplanetary," news release, April 30, 2020. <https://www.rocketlabusa.com/updates/rocket-lab-closes-acquisition-of-satellite-hardware-manufacturer-sinclair-interplanetary/>. Accessed May 6, 2025.

<sup>78</sup> Michael Fabey, "Sierra Nevada Corp. Acquires SpaceDev Inc.," *Military & Aerospace Electronics*, January 17, 2009. <https://www.militaryaerospace.com/defense-executive/article/16720962/sierra-nevada-corp-acquires-spacedev-inc>. Accessed May 6, 2025.

<sup>79</sup> Stephen Ganote et al., "Fixing the Space Supply Chain Requires Elevating Its Role," Oliver Wyman, accessed May 2, 2025. <https://www.oliverwyman.com/our-expertise/insights/2024/may/space-industry-supply-chain-solutions.html>.

## Stakeholder Interests

Cislunar space is a focal point for a diverse array of stakeholders seeking to extend human capabilities beyond Earth orbit. At the center is the U.S.-led Artemis Program, which operates within an integrated "triple helix" framework where government funding supports academic research, driving innovations that industry can commercialize.<sup>80</sup> This collaborative ecosystem spans government agencies, technology companies, and research institutions, each contributing distinct capabilities and perspectives. The coordinated efforts of U.S. entities, complemented by international partnerships, are establishing the foundation for sustainable operations in the Earth-Moon system, creating new opportunities for scientific advancement, economic opportunity, and strategic positioning in the coming decades.

### U.S. Government

The U.S. government plays a foundational role in the cislunar domain, acting as regulator, investor, security guarantor, and anchor customer. Although the Department of Defense (DoD), the Intelligence Community (IC), NASA, and the Department of Commerce (DoC) approach space from different angles, each carries distinct yet overlapping equities that shape the nation's space enterprise.

A common framework guides this institutional diversity. The *National Cislunar Science and Technology Strategy*, issued in 2022 by the White House Office of Science and Technology Policy (OSTP), outlines four priorities: fund foundational R&D, expand international cooperation, extend domain awareness into the Earth–Moon system, and build scalable, interoperable communications and PNT infrastructure. The strategy assigns NASA the lead in crafting a cislunar PNT backbone, while charging DoD with fielding the sensors required for

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<sup>80</sup> Henry Etzkowitz and Chunyan Zhou, *The Triple Helix: University–Industry–Government Innovation and Entrepreneurship* (London: Routledge, 2017), 21.

cislunar awareness. By aligning technical standards and budget objectives across agencies, the strategy aims to knit civil, commercial, and security efforts into a coherent push for U.S. leadership in the emerging cislunar economy.<sup>81</sup>

### *Department of Defense*

The DoD, primarily through U.S. Space Command (USSC) and the U.S. Space Force (USSF), views cislunar operations through freedom of maneuver, domain awareness, and deterrence. The DoD's 2020 *Defense Space Strategy* emphasized that space, including cislunar space, must be considered a warfighting domain and warned of adversary efforts to deny U.S. access and operations.<sup>82</sup> Meanwhile, USSF's *Space Warfighting Framework* notes the complexity that cislunar space adds to achieving persistent space superiority.<sup>83</sup>

The DoD invests the most in the space industry. The USSF's FY25 budget request included over \$24 billion in research and development (R&D), procurement, and operations and maintenance. The Space Development Agency's budget grew to over \$4 billion, funding proliferated constellations.<sup>84</sup> The National Reconnaissance Office (NRO) is the defense agency that procures and operates intelligence, surveillance, and reconnaissance (ISR) satellites and purchases commercial products and services. With an estimated \$6 billion annual budget, the NRO has contracts with multiple space industry companies.<sup>85</sup>

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81 Office of Science and Technology Policy, National Cislunar Science & Technology Strategy (Washington, DC: The White House, November 2022). <https://bidenwhitehouse.archives.gov/wp-content/uploads/2022/11/11-2022-NSTC-National-Cislunar-ST-Strategy.pdf>.

82 U.S. Department of Defense, *Defense Space Strategy*, 2020, 23–27.

83 "Space Warfighting: A Framework for Planners," 7. Accessed April 30, 2025. [https://www.spaceforce.mil/Portals/2/Documents/SAF\\_2025/Space\\_Warfighting\\_-\\_A\\_Framework\\_for\\_Planners\\_BLK2\\_\(final\\_20250410\).pdf](https://www.spaceforce.mil/Portals/2/Documents/SAF_2025/Space_Warfighting_-_A_Framework_for_Planners_BLK2_(final_20250410).pdf).

84 "Fiscal Year 2025 Budget Request," Department of the Air Force, accessed April 29, 2025. <https://www.saffm.hq.af.mil/FM-Resources/Budget/>.

85 "Intelligence Agency Budgets," accessed May 9, 2025, <https://irp.fas.org/commission/budget.htm>.

## *NASA*

NASA leads civil exploration initiatives, operating on an annual budget of just over \$25 billion (FY25), including its most prominent program, Artemis, which seeks to land humans back on the Moon.<sup>86</sup> NASA's Artemis Accords form a non-binding international framework pivotal in establishing international norms around sustainable lunar operations, transparent resource extraction, and non-interference.<sup>87</sup> NASA's role as the anchor customer through programs like Commercial Lunar Payload Services (CLPS) also stimulates the commercial base critical for dual-use infrastructure. CLPS satellites and payloads will send data back to Earth regarding the Moon's surface and resources, experiment with effective communications, and develop techniques for PNT without a global navigation satellite system (GNSS) constellation. With \$2.6 billion identified for contracts through 2028, NASA paves the way for small, innovative firms to enter the cislunar market.<sup>88</sup> These efforts provide a baseline to measure progress in creating a cislunar infrastructure and economy.

## *Department of Commerce (DoC)*

The DoC increasingly serves as the primary interface with commercial space, tasked with licensing, facilitating space traffic management, and promoting U.S. industrial competitiveness. Within the DoC, the Office of Space Commerce, envisioned to evolve into a mission authorization group, will be critical in managing activities such as on-orbit servicing and lunar mining.<sup>89</sup> However, current regulatory fragmentation across the Federal Aviation Administration

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<sup>86</sup> "FY 2025 Budget Request - NASA," accessed May 9, 2025, <https://www.nasa.gov/fy-2025-budget-request/>.

<sup>87</sup> National Aeronautics and Space Administration (NASA), *The Artemis Accords: Principles for a Safe, Peaceful, and Prosperous Future* (NASA, 2020).

<sup>88</sup> NASA, "Commercial Lunar Payload Services," accessed April 29, 2025. <https://www.nasa.gov/commercial-lunar-payload-services/>.

<sup>89</sup> Aerospace Corporation, *Space Agenda 2025*, October 2024, 114–16. [https://csps.aerospace.org/sites/default/files/2024-10/SpaceAgenda2025\\_Compilation\\_Web.pdf](https://csps.aerospace.org/sites/default/files/2024-10/SpaceAgenda2025_Compilation_Web.pdf).

(FAA), Federal Communications Commission (FCC), and other bodies underscores the need for reform if the U.S. government is to support rapid commercial expansion. A unified interagency effort—balancing security, innovation, and governance—is essential if the United States is to secure enduring advantages in the cislunar domain.

### *Mobilization*

Despite significant investment, the U.S. space industrial base faces critical mobilization constraints. A typical DoD satellite launch currently requires over two years from contract award to deployment—a timeline that could prove problematic in a contested cislunar environment demanding rapid asset repositioning. The USSF’s Tactically Responsive Space missions have shown the potential to compress mission timelines from months to weeks, but these accelerated deployments remain dependent on carefully aligned resources and may not be consistently achievable in more complex operational scenarios.

### Commercial Industry

On the other side of the government-business relationship are the companies that produce the goods and services of the space industry. Complementing the government’s policy and funding apparatus are the firms that build and operate the space ecosystem—launch providers, satellite and subsystem manufacturers, operators, and service companies. Reaching the Moon and exploiting the nearby orbits pose engineering challenges different from LEO, demanding innovations in high-energy propulsion, radiation-hardened electronics, and long-duration autonomous operations.

Individual firms rely heavily on early government contracts to achieve viability. International regulatory ambiguity in the 1967 Outer Space Treaty (OST) regarding resource rights may dissuade commercial investment. Additional exposure to geopolitical risk if

international governance collapses or fragments adds to the uncertainty. The United States must support and de-risk private investment while aligning commercial expansion with national security imperatives.

### *Launch Providers*

The commercial sector is both an enabler and a beneficiary of cislunar development. Companies across multiple domains have expanded into cislunar applications, driven by falling launch costs, government contracts, and emerging demand. Launch providers such as SpaceX, Blue Origin, and United Launch Alliance (ULA) are critical enablers of mass deployment beyond Earth's orbit, providing the lift capacity necessary for sustained operations in cislunar space. SpaceX's *Starship*, already on contract to support NASA's Artemis program logistics, offers a high-mass, low-cost launch capability poised to transform Earth-to-cislunar transportation.<sup>90</sup>

### *In-Space Servicing, Assembly, and Manufacturing (ISAM)*

Emerging firms like Redwire, Astroscale, and OrbitFab focus on ISAM technologies key for infrastructure resilience and servicing in the Earth-Moon system.<sup>91</sup> Additionally, startups like Astrobotic, Firefly Aerospace, and Intuitive Machines, supported by NASA's CLPS contracts, demonstrate the growing nature of commercial lunar infrastructure.

### *Mobilization*

Launch providers are critical for mass deployment beyond Earth's orbit, providing the lift capacity necessary for sustained operations in cislunar space. Private industry, particularly SpaceX's Starlink constellation, offers a compelling model for space mobilization by

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<sup>90</sup> SpaceX, "Starship Overview," accessed April 2025. <https://www.spacex.com/vehicles/starship/>.

<sup>91</sup> Markets and Markets Research, "On-Orbit Satellite Servicing Market Size, Share & Growth 2030," MarketsandMarkets, accessed April 18, 2025. <https://www.marketsandmarkets.com/Market-Reports/on-orbit-satellite-servicing-market-206789424.html>.

demonstrating the ability to produce and launch dozens of satellites weekly. As the nation looks toward 2055, a developed cislunar economy will require supporting infrastructure with regular, low-cost space transportation. As the launch cadence and capacity to space increases, the United States will need to factor in the appropriate level of mobilization to secure its interests.

### Academia and Research Organizations

Universities and research institutions are vital stakeholders in cislunar space, serving as incubators for scientific discovery, engineering innovation, and policy analysis that underpin government and commercial activities. Academia and R&D organizations supply an innovative spirit—an asymmetric advantage against China. Federally Funded Research and Development Centers (FFRDCs), university-affiliated research centers (UARCs), and civilian academic partnerships with NASA and DoD contribute to advancements in areas such as in-situ resource utilization (ISRU), space domain awareness (SDA), and autonomous robotics.

These organizations are at the heart of the triple helix. One prominent example is the Johns Hopkins Applied Physics Laboratory (APL), a UARC supporting space missions for NASA and national security agencies, including trajectory and orbital design, lunar mission planning, and resilient communications architecture. Sustained investment in academic research and strategic collaboration across disciplines will be critical to safe, sustainable, and interoperable operations in the Earth-Moon system.

### Allies and Partners

Allied and partner participation in cislunar development is both a force multiplier and a strategic necessity. These partners share the U.S. vision for the next phase of civil space exploration and the use of outer space and are developing cislunar capabilities: Japan contributes

advanced lunar landers (iSpace), robotics, and the Quasi-Zenith Satellite System (QZSS)<sup>92</sup>; Australia invests in lunar communications<sup>93</sup> and surface mobility (ELO<sub>2</sub>);<sup>94</sup> the European Space Agency (ESA) provides logistics modules, surface habitation technologies, orbital servicing, and space sustainability through regulatory initiatives and technical investments; Luxembourg advances legal frameworks regarding space resources, in conjunction with similar laws passed by the United States and Japan, to demonstrate its commitment to ISRU; India landed its first mission on the Moon in 2023.

Deeper coordination with partners can allow pooling resources and expertise, enabling cost-sharing while accelerating capability development. The Artemis Accords exemplify the strength of U.S.-led coalitions and the power of diplomatic partnerships in shaping the emerging cislunar order. Leveraging this broad coalition provides a practical foundation for establishing interoperability across civil, commercial, and military infrastructures operating beyond GEO. Bilateral and multilateral agreements are essential to set standards, ensure access, and reinforce collective leadership. Failure to maintain allied leadership risks ceding normative and economic influence on U.S. and allied competitors in the new strategic high ground.

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92 Quasi-Zenith Satellite System (QZSS) is Japan's satellite navigation system that enhances GPS. It delivers positioning, navigation, and timing services, focusing on the Asia-Oceania region. "Overview of the Quasi-Zenith Satellite System (QZSS)," Quasi-Zenith Satellite System(QZSS), accessed May 7, 2025, [https://qzss.go.jp/en/overview/services/sv01\\_what.html](https://qzss.go.jp/en/overview/services/sv01_what.html).

93 Francis Bennet, "A Deep-Space and Lunar Optical Communication System: Optical Ground Station to Support Artemis II," Australian National University, accessed April 29, 2025. <https://rsaa.anu.edu.au/research/research-projects/deep-space-and-lunar-optical-communication-system-optical-ground-station>.

94 "Team Chosen to Build Australia's Moon Rover," Australian Space Agency, December 17, 2024. <https://www.space.gov.au/news-and-media/team-chosen-to-build-australias-moon-rover>.

## PESTL Analysis of U.S. Efforts in Cislunar Space

Dominance in cislunar space requires a robust space industrial base capable of supplying the resources needed to establish and sustain operations beyond GEO. The space industrial base consists of three broad, interconnected markets, referenced in Figure 3, providing the required space operations resources: launch services, spacecraft manufacturing, and space services. The PESTL framework (Political, Economic, Social, Technological, and Legal factors) facilitates analysis of these industries and their viability for cislunar operations. Each of these industries includes critical, interrelated sectors with unique opportunities and challenges that must be addressed to build a permanent and secure presence beyond GEO. This analysis shows that the United States is positioning itself as a dominant force in this strategically critical domain, despite various systemic, regulatory, and infrastructure challenges.

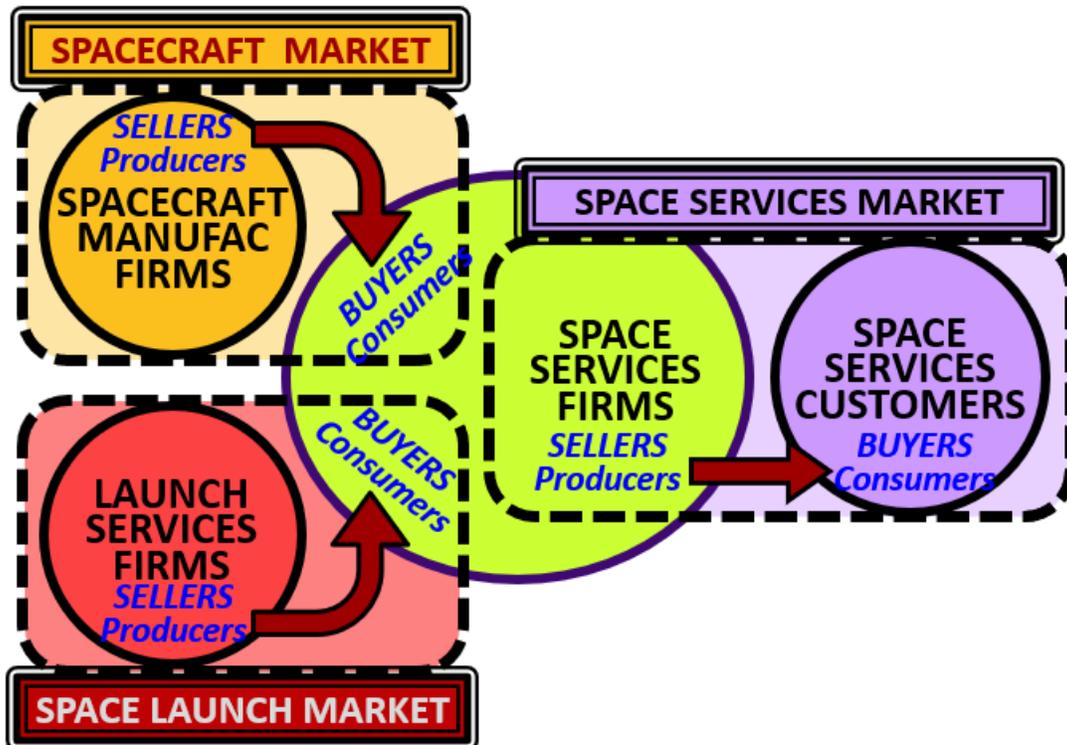


Figure 3: Markets in the Space Domain<sup>95</sup>

95 Dr. Clark Groves and Dr. Peter Coughlan, "Space Markets," 2022, National Defense University.

## Political Factors

U.S. efforts in cislunar space are founded upon robust public enthusiasm and bipartisan political support for space activities. Additionally, legislation beginning in the 1980s and continuing to the present encouraged private industry to operate in a realm once exclusively dominated by the government.<sup>96</sup> In 2017, the Trump Administration accelerated cislunar exploration by reestablishing the National Space Council and publishing Space Policy Directive 1, which directed the federal government to “lead an innovative and sustainable program of exploration with commercial and international partners ... the U.S. will lead the return of humans to the Moon for long-term exploration and utilization.”<sup>97</sup> This directive established the framework for the subsequent Artemis Program and Artemis Accords to return humans to the Moon and create an international agreement on rules concerning cislunar operations.

Recent geopolitical developments with Russia and China have sharpened U.S. strategic thinking and highlighted eroding U.S. dominance in space. In response, in 2019, the Trump Administration and Congress created the U.S. Space Force “for the purpose of securing the Nation's vital interests in space.”<sup>98</sup> The current Trump Administration remains focused on space, as evidenced by the publication of Executive Order (E.O.) 14186, commonly called the “Golden Dome,” within a week of the inauguration. This E.O. mandates a robust, space-based infrastructure to defend the American homeland against the “threat of attack by ballistic,

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96 Space Foundation Editorial Team, “U.S. Space Law,” Space Foundation (blog), accessed April 15, 2025. [https://www.spacefoundation.org/space\\_brief/us-space-law/](https://www.spacefoundation.org/space_brief/us-space-law/).

97 Donald Trump, “Presidential Memorandum on Reinvigorating America's Human Space Exploration Program,” December 11, 2017. <https://trumpwhitehouse.archives.gov/presidential-actions/presidential-memorandum-reinvigorating-americas-human-space-exploration-program/>.

98 U.S. Space Force, Space Force Doctrine Document 1, April 3, 2025, 7. [https://www.starcom.spaceforce.mil/Portals/2/Space%20Force%20Doctrine%20Document%201%20FINAL\\_4Apr25.pdf](https://www.starcom.spaceforce.mil/Portals/2/Space%20Force%20Doctrine%20Document%201%20FINAL_4Apr25.pdf). Force, “Space Force Doctrine Document 1,” Apr. 3, 2025, 7, chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.starcom.spaceforce.mil/Portals/2/Space%20Force%20Doctrine%20Document%201%20FINAL\_4Apr25.pdf.

hypersonic, and cruise missiles, and other advanced aerial attacks.”<sup>99</sup> There is also a vibrant debate concerning whether the United States should focus on returning to the Moon or on a crewed mission to Mars. Despite this debate and the growing political influence of space entrepreneurs, the political climate that spurred rapid growth of the space industry and created the U.S. Space Force (USSF) continues to drive advances in launch services, spacecraft manufacturing, and operations needed to succeed in the cislunar domain.

### Economic Factors

Cislunar space presents both economic opportunities and significant fiscal challenges. A 2024 Center for Strategic and International Studies report suggests little market value in the cislunar economy until the distant future.<sup>100</sup> In contrast, a 2021 assessment projected the value of the cislunar economy at \$170 billion in the 20 years to 2040.<sup>101</sup> While cislunar space has generated little revenue, some visionaries envision trillions of dollars in economic activity in 30 years.<sup>102</sup> Cislunar activities today remain anchored in government funding, primarily through NASA’s CLPS program; however, there is emerging commercial interest in lunar transportation, resource extraction, and infrastructure development.<sup>103</sup> While many private companies are leveraging government contracts for cislunar activities, no company has generated revenue in the sector beyond government CLPS contracts. Economic trends suggest the government may face

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99 “The Iron Dome for America,” The White House, January 28, 2025.

<https://www.whitehouse.gov/presidential-actions/2025/01/the-iron-dome-for-america/>.

100 Clayton Swope and Louis Gleason, “Salmon Swimming Upstream: Charting a Course in Cislunar Space” (Center for Strategic and International Studies, October 2024), 3. [https://csis-website-prod.s3.amazonaws.com/s3fs-public/2024-10/241021\\_Swope\\_Swimming\\_Upstream\\_0.pdf](https://csis-website-prod.s3.amazonaws.com/s3fs-public/2024-10/241021_Swope_Swimming_Upstream_0.pdf).

101 Luigi Scatteia and Yann Perrot, “Lunar Market Assessment: Market Trends and Challenges in the Development of a Lunar Economy” (PricewaterhouseCoopers, September 2021), 33. <https://www.pwc.com.au/industry/space-industry/lunar-market-assessment-2021.pdf>.

102 Tony Bruno, “This Time to Stay: How the Moon Will Open Up a Cislunar Economy and Human Exploration of Mars” (ULA, May 2023). [https://www.exploremars.org/wp-content/uploads/2023/08/0516\\_1420\\_TBruno\\_Future-of-Space.pdf](https://www.exploremars.org/wp-content/uploads/2023/08/0516_1420_TBruno_Future-of-Space.pdf).

103 Mariel Borowitz, “Returning to the Moon Can Benefit Commercial, Military and Political Sectors – a Space Policy Expert Explains,” The Conversation, July 18, 2023. <http://theconversation.com/returning-to-the-moon-can-benefit-commercial-military-and-political-sectors-a-space-policy-expert-explains-209300>.

growing difficulties in funding discretionary spending, including cislunar exploration. A rising U.S. government debt-to-GDP ratio, around 123%, and rising mandatory federal payments and interest may limit available resources for space initiatives.<sup>104</sup> Cislunar exploration may be delayed until the government or industry identifies a viable economic incentive to justify sustained investment.

### Social Factors

Social factors significantly influence the U.S. space industry's cislunar trajectory. According to a 2023 Pew Research study, almost two-thirds of respondents “say it is essential for the U.S. to be a leader in space exploration.”<sup>105</sup> This support creates a strong domestic environment of investment, innovation, and commitment to space-related activities. Public enthusiasm for space exploration, fueled by high-profile NASA missions and commercial launches by companies like SpaceX, has generated strong support for sustained investment in the space industry.<sup>106</sup> However, the launch sector still faces talent gaps in manufacturing, especially software and systems engineering.<sup>107</sup> Also, public concerns over the environmental impact of rocket emissions and spaceport developments are increasing pressure on firms to adopt sustainable practices.<sup>108</sup> With increased awareness of orbital debris and congestion in LEO, concerns are growing over who will have equitable access to space resources, how space-based manufacturing will be governed, and whether profits and capabilities will be concentrated among

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<sup>104</sup> “Fiscal Data Explains the National Debt,” accessed May 7, 2025.  
<https://fiscaldata.treasury.gov/americas-finance-guide/national-debt/>.

<sup>105</sup> Brian Kennedy and Alec Tyson, “Americans’ Views of Space: U.S. Role, NASA Priorities and Impact of Private Companies,” Pew Research Center (blog), July 20, 2023.  
<https://www.pewresearch.org/science/2023/07/20/americans-views-of-space-u-s-role-nasa-priorities-and-impact-of-private-companies/>.

<sup>106</sup> Ibid.

<sup>107</sup> Heidi Thiemann and Joseph Dudley, Space Sector Skills Survey 2023 Results, Space Skills Alliance, September 13, 2023. <https://spaceskills.org/space-sector-skills-survey>.

<sup>108</sup> Jeffrey Kluger, “There’s No Way to Make Space Travel Good for Planet Earth Right Now,” Time, April 19, 2023. <https://time.com/6273065/space-travel-climate-impact/>.

a few dominant players.<sup>109 110</sup> The space services sector, vital to cislunar operations, is increasingly concerned that dual-use proximity technologies like satellite docking may enable peaceful missions and military applications.<sup>111</sup> Just as a 1963 Gallup poll showed that 69% of Americans supported continuing or speeding up the Apollo space program, the next phase of lunar exploration can inspire national pride and unity.<sup>112</sup> By highlighting practical benefits, such as scientific progress, economic growth, and global leadership, the U.S. government can show how investing in space exploration today will bring long-lasting, future benefits.

### Technological Factors

Innovation forms the cornerstone of America's expanding cislunar capabilities. Despite the breakthroughs across multiple industries for an integrated ecosystem for lunar exploration and development, cislunar capabilities remains nascent. Reusable heavy-lift rockets like SpaceX's Starship and NASA's Space Launch System (SLS) are reducing launch costs while increasing payload capacity, which is essential for transporting habitats, cargo, and infrastructure to the Moon.<sup>113</sup> Complementing the growth of commercial space launch, advances in automation, robotics, and AI enable modular spacecraft to be adapted for long-duration missions and reduce the need for humans in high-risk operations.<sup>114</sup> Future development of lunar construction

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109 “The Guardian View on Owning the Heavens: The Perils of Letting Capitalism Colonise the Cosmos | Editorial,” The Guardian, accessed May 1, 2025. <https://www.theguardian.com/commentisfree/2025/apr/27/the-guardian-view-on-owning-the-heavens-the-perils-of-letting-capitalism-colonise-the-cosmos>.

110 Erika Nesvold, “Closing the Gaps: Space Policy Considerations Beyond Security and Economy,” Georgetown Journal of International Affairs, November 14, 2022. <https://gjia.georgetown.edu/2022/11/14/closing-the-gaps-space-policy-considerations-beyond-security-and-economy/>.

111 Sandra Erwin, “On National Security: Commercial In-orbit Vehicles Caught in the Space Arms Crossfire,” SpaceNews, September 16, 2022. <https://spacenews.com/on-national-security-commercial-in-orbit-vehicles-caught-in-the-space-arms-crossfire/>.

112 Justin McCarthy, “50 Years After Moon Landing, Support for Space Program High,” Gallup, July 11, 2019. <https://news.gallup.com/poll/260309/years-moon-landing-support-space-program-high.aspx>.

113 “BryceTech Global Space Launch Activity 2024,” accessed May 1, 2025. <https://brycetek.comreports/report-documents/global-space-launch-activity-2024>.

114 “Defense Innovation Unit FY23 Annual Report | DIU,” accessed May 1, 2025. <https://www.diu.mil/fy23>.

technologies and ISRU capabilities will reduce dependency on terrestrial supply chains by leveraging local resources.<sup>115</sup> These technological foundations support growing cislunar service categories, including lunar navigation, power generation, and communications infrastructure such as NASA’s Lunar Gateway station. These innovations create the foundation for sustained cislunar operations and a permanent lunar presence.

### Legal Factors

Legal and regulatory frameworks governing cislunar space remain underdeveloped relative to the rapid pace of technological advancements.<sup>116</sup> The 1967 Outer Space Treaty (OST) outlines a foundational set of principles that prohibit sovereign appropriation of the Moon and other celestial bodies. The U.S. has attempted to address the OST’s gaps through domestic legislation, including the 2015 Commercial Space Launch Competitiveness Act, which affirms commercial rights to space resources by promoting international cooperation via the Artemis Accords. However, the lack of universally accepted legal agreements creates uncertainty in long-term commercial planning and government investment. Export control regimes such as ITAR restrict technology transfers and economic development and hamper international collaboration. Legal clarity, international cooperation, and updated regulatory guidance will be essential to enable safe, scalable commercial activity in the lunar and cislunar domain.

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<sup>115</sup> Peng Zhang et al., “Overview of the Lunar In Situ Resource Utilization Techniques for Future Lunar Missions,” *Space: Science & Technology* 3 (June 2023): 2. <https://doi.org/10.34133/space.0037>; TWG ISRU GAT, *In-Situ Resource Utilization Gap Assessment Report*, n.d., 9.

<sup>116</sup> Clayton Swope and Louis Gleason, "Salmon Swimming Upstream: Charting a Course in Cislunar Space," October 21, 2024. <https://www.csis.org/analysis/salmon-swimming-upstream-charting-course-cislunar-space>.

## **Policy Recommendations: Three Integrated Lines of Effort for Cislunar Leadership**

Achieving and maintaining U.S. leadership in cislunar space by 2055 will require significant policy shifts and investments. The United States and our allies and partners have long relied on Earth orbits for communications, PNT, and a broad range of civil and national security capabilities. Significant risks will accompany government and private industry efforts to develop cislunar space. However, failure to seize these opportunities risks ceding the celestial high ground to China. U.S. investments in cislunar infrastructure can foster an innovative, thriving commercial cislunar sector that will reinforce American security in space and on Earth.

By reorganizing existing authorities and budgets and consolidating leadership for civil and commercial space within the U.S. government, deepening international partnerships and burden sharing with allies and partners, leveraging innovative financial tools to catalyze private investment, and cultivating the growing private space industry, the United States can strengthen its dominant position in cislunar space. Prioritizing unmanned systems for cislunar space over human spaceflight will reduce costs and risk, enabling faster development and integration. Three Lines of Effort (LOEs) provide the path forward:

1. **Consolidate U.S. Leadership** – Strengthen national security and economic development in cislunar space by centralizing U.S. authorities, shaping U.S. and global regulatory bodies and policies, and coordinating the efforts of allies and partners.
2. **Build and Secure Cislunar Infrastructure** – Leverage public and private capital to invest in the security, logistics, communications, mobility, and resource-extraction backbone that underpins all cislunar activity.
3. **Cultivate the Private-Sector Economy** – Reduce barriers to entry; mobilize private capital; create predictable, long-term demand; and cultivate fertile innovation ecosystems

that anchor commercial leadership to U.S. interests.

### LOE 1 – Consolidate U.S. Leadership

The United States has dominated civil, commercial, and national security space since the 1960s, developing a broad ecosystem of policy, regulatory, and operational institutions and authorities across multiple departments and agencies. This approach has cultivated innovation and experimentation. However, tighter budgets and increased competition require a different approach over the coming decades. Consolidating budgets and authorities for civil and commercial space regulation, exploring novel methods of financing, streamlining bureaucracy, and establishing a favorable international regulatory regime will cement U.S. leadership in space, lower investor risk, and offer allies and partners a long-term vision for cislunar cooperation.

1. **Establish a U.S. Department of Space:** The United States needs a unified vision for dominating cislunar space, a strong advocate for the large and growing civil and commercial space sector, and a bureaucracy aligned to achieving those goals. By consolidating authorities and budgets over non-defense aspects of space into a single, permanent, cabinet-level agency, the U.S. government would be better postured to lead in civil and commercial space, support science and space exploration, manage space traffic and orbital debris, license launches, adjudicate spectrum, and coordinate on export controls and national security policy from LEO to cislunar space. Modeled after the Department of Energy, with a focus on both national security and economic prosperity, this new department should have broad authority to shape U.S. policy and oversee space activities across the government.<sup>117</sup> Budget authorities for defense and warfighting

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<sup>117</sup> Peter Garretson et al., “State of Space Industrial Base 2023” (Defense Innovation Unit, December 2023), 14.  
[https://assets.ctfassets.net/3nanhbfr0pc/5qTI9wqmgHP1GBKFEeReMN/2c007046f6c5cbc1ed0ffaf06e91d780/State\\_of\\_the\\_Space\\_Industrial\\_Base\\_2023\\_Report\\_-\\_FINAL\\_\\_1\\_.pdf](https://assets.ctfassets.net/3nanhbfr0pc/5qTI9wqmgHP1GBKFEeReMN/2c007046f6c5cbc1ed0ffaf06e91d780/State_of_the_Space_Industrial_Base_2023_Report_-_FINAL__1_.pdf).

should remain with DoD. Select budget authorities from the Department of Commerce (DoC), NASA, the Federal Communications Commission (FCC), the Federal Aviation Authority (FAA), and DoD could be integrated into the new department.

2. **Create an International Cislunar Infrastructure Bank (ICIB):** Capitalized with an initial U.S. contribution of \$10 billion to incentivize significant contributions from like-minded spacefaring nations, the ICIB could issue low-interest loans, provide credit guarantees, and issue "Lunabonds" to finance qualifying cislunar infrastructure projects.<sup>118</sup> Initial funding at this scale could unlock ten times as much funding by catalyzing private investment, a practice common to other government-backed infrastructure investment programs.<sup>119</sup> The ICIB would lower barriers for private sector participation in cislunar infrastructure and ensure U.S. industry, as well as that of our allies and partners, can compete with state-backed competitors from China. Building on the success of the Artemis Accords, the ICIB would allow emerging partners to invest in the U.S. vision for cislunar space. It would also provide a means of implementing policy and setting standards for high-quality projects that align with U.S. and allied goals.
3. **Establish and Lead International Standards Organizations for Cislunar Space:** Establish permanent bodies analogous to the International Civil Aviation Organization (ICAO) and the International Telecommunications Union (ITU) to negotiate technical and operational standards and provide frameworks for cooperation and dispute resolution on cislunar issues, including navigation, communications, resource utilization, and

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<sup>118</sup> Congressional Research Service, "National Infrastructure Bank: Proposals in the 118th Congress," Congress.gov, February 5, 2024. <https://www.congress.gov/crs-product/IF12585>.

<sup>119</sup> World Bank Group, "Identifying Key Design Features and Success Factors for Public Infrastructure Funds," Global Review of Public Infrastructure Funds (Washington, DC: World Bank Group, April 2020). [https://ppp.worldbank.org/public-private-partnership/sites/ppp.worldbank.org/files/2022-02/PIF\\_Global\\_Review-Volume\\_I\\_-\\_final.pdf](https://ppp.worldbank.org/public-private-partnership/sites/ppp.worldbank.org/files/2022-02/PIF_Global_Review-Volume_I_-_final.pdf).

servicing.<sup>120</sup> The UN Committee on the Peaceful Uses of Outer Space (COPUOS) has proposed developing an international mechanism on sustainable lunar activities to address "technical and operational issues that could be faced by lunar operators".<sup>121</sup> The United States should support such efforts, and consistently seek leadership roles in these bodies and promote U.S. involvement at the working levels.

## LOE 2 – Build and Secure Cislunar Infrastructure

The U.S. government has long played a vital role in stimulating economic growth by funding broad-based infrastructure development to benefit the public and private sectors. Just as the government fostered the nation's economic growth in the 19<sup>th</sup> and 20<sup>th</sup> centuries through public financing and construction of canals, railways, and highways, so should it play a leading role in building space infrastructure to grow the cislunar economy. Such measures will be costly. However, these investments would be negligible relative to the potential economic benefits derived from cislunar commercial activities and the cost of ceding the cislunar domain to adversaries. The following recommendations enable national security and commercial expansion beyond GEO by focusing on cislunar infrastructure development.

1. **Develop a Robust SSA/SDA Architecture:** Establishing a secure cislunar operating environment is foundational to promoting economic development in space. The United States should leverage the commercial sector to implement a resilient cislunar space situational awareness (SSA) and space domain awareness (SDA) architecture. This would entail employing sophisticated sensing and communications technology capable of

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120 Nina M. Armagno and Jane Harman, "Securing Space: A Plan for U.S. Action," Council on Foreign Relations, accessed May 1, 2025. <https://www.cfr.org/task-force-report/securing-space/recommendations>.

121 Committee on the Peaceful Uses of Outer Space, Proposal on a Consultative Mechanism on Lunar Activities: Paper Submitted by the Delegation of Romania, A/AC.105/C.1/2024/CRP.30 (Vienna: United Nations, February 8, 2024), 1.

detecting, identifying, tracking, and characterizing the behavior of objects (natural and manmade) in cislunar space to mitigate potential risks to American space assets. Private firms, such as iSpace, SES, and Astroscale, have demonstrated sensing, communications, and maneuvering capabilities that could be applied to cislunar operations. Indeed, initial steps have been taken to advance cislunar SSA/SDA (e.g., Air Force Research Lab's (AFRL's) partnership with Advanced Space on the Oracle project), and the manufacturing capacity exists to produce satellites that could be used to support cislunar SSA/SDA operations.<sup>122</sup> Moreover, a cislunar SSA/SDA architecture would contribute to a future space traffic management system. Such a system would align with the Artemis Accords' call for registration of space objects, and it would enhance safe cislunar activities by requiring tracking of all spacecraft operating beyond GEO.<sup>123</sup> A new Department of Space, with jurisdiction over the cislunar domain, could have responsibility for space traffic management, and space traffic control systems could emulate those used by the FAA's air traffic control model. Additionally, emphasis should be placed on the development of predictive modeling tools using AI to advance collision avoidance and enhance traffic forecasting. Such technology could process vast amounts of tracking data in real-time to improve detection, characterization, and prediction of object behavior.<sup>124</sup>

## **2. Establish Reliable Communications and Navigation Infrastructure:** Continuous,

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<sup>122</sup> Francesca Conner, "AFRL's Oracle Family of Systems Developing Nation's 1st Cislunar Space Situational Awareness Capabilities," Air Force Research Labs Public Affairs, December 11, 2023. <https://www.afrl.af.mil/News/Article-Display/Article/3611977/afrls-oracle-family-of-systems-developing-nations-1st-cislunar-space-situational/>.

<sup>123</sup> NASA, The Artemis Accords: Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes (Washington, DC: NASA, October 13, 2020). <https://www.nasa.gov/specials/artemis-accords/img/Artemis-Accords-signed-13Oct2020.pdf>.

<sup>124</sup> Ryan Schradin, "Is AI the Key to Greater Situational Awareness in GEO?" Kratos, March 11, 2025. <https://www.kratosdefense.com/constellations/articles/is-ai-the-key-to-greater-situational-awareness-in-geo>.

high-bandwidth communications and precise navigation are necessary for safe and effective operations in cislunar space. The United States should accelerate the deployment of reliable, resilient communications networks throughout the domain, including programs such as NASA’s LunaNet lunar communications and navigation concept.<sup>125</sup> Emphasis should also be placed on operationalizing a dedicated cislunar PNT system to enable spacecraft and surface operations in cislunar space without reliance on Earth-based navigation. Concurrently, research into optical-based communication systems for space applications should continue with the aim of establishing secure, high-capacity links across cislunar distances.<sup>126</sup>

- 3. Develop an In-Space Logistics, Transportation, and Energy Backbone:** Access to cislunar space will depend heavily on reliable logistical, transportation, and energy support. In the near term, investments should focus on developing on-orbit servicing and refueling capabilities. Northrop Grumman has demonstrated the viability of orbital servicing near GEO.<sup>127</sup> Astroscale plans to demonstrate a similar capability above GEO as early as 2026.<sup>128</sup> Expanding such capabilities into cislunar space will help reduce costs and extend the operational life of government and commercial space assets. The United States should prioritize establishing reusable cislunar transport vehicles and invest in

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125 David J. Israel et al., “LunaNet: A Flexible and Extensible Lunar Exploration Communications and Navigation Infrastructure,” NASA Goddard Space Flight Center, 2020. <https://ntrs.nasa.gov/api/citations/20200001555/downloads/20200001555.pdf>.

126 Heather Monaghan, “Quantum Communications,” NASA, April 13, 2022. <https://www.nasa.gov/directorates/somd/space-communications-navigation-program/quantum-communications/>.

127 Northrop Grumman, “Space Logistics Services,” accessed April 29, 2025. <https://www.northropgrumman.com/space/space-logistics-services>.

128 Astroscale, “Astroscale U.S. to Lead the First-Ever Refueling of a United States Space Force Asset,” April 8, 2024. <https://astroscale.com/astroscale-u-s-to-lead-the-first-ever-refueling-of-a-united-states-space-force-asset/>.

prepositioned propellant depots located at Lagrange points and on the Moon's surface to reduce the cost of cislunar missions.

### LOE 3 – Cultivate the Private-Sector Cislunar Economy

The United States cannot rely solely on government missions to dominate cislunar space by 2055. It must leverage private ingenuity, capital, and speed to build, launch, and operate faster than any government can to gain decisive advantages. LOE 3 focuses on stimulating and cultivating the private-sector economy to make U.S. legal, technical, and financial standards the default operating system of the emerging lunar marketplace. The recommendations below expand investment, shrink development timelines, and bind allied industries to U.S. supply chains while delivering measurable returns to taxpayers.

1. **Stable Government Demand:** Commercial firms need a significant and steady demand signal from the U.S. government to fully build the infrastructure necessary for cislunar dominance. To create this signal, NASA, the U.S. Space Force, and the Defense Logistics Agency (DLA) should issue \$10 billion in 10-year take-or-pay contracts for in-situ resource utilization (ISRU), surface logistics, power, and communication relays. NASA should scale its proven CLPS framework (\$2.6 billion max through 2028), catalyzing significant additional private investment.<sup>129</sup>
2. **Legal Clarity and Financial Incentives:** The U.S. must provide legal clarity and financial stability to attract more investors. Congress should pass a Space Resources Act that reduces ambiguity, clearly defines commercial recovery, provides a multi-decade royalty holiday, and codifies safety zones aligned with the Artemis Accords and any

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<sup>129</sup> NASA, "New Report Shows NASA's \$75.6 Billion Boost to US Economy," press release 24-130, October 24, 2024. Accessed April 30, 2025. <https://www.nasa.gov/news-release/new-report-shows-nasas-75-6-billion-boost-to-us-economy/>.

potential successor treaties. Concurrently, the United States should create Cislunar Enterprise Zones where firms reap the rewards of tax exemptions, tariff-free lunar imports, and other economic benefits to incentivize cislunar commercial activities. Like Luxembourg’s 2017 Law on the exploration and use of space resources,<sup>130</sup> the United States must clarify, remove obstacles, and incentivize private investment.

**3. Accelerate Future Technologies through Bigger, Faster Grants and Financing:**

Expanding Small Business Innovation Research (SBIR), Small Business Technology Transfer (STTR), Strategic Funding Increase (STRATFI), and Tactical Funding Increase (TACFI) authorities should triple early phase ceilings for lunar technologies while unifying application portals across NASA, U.S. Space Force, the Export-Import Bank, and a new ICIB (see LOE 1.2).<sup>131,132,133</sup> Provide a single portal and reward milestones to expedite proven technologies through the ‘valley of death.’ U.S. government contracts with and subsidies keep many small space businesses afloat and are needed in the short term until a viable cislunar economy comes to fruition.

**4. Expand and Protect Cislunar Partners:** Co-funded centers with partner nations would pair U.S. venture-style management with local talent and public grants.<sup>134</sup> Partner nations gain limited production licenses and offset workshare. At the same time, U.S.-controlled

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130 Grand Duchy of Luxembourg, Loi du 20 juillet 2017 sur l’exploration et l’utilisation des ressources de l’espace [Law of 20 July 2017 on the Exploration and Use of Space Resources], Journal officiel du Grand-Duché de Luxembourg, Mémorial A, no. 674 (July 28, 2017). Accessed May 1, 2025. <https://legilux.public.lu/eli/etat/leg/loi/2017/07/20/a674/jo/en>.

131 U.S. Small Business Administration, “SBIR/STTR—America’s Seed Fund,” accessed April 30, 2025. <https://www.sbir.gov/>.

132 SBIR and STTR Extension Act of 2022, Pub. L. 117-183, 136 Stat. 2180 (September 30, 2022). <https://www.congress.gov/117/plaws/publ183/PLAW-117publ183.pdf>.

133 AFWERX, “STRATFI/TACFI,” accessed April 30, 2025. <https://afwerx.com/divisions/ventures/stratfi-tacfi/>.

134 Defense Acquisition University, “National Technology and Industrial Base (NTIB) Expansion – Australia and UK,” presentation notes, 2017. <https://www.dau.edu/cop/iam/documents/national-technology-and-industrial-base-ntib-expansion-australia-and-uk>.

intellectual property lures foreign investment into critical manufacturing like lunar avionics and space-rated processors, while providing additional security to global supply chains. Complementary ITAR reforms can re-classify routine cislunar components to the Commerce Control List, cutting licensing times by months and enabling small firms to iterate prototype hardware within a single fiscal year.<sup>135</sup>

Collectively, these proposals would unlock innovation and capital, create predictable demand, unify and strengthen governance, and drive down critical launch and operations costs in LEO and cislunar space. Strengthened alliances and partnerships would harden the architecture against coercion, and a diversified supplier base would increase resilience. These integrated Lines of Effort position the United States, its allies, and partners to shape the cislunar domain for U.S. leadership through 2055 and beyond.

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<sup>135</sup> Dilyn Loveless, “ITAR Revisions and Space Technologies: Modernization with Complexities,” Centre Law & Consulting (blog), January 16, 2025. <https://centrelawgroup.com/blog/itar-revisions-and-space-technologies-modernization-with-complexities/>.

## Conclusion

*“The history of failure in war can almost always be summed up in two words: ‘Too late.’ Too late in comprehending the deadly purpose of a potential enemy; too late in realizing the mortal danger; too late in preparedness; too late in uniting all possible forces for resistance.”<sup>136</sup>*

- General Douglas MacArthur, 1940

MacArthur’s warning echoes with urgency across the cislunar domain, where the strategic contours are still being drawn. This report has shown that U.S. leadership between the Earth and the Moon is neither inevitable nor assured. Failure to act risks ceding the high ground to competitors who recognize the profound economic, military, and political stakes of the Earth-Moon system. Yet while the risks are real, the path forward remains gilded with possibility. The U.S. possesses extraordinary tools: a resurgent industrial base, global alliances, and the power to shape norms before they calcify under rival influence. If the United States is intrepid enough to consolidate national leadership, invest in resilient cislunar infrastructure, and galvanize private enterprise, it can secure a future of cislunar space informed by American values and driven by American interests. To lead in cislunar space is not just to avoid being, as MacArthur warned, “too late.” It is to arrive first, to build boldly, and to endure.

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<sup>136</sup> Ben Blane, “Positioning, Training, and Integration: A Vision of Transformation in Contact for the US Army in the Pacific,” Modern War Institute, March 1, 2024. <https://mwi.westpoint.edu/positioning-training-and-integration-a-vision-of-transformation-in-contact-for-the-us-army-in-the-pacific/>. Accessed May 13, 2025.

## Appendix A: Wargaming and the Cislunar Space Economy for 2055

### Introduction

The emergence of cislunar space as a strategic and economic domain demands forward-looking educational wargaming to prepare policymakers, industry leaders, and military planners for the complexities of 2055. Yet, despite the accelerating discourse around lunar and cislunar operations, most existing space wargames remain bounded by low Earth orbit (LEO) and geosynchronous orbit (GEO) challenges, neglecting the unique dynamics of cislunar logistics, governance, and industrialization. Educational wargames must bridge this gap, expanding beyond near-term conflict scenarios to envision and interrogate the infrastructure, commerce, and partnerships necessary for sustained presence beyond Earth’s immediate orbits.

### Expanding Horizons through Useful Fiction

A critical input to such wargames is the genre of speculative fiction promoted by authors like Daniel Suarez, P. W. Singer, and August Cole. These writers explore future techno-industrial ecosystems through narrative lenses, providing imaginative yet plausible visions of emerging technologies, economic drivers, and geopolitical tensions in space. Their works and initiatives like Useful Fiction offer narrative scaffolding that can seed more expansive, imaginative wargames that challenge present-day assumptions and explore disruptive futures.<sup>137</sup>

### Operational Realities

A persistent shortfall in space wargaming is the tendency to “white-card” critical enablers such as launch, logistics, and orbital infrastructure—assuming they will be available without friction or delay. This assumption undermines the realism of cislunar scenarios, where distance,

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<sup>137</sup> “Useful Fiction - Useful Fiction Works at the Intersection of Strategic Narrative, Foresight and Change Management, Helping Organizations to Identify and Better Tell Their Key ‘Stories.’,” accessed May 2, 2025, <https://useful-fiction.com/>, <https://useful-fiction.com/>.

energy costs, and dependency on Earth-based supply chains introduce profound operational vulnerabilities.<sup>138</sup> Without robust modeling of these logistical challenges, wargames risk reinforcing an unrealistic sense of space as frictionless terrain, rather than a contested and resource-constrained environment.

### Institutional Barriers and Classification Challenges

Compounding these design gaps is the classification barrier: many space wargames operate under special access program (SAP) restrictions, limiting their content, lessons learned, and methodologies from broader academic, industry, and allied engagement.<sup>139</sup> This opacity constrains knowledge diffusion and inhibits the iterative refinement that comes from diverse stakeholder participation. Furthermore, prominent wargames like the Schriever Wargames often remain focused on nearer-term threats in LEO and GEO, leaving cislunar contingencies underexplored or sidelined.<sup>140</sup> As a result, cislunar space remains a conceptual blind spot in collective strategic education.

### Recommendations

Educational wargaming must deliberately counter this tendency by integrating not only military stakeholders but also industry, academia, and international partners into unclassified, collaborative settings. Doing so would mirror the multi-actor reality of future cislunar operations, fostering shared understanding of regulatory frameworks, dual-use technologies, and contested

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138 S. L. Nelson, “Adapt or Die: Redefining Wargaming for the Age of Algorithmic Warfare | RealClearDefense,” May 2, 2025, [https://www.realcleardefense.com/articles/2025/05/02/adapt\\_or\\_die\\_redefining\\_wargaming\\_for\\_the\\_age\\_of\\_algorithmic\\_warfare\\_1107614.html](https://www.realcleardefense.com/articles/2025/05/02/adapt_or_die_redefining_wargaming_for_the_age_of_algorithmic_warfare_1107614.html).

139 Mohammad Tasrif Khan, “The Future of Space Wargaming: Conflicting or Reasonable with What’s Ahead?,” *Space Education & Strategic Applications* 4, no. 4 (July 15, 2024): 3–27, <https://doi.org/10.18278/gsis.4.4.2>.

140 “Schriever Wargame 2025: Space Planning For Future Operations,” Space Systems Command, August 29, 2024, <https://www.ssc.spaceforce.mil/Newsroom/Article-Display/Article/3890751/https%3A%2F%2Fwww.ssc.spaceforce.mil%2FNewsroom%2FArticle%2F3890751%2Fschriever-wargame-2025-space-planning-for-future-operations>.

economic interests. Platforms like MOSAIC, developed by True Anomaly, illustrate how cloud-based, modular, and AI-enabled tools could facilitate accessible, adaptive wargames that accommodate a wider participant base while modeling complex orbital dynamics and competitive interactions.<sup>141</sup>

### Conclusion

Ultimately, educational wargaming for cislunar space in 2055 must be both imaginative and rigorous—challenging outdated assumptions, embedding logistical realism, and incorporating nontraditional actors. By drawing on speculative fiction, digital innovation, and inclusive design, these wargames can cultivate the foresight and strategic literacy necessary for navigating an emerging domain that blends commerce, competition, and cooperation far beyond Earth.

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<sup>141</sup> “Mosaic,” accessed April 29, 2025, <https://www.trueanomaly.space/mosaic>.

## Appendix B: Artificial Intelligence in Cislunar Operations<sup>142</sup>

Artificial intelligence (AI) has moved from niche augmentation to the connective tissue of every serious cislunar concept of operations.<sup>143</sup> Vast Earth–Moon distances, three-body orbital mechanics, light-second latencies, and a still-immature ground network force spacecraft, habitats, and logistics chains to think for themselves far more than traditional low-Earth-orbit missions. Machine-learning pipelines now steer navigation, space-domain awareness (SDA), surface robotics, and crew decision aids, providing civil agencies, defense planners, and commercial ventures a common technology path to a durable lunar presence.

### Why AI Matters Between Earth and Moon

Cislunar traffic—NASA projects more than thirty active lunar missions by 2030—must cope with intermittent line-of-sight, multi-minute command loops, and unfamiliar gravitational regimes.<sup>144</sup> AI mitigates three critical pain points:

- **Self-reliant navigation.** Sensor-fusion algorithms blend optical, star-tracker, range-and-bearing, and environmental cues, allowing spacecraft such as CAPSTONE to station-keep in Near-Rectilinear Halo Orbit (NRHO) with minimal ground intervention.<sup>145</sup>

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<sup>142</sup> ChatGPT, response to “Streamline this appendix down to 1000 words (count exclusive of tables and notes, avoiding numbered lists and preserving the use of tables,” May 5, 2025, OpenAI. See Appendix E for additional information

<sup>143</sup> National Aeronautics and Space Administration (NASA), *AI Strategic Plan 2024* (Washington, DC: NASA, 2024).

<sup>144</sup> NASA, “Moon to Mars Architecture: White Papers,” 2023, <https://www.nasa.gov/wp-content/uploads/2024/12/acr24-compiled-white-papers.pdf?emrc=f2e28d>.

<sup>145</sup> NASA, “What Is CAPSTONE?,” accessed April 15, 2025, <https://www.nasa.gov/smallspacecraft/capstone/>.

- **Persistent detection.** Computer-vision models filter faint satellites from star-rich backdrops, extending SDA beyond geosynchronous orbit and into Earth-Moon Lagrange points; AFRL’s Oracle pathfinder will be the first dedicated test.<sup>146</sup>
- **Hands-off surface operations.** Robotic excavators and additive-construction systems must perceive, plan, and recover from faults two light-seconds from Earth without constant human oversight, a principle that NASA’s VIPER rover will prove at the Moon’s south pole.<sup>147</sup>

*Current Capability Snapshot (2025)*

<b>Capability Area</b>	<b>Representative Demonstrations &amp; Metrics</b>
<b>Navigation &amp; Guidance</b>	CAPSTONE’s Cislunar Autonomous Positioning System proved peer-to-peer ranging and onboard orbit determination; commercial terrain-relative navigation achieves <100 m landing error. <sup>148</sup>
<b>Cislunar SDA</b>	The U.S. Space Force/AFRL <b>Oracle</b> pathfinder (launch 2025) will test onboard object classification at Earth–Moon L1; physics-informed ML cuts trajectory propagation error by an order of magnitude. <sup>149</sup>
<b>Launch &amp; Mission Ops</b>	SpaceX telemetry classifiers reduce Falcon 9 aborts; Rocket Lab applies ML to additive-manufactured engine QA and weather-constrained launch windows.
<b>In-Situ Resource Utilization</b>	NASA’s VIPER rover employs autonomous path planning to map south pole ice; a 2022 Centennial Challenge showcased multirobot excavation managed by a central AI scheduler. <sup>150</sup>
<b>Crew Support</b>	The ISS <b>CIMON</b> assistant enables context-aware voice interaction; Orion and Starship integrate AI caution and warning systems to rank alarms and propose corrective actions.

*Near-Term Trajectory (2025 – 2030)*

<b>Forthcoming Milestone</b>	<b>Operational Effect</b>
<b>LunaNet / Moonlight cooperative navigation constellation</b>	Offers global lunar positioning, navigation, and timing (PNT), freeing landers from Earth-based Doppler tracking. <sup>151</sup>
<b>First AI-driven traffic management prototypes</b>	Oracle-seeded catalogs will generate conjunction alerts within minutes, accelerating maneuver coordination across actors. <sup>152</sup>

146. Air Force Research Laboratory, “Oracle Pathfinder Program Overview,” in *Industry Study Papers*, April 2025.

147 NASA, “Why Artemis Will Focus on the Lunar South Polar Region,” 2022.

148 NASA, “What Is CAPSTONE?”

149 Air Force Research Laboratory, “Oracle Pathfinder Program Overview.”

150 Bernardo Martinez Rocamora et al., “Multi-robot Cooperation for Lunar In-Situ Resource Utilization,” *Frontiers in Robotics and AI* 10 (March 23, 2023), 1-23, <https://www.frontiersin.org/journals/robotics-and-ai/articles/10.3389/frobt.2023.1149080/full>

151 Katherine Schauer and Danny Baird, “LunaNet: Empowering Artemis with Communications and Navigation Interoperability,” NASA, October 7, 2021, <https://www.nasa.gov/humans-in-space/lunanet-empowering-artemis-with-communications-and-navigation-interoperability/>.

152 Air Force Research Laboratory, “Oracle Pathfinder Program Overview.”

<b>Autonomous surface campaigns</b>	Reinforcement learning (RL) schedulers will orchestrate regolith excavation, electrolysis, and 3D printing while balancing power margins and eclipse periods. <sup>153</sup>
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### Mid-Term Vision (2030 – 2040)

- **Autonomous lunar base.** Multi-agent planners dispatch haulers, excavators, and additive-manufacturing rigs while adapting to tool wear, dust adherence, and crew absence.
- **Space logistics network.** Generative-design engines co-optimize depot architectures and tanker routes; marketplace algorithms price delta-v, cryogenic boil-off, and launch manifests in real time.
- **Fail-operational crew vehicles.** AI flight directors will handle nominal burns, safe-mode entries, and contingency landings, leaving astronauts with ultimate veto authority but far less routine workload.

### *Risks and Limitations*

<b>Risk Vector</b>	<b>Challenge</b>	<b>Emerging Mitigation</b>
<b>Verification &amp; Trust</b>	Adaptive models resist traditional test-as-you-fly certification.	"Bounded autonomy" modes and posth-oc interpretability layers are contemplated by readiness models. <sup>154</sup>
<b>Sparse Training Data</b>	Few real lunar datasets exist; sim-to-real gaps persist.	Physics augmented networks and domain randomization to harden models.
<b>Dual-Use Ambiguity</b>	Servicing arms and proximity sensors can repair—or disable—satellites.	Greater transparency, intent broadcasting, and interoperable SDA data exchanges.
<b>Cyber-Physical Threats</b>	Radiation upsets and cyber intrusions target shared AI stacks.	Triplicated fault-tolerant processors and formal-methods hardening.

### Human Oversight Still Matters

Historic rescues—from Apollo 14’s manual re-entry to JWST sunshield

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153 NASA Jet Propulsion Laboratory, “The Lunar Gold Rush: How Moon Mining Could Work,” accessed April 15, 2025, <https://www.jpl.nasa.gov/infographics/the-lunar-gold-rush-how-moon-mining-could-work/>.

154 Kerianne L. Hobbs et al., “Space Trusted Autonomy Readiness Levels,” paper presented at the 2023 IEEE Aerospace Conference, Big Sky, MT, March 4–11, 2023, 2-6, <https://doi.org/10.1109/AERO55745.2023.10115976>.

troubleshooting—underscore the value of intuitive human judgment when sensors lie or dynamics change. For at least the next decade, crews and mission controllers will remain on-the-loop for abort calls, crew-rated landings, and unmodeled contingencies. NASA’s own autonomy guidance stresses “trusted autonomy” with easy human override.<sup>155</sup> AI shifts the workload, not the ultimate accountability.

### Strategic Implications

- AI multiplies lean operations cadre, an essential advantage as lunar sortie rates grow tenfold.
- Early U.S. deployments—Oracle, Gateway autonomy—shape data-exchange norms before rival models become de facto standards.<sup>156</sup>
- Successes in navigation, mining, and logistics feed terrestrial spin-offs (edge-AI, resilient autonomy), creating an economic flywheel for further exploration.<sup>157</sup>

### Priority Recommendations

<b>Recommendation</b>	<b>Rationale</b>
<b>Expand open lunar datasets.</b>	Rich, labeled telemetry and imagery accelerate community model training and validation.
<b>Deploy a Cislunar Autonomy Testbed.</b>	Radiation-hardened edge-computed edge-compute boards on CLPS landers let updates fly in situ and derisk later crewed missions.
<b>Codify traffic-management APIs within the Artemis Accords.</b>	Machine-readable, cryptographically signed state vectors enable rapid, trusted maneuver adjudication.
<b>Invest in formal methods / ML-assurance research.</b>	Blending mathematical proofs with runtime anomaly detection paves a path to certifiable adaptive systems.

### Conclusion

AI is transforming cislunar operations from episodic, Earth-dependent sorties into a

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<sup>155</sup> Michael Freed, Pete Bonasso, Mitch Ingham, David Kortenkamp, Barney Pell, and John Penix, “Trusted Autonomy for Space Flight Systems” (paper presented at the AIAA 1st Space Exploration Conference, Orlando, FL, January 29–February 1, 2005), NASA Technical Reports Server (Document ID 20050156644), 1, <https://ntrs.nasa.gov/api/citations/20050156644/downloads/20050156644.pdf> (accessed May 2, 2025).

<sup>156</sup> Air Force Research Laboratory, “Oracle Pathfinder Program Overview.”

<sup>157</sup> NASA Jet Propulsion Laboratory, “The Lunar Gold Rush.”

resilient, scalable ecosystem. Demonstrations this decade will mature into integrated autonomy in the 2030s, unlocking affordable lunar logistics, continuous surface industry, and safer human journeys to Mars. That future rests on transparent early deployments, rigorous validation, and balanced human-machine teaming today.

## Appendix C: Science Fiction in the Cislunar Domain

Space has captivated human imagination, inspiring centuries of poetry, painting and prose. One of the earliest known works of science fiction, dating to the 2nd century AD, recounts the tale of a Greek sheep blown to the surface of the Moon.<sup>138</sup> In a domain like cislunar space – where practical warfighting remains limited – imagination must be considered an essential tool for strategic planning. This means embracing non-traditional sources of insight, including speculative fiction. As strategist Mick Ryan argues, "Reading fiction, especially science fiction, can nurture the imaginative mindset in the military and national security professional."<sup>139</sup> Science fiction offers more than just escapism; it provides a scenario-based framework for exploring emerging dilemmas. For policymakers, speculative fiction offers a tool to visualize extreme yet plausible futures – such as a battle for cislunar resources or a militarized Chinese Moon base. Imagination in operational planning should not be seen as a luxury; it is a strategic necessity.

Today, that includes Large Language Models (LLMs) like ChatGPT, Claude, and Grok, which have demonstrated the potential to revolutionize the military through rapid adaptability. As one recent analysis surmised, "LLMs allow planners to define brand-new structures, fundamentally transforming our ability to adapt to unexpected conditions with unparalleled strategic flexibility."<sup>158</sup> In the context of the space domain, that means developing approaches that can bridge the conceptual and operational gap between Earth-bound conflict and warfighting in the heavens above.

The Space IS asked the ChatGPT LLM to imagine a future where U.S. leadership and advantage in cislunar space were lost. The year is 2055....

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<sup>158</sup> Ben Van Roo, "Tabletop Exercises Are Old School. But Are LLMs Better at War Planning?" Beyond Visual Range, Substack, November 2024. <https://benvanroo.substack.com/p/tabletop-exercises-are-old-school>. Accessed May 11, 2025.

## Clearance Pending

The dim glow of dawn illuminated Kennedy Space Center's Launch Complex Pad 39A, casting a stark silhouette of a towering rocket and its scaffolding against the pale Florida sky. Once the launch site of Apollo 11, where Neil Armstrong and Buzz Aldrin began humanity's first journey to the Moon, it now serves a new generation under very different circumstances. Inside the brightly lit command center, Mark Hamilton nervously adjusted his headset, eyes darting between his digital tablet and the massive monitor displaying pre-launch diagnostics. Instead of finalizing rocket telemetry or orbital insertion data, Mark and his colleagues were rehearsing diplomatic protocol.

"Wǒmen yào qǐngqiú rùjìng quánxiàn ((我们要请求入境权限)," Mark said carefully, his tone hesitant. *We request entry clearance.*

"Close," Mei Lin, the team's protocol officer, offered, nodding encouragingly. "But remember the ICB prioritizes precision in official communications – especially with high-traffic lunar corridors."

Mark exhaled sharply. "I didn't sign up for this," he muttered under his breath.

Beyond the glass, the American flag painted across the rocket's fuselage stood out starkly—a bold emblem of a legacy now in question. Though the launch platform bore a U.S. seal, final approval rested with the International Cislunar Bureau (ICB)—a governing consortium established by early lunar stakeholders, led by China, Russia, and their allies. With their sustained investment in cislunar logistics and lunar-surface infrastructure, the ICB had claimed regulatory authority over transit, landing rights, and resource zones across the Moon's most strategic regions.

"Again," Mei said firmly. "Clearance requests must include your orbital trajectory, payload manifest, and all resource access plans."

Mark nodded grimly. Around him, his colleagues glanced up from consoles filled with blinking indicators and scrolling telemetry. The room felt heavier than it should have—weighted with the consequences of missed opportunity.

Back in 2025, it all seemed manageable. The warnings, the early missions by competitor nations, the incremental buildup of permanent outposts at the lunar south pole—all easy to dismiss amid Earthbound crises. But one policy delay after another turned temporary setbacks into structural disadvantages. Now, the Bureau's central hub oversaw both lunar navigation and export operations—an economic and strategic chokepoint the U.S. once aimed to create.

"Once more," Mei said. "This time with confidence."

Mark steadied himself. "Wǒmen yào qǐngqiú rùjìng quánxiàn."

"Good," she replied. "Now, prepare for the scenario in which access is deferred due to regional congestion or pending adjudication by the Resource Allocation Council. The Bureau's response may take hours."

Outside, banners hung across the complex reading "*Future Forward, Together*"—a carefully chosen phrase of diplomatic optimism. Yet to some in the room, the slogan echoed a deeper truth: that the future had indeed moved forward—without them.

A technician leaned over quietly. "Feels like we're always last to the table."

Mark didn't respond at first. He stared at the Moon on the live feed from orbit, glinting just above the horizon. Then, softly: "We had our chance. We didn't take it."

The countdown timer glowed steadily: twenty-four hours until launch. The test ahead wasn't just of engineering or endurance. It was a test of humility, of negotiation, and of whether a once-dominant spacefaring nation could learn to operate in a world it no longer led.

## Appendix D: AI Prompts and Output for Executive Summary

### Prompt

“Please create an executive summary for the attached group paper.”

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 DRAFT - Space Industry Group Pap...  
Document

Please create an executive summary for the attached group paper.

Based on the full review of your group paper titled *[Title TBD]* for the AY 2024–2025 Space Industry Study at the Dwight D. Eisenhower School, here is a draft **Executive Summary**:

### Executive Summary

The United States faces a strategic inflection point: it must act decisively to secure the cislunar domain—the region of space between geosynchronous Earth orbit and the Moon—or risk ceding this critical high ground to global competitors like China and Russia. This paper argues that cislunar space is the 21st-century equivalent of the maritime commons Alfred Thayer Mahan once deemed central to national power. As space becomes increasingly commercialized and contested, a deliberate U.S. strategy is essential to preserve freedom of maneuver, enable economic expansion, and set the normative foundations for responsible behavior beyond Earth orbit.

Drawing from field studies across the United States and Japan and incorporating insights from government, industry, and academic stakeholders, this analysis examines the current strategic environment, innovation trends, supply chain dynamics, and governance gaps shaping the Earth–Moon system. It identifies a growing risk from adversarial civil–military fusion efforts, ambiguous legal regimes, and a lack of cohesive U.S. infrastructure and investment coordination in the cislunar domain. Meanwhile, opportunities abound in infrastructure-first advantages, in-space servicing and manufacturing, lunar resource extraction, and public-private partnerships that can catalyze a projected \$100 billion+ cislunar economy.

The paper recommends a comprehensive approach anchored by three integrated Lines of Effort:

- 1. Consolidate U.S. Leadership:** Establish a U.S. Department of Space to centralize civil and commercial space governance, create an International Space Infrastructure Bank to mobilize allied investment, and lead new global standard-setting organizations for cislunar operations.
- 2. Build and Secure Cislunar Infrastructure:** Invest in a domain awareness architecture, resilient communications and navigation systems, and in-space logistics platforms such as depots and reusable transport vehicles to anchor a durable American presence.
- 3. Cultivate the Private-Sector Cislunar Economy:** Generate stable demand through long-term government contracts, pass a Space Resources Act to incentivize lunar extraction, expand innovation financing tools, and launch international innovation hubs to align global industry with U.S. standards.

The report also underscores the importance of educational wargaming and artificial intelligence in shaping future cislunar strategies, highlighting the need for scenario-driven learning and autonomous operational capabilities. The time to act is now. As Mahan once warned, “Whether they will or no, Americans must now begin to look outward.” The cislunar domain will define the next era of strategic competition, and the United States must lead—or be led.

## Appendix E: AI Prompts and Outputs for Appendix B - AI in Cislunar Operations

Prompt:

“Streamline this appendix down to 1000 words (count exclusive of tables and notes), avoiding numbered lists and preserving the use of tables.”

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### Appendix B: Artificial Intelligence in Cislunar Space Operations

Artificial intelligence has emerged as a crucial component in today's space industry. AI systems are becoming indispensable for managing increasingly complex operations within the cislunar domain. This appendix explores how AI is transforming cislunar activities, examining current applications, projected developments through 2030, and potential advancements by 2040. We delve into key areas including spacecraft navigation, space domain awareness, launch operations, and in-situ resource utilization. The appendix addresses legitimate concerns about deploying AI in high-stakes scenarios involving crewed missions or valuable spacecraft, with case studies highlighting why human oversight remains essential in certain contexts.

#### AI in Cislunar Space: Overview and Context

Cislunar space is quickly emerging as a domain of strategic significance as both government agencies and private companies prepare for long-term lunar exploration initiatives. By 2030, more than 30 missions are expected to operate in cislunar space—ranging from NASA's ambitious Artemis program to various commercial lunar landing ventures.<sup>159</sup> This increasing traffic introduces unique operational challenges that AI is particularly well-positioned to address.

Unlike the more familiar Earth orbital environment, cislunar operations involve complex three-body gravitational dynamics (Earth-Moon-spacecraft) and limited supporting infrastructure, necessitating higher levels of autonomous operation. Machine learning algorithms and autonomous decision-making systems can enable spacecraft to navigate effectively with intermittent Earth contact, identify and track objects in distant lunar orbits, and manage onboard systems in unpredictable conditions.

According to the U.S. Air Force Research Laboratory, operating safely within cislunar space will demand new technological capabilities for object detection, trajectory prediction, and collision avoidance that go beyond conventional approaches.<sup>160</sup> Industry experts further emphasize an urgent need for sophisticated AI solutions as space becomes increasingly "competitive, congested, and contested," with projections indicating tens of thousands of satellites—including numerous lunar missions—will be operating by 2030.<sup>161</sup>

AI in this context represents an evolution of spaceflight automation that has been

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<sup>159</sup> Brian Baker-McEvelly, Sebastian Doroba, Annika Gilliam, Franco Criscola, David Canales Garcia, Carolin Frueh, and Troy Henderson, “A Review on Hot-Spot Areas within the Cislunar Region and upon the Moon Surface, and Methods to Gather Passive Information from These Regions” (paper presented at the 33rd AAS/AIAA Space Flight Mechanics Meeting, Austin, TX, January 15–19, 2023), AAS 23-194, <https://commons.erau.edu/discovery-day/db-discovery-day-2023/poster-session-2/26/> (accessed May 1, 2025).

<sup>160</sup> Booz Allen Hamilton, “Linking Large Language Models for Space Domain Awareness,” *Defense One*, January 12, 2024

<sup>161</sup> Booz Allen Hamilton, “Linking Large Language Models”

developing for decades, now extending capabilities into domains where direct human control simply isn't feasible. While NASA has employed AI for years in applications like Martian rover navigation and satellite observation scheduling, these technological approaches are now being adapted and enhanced for the more immediate challenge of lunar exploration and cislunar operations.<sup>162</sup>

The applications of AI in cislunar space aren't merely theoretical, they're already addressing practical challenges that would otherwise limit mission effectiveness. Table 1 provides a snapshot of representative AI applications within the cislunar environment, demonstrating how these technologies are currently enhancing mission capabilities and how they're expected to evolve in the coming years. These examples highlight the transition from AI as an optional enhancement to its role as a fundamental enabler of sustainable cislunar operations.

**Table 1. Current and Near-Term AI Applications in Cislunar Space (through ~2030)**

Domain	AI Application	Examples and Status	Benefits in Cislunar Context
<b>Navigation &amp; Guidance</b>	Autonomous navigation for spacecraft; terrain-relative navigation for landers; trajectory optimization	<i>CAPSTONE</i> CubeSat testing autonomous orbit navigation (CAPS; Terrain Relative Navigation on lunar landers (e.g. precision landing algorithms used in Artemis program landers) <sup>163</sup>	Reduces reliance on Earth tracking, enables precise orbit insertion and landing in lunar gravity environment
<b>Space Domain Awareness</b>	AI-assisted object tracking and orbit prediction beyond GEO; sensor data processing (computer vision)	AFRL's <i>Oracle</i> satellites (2025–27) with onboard AI to detect and track objects near the Moon; University research using physics-informed machine learning to improve orbit predictions in cislunar space <sup>164</sup>	Automates detection of satellites/debris around Moon, handles complex three-body orbits, and predicts trajectories for collision avoidance
<b>Launch &amp; Mission Operations</b>	AI for launch vehicle telemetry analysis, anomaly detection, and mission planning; predictive maintenance; automated launch processes	SpaceX & Rocket Lab use AI for launch pad automation, trajectory planning, and real-time telemetry analysis. Rocket Lab employs ML for engine 3D-printing QC and predictive maintenance of launch systems. NASA testing AI for range safety and weather forecasting. <sup>165</sup>	Improves launch success rate and efficiency through early fault detection and optimized flight trajectories; reduces human error in complex countdown and flight operations
<b>In-Situ Resource Utilization</b>	Autonomous robotic resource prospecting, mining, and processing; multi-robot coordination via AI planners	NASA's VIPER rover (2024) will use autonomous navigation to seek water ice at lunar south pole. The NASA/OSAM <i>Space Robotics Challenge</i> demonstrated cooperative robotic mining in simulation (See Figure 1). Caterpillar & NASA developing autonomous excavators (e.g. <i>IPEX</i> demo) to build lunar	Enables continuous resource extraction without constant teleoperation (critical due to 1–3 second communication delays); multiple AI-driven robots can work in tandem to excavate regolith and produce water or fuel, supporting a sustainable lunar base

<sup>162</sup> “Artificial Intelligence – NASA,” *NASA*, accessed May 1, 2025

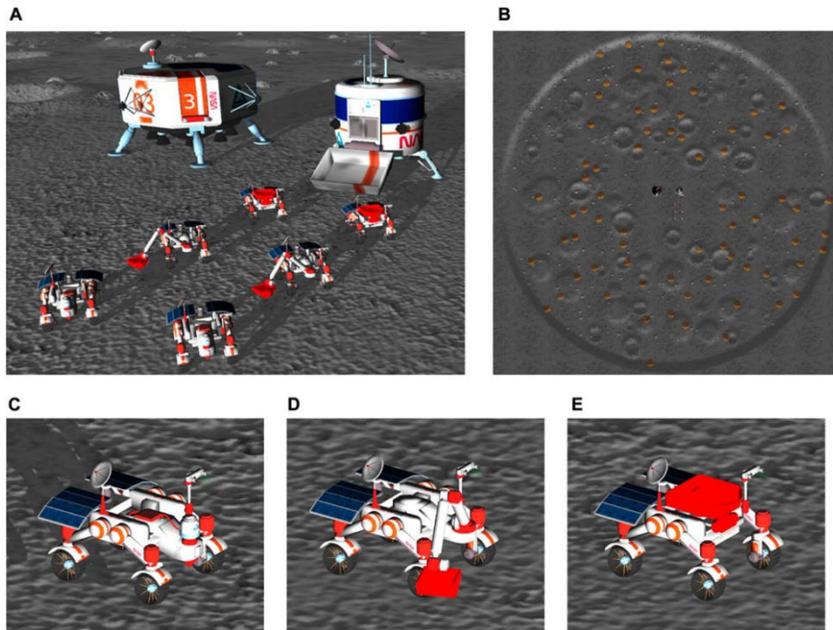
<sup>163</sup> Advanced Space, “CAPSTONE™

to Host Additional Experiments to Support Technology Shortfalls for Cislunar Space,” *Missions* (blog), April 2, 2025, <https://advancedspace.com/capstone-to-host-additional-experiments-to-support-technology-shortfalls-for-cislunar-space/> (accessed May 2, 2025).

<sup>164</sup> Theresa Hitchens, “Oracle’s Vision: Understanding Cislunar Satellite Images Poses AFRL’s ‘Biggest’ Challenge,” *Breaking Defense*, November 28, 2022, <https://breakingdefense.com/2022/11/oracles-vision-understanding-cislunar-satellite-images-poses-afrls-biggest-challenge/> (accessed May 2, 2025); Stephanie Doster, “UArizona Researchers Develop AI-Powered Methods to Improve Safety in Space,” *Space4 Center News* (University of Arizona), September 7, 2023, <https://s4.arizona.edu/news/uarizona-researchers-develop-ai-powered-methods-improve-safety-space> (accessed May 2, 2025).

<sup>165</sup> MarketsandMarkets, “AI Impact Analysis on the Rocket and Missile Industry,” *Research Insight* (blog), April 25, 2025, <https://www.marketsandmarkets.com/ResearchInsight/ai-impact-analysis-rocket-missile-industry.asp> (accessed May 2, 2025); Melvine Manchau, “How Rocket Lab is Using AI to Revolutionize Space Exploration: The Future of Generative AI in Aerospace,” LinkedIn, Oct 2023, <https://www.linkedin.com/pulse/how-rocket-lab-using-ai-revolutionize-space-future-in-depth-manchau-b1ske#>.

Domain	AI Application	Examples and Status	Benefits in Cislunar Context
		infrastructure. <sup>166</sup>	
<b>Crew Support</b> (LEO→Cislunar)	Intelligent assistants for astronauts; autonomous habitat systems management	<i>CIMON</i> AI assistant on ISS (since 2018) understands voice commands to help crew with information. For Artemis lunar missions, AI-driven systems will monitor spacecraft life support and advise crew (e.g. caution and warning systems with AI anomaly detection).	Augments crew capabilities during lunar missions, providing decision support and reducing cognitive load; can maintain habitat operations when crew are absent (as will be the case on Gateway station between visits)



**Figure 1.** Multi-robot autonomy for lunar ISRU demonstrated in simulation. A team of AI-controlled rovers (scout, excavator, hauler) cooperatively searches for and collects simulated resources, supervised by a central autonomous planner. This 2022 NASA challenge showed that coordinated robotics can perform complex lunar mining tasks autonomously, a key capability for future lunar bases.<sup>167</sup>

As demonstrated above, AI integration across cislunar activities is already well underway. During this decade, these applications largely occupy the technology demonstration phase or early operational deployment: NASA's CAPSTONE mission in 2022–23 successfully validated an autonomous navigation system in lunar orbit, demonstrating that spacecraft can determine their position through peer-to-peer ranging with the Lunar Reconnaissance Orbiter without requiring continuous ground tracking. This Cislunar Autonomous Positioning System represents an "autopilot" experiment that lays groundwork for more self-sufficient navigation capabilities on the upcoming Lunar Gateway.<sup>168</sup>

In the space domain awareness arena, the U.S. Space Force's Oracle project (previously known as the Cislunar Highway Patrol System) plans to deploy a satellite to the Earth-Moon L1 point by 2025. This spacecraft will carry AI-enhanced vision systems designed to detect and classify objects against star-

<sup>166</sup> Rachel Wallace, "Caterpillar & NASA: Autonomous Technology on the Moon," *Cat® Blog* (Caterpillar), January 8, 2024, [https://www.cat.com/en\\_US/blog/nasa-using-caterpillar-technology.html](https://www.cat.com/en_US/blog/nasa-using-caterpillar-technology.html) (accessed May 2, 2025); Bernardo Martinez Rocamora et al., "Multi-robot Cooperation for Lunar In-Situ Resource Utilization," *Frontiers in Robotics and AI* 10 (March 23, 2023): fig. 1, <https://www.frontiersin.org/journals/robotics-and-ai/articles/10.3389/frobt.2023.1149080/full> (accessed May 2, 2025).

<sup>167</sup> Rocamora, "Multi-robot Cooperation," fig. 1.

<sup>168</sup> Advanced Space, "CAPSTONE™ To Host Additional Experiments to Support Technology Shortfalls for Cislunar Space," press release, April 2, 2025, [advancedspace.com](https://www.advancedspace.com).

dense backgrounds—a capability that Air Force officials identify as their "biggest challenge" due to the unfamiliar perspective and necessity for onboard processing.<sup>169</sup>

Closer to home, launch providers are increasingly leveraging AI capabilities: SpaceX's Falcon 9 employs automated guidance and control systems for booster recovery, while companies like Rocket Lab implement machine learning for trajectory optimization and engine monitoring, alongside AI-driven mission control software that identifies anomalies in real time. These innovations enhance reliability for the frequent launches required to support expanding cislunar operations.

On the lunar surface itself, autonomy becomes essential. NASA's Artemis program envisions deploying robotic assets for reconnaissance and construction in advance of human arrival. The VIPER rover, scheduled for 2024, will autonomously navigate challenging terrain at the lunar south pole to map water ice deposits.<sup>170</sup> Within the coming years, likely by the late 2020s, NASA and its partners aim to demonstrate in-situ resource utilization by extracting oxygen from lunar regolith or ice deposits.

Caterpillar Inc., drawing on its extensive experience developing self-driving mining equipment for terrestrial applications, has collaborated with NASA since 2007 on lunar excavation robotics. Their In-Situ Pilot Excavator prototype will test autonomous excavation capabilities as part of Artemis infrastructure development.<sup>171</sup> These systems integrate robotics, computer vision for environmental perception, and sophisticated planning algorithms to function with minimal human intervention. The advantages are substantial: autonomous ISRU operations could continue uninterrupted to produce water, fuel, or construction materials even during periods without human presence, dramatically expanding the scope and sustainability of lunar activities.<sup>172</sup>

### Mid-Term Prospects (2030–2040): Expanding AI's Role

Looking further ahead to the 2030–2040 timeframe, AI will likely evolve from being merely a supporting tool to becoming a fundamental layer of cislunar infrastructure. By 2030, many of today's early demonstrations will have matured into fully operational systems. By 2040, assuming current trajectories continue, AI could enable capabilities that remain largely aspirational today. Table 2 outlines several anticipated mid-term developments and their expected impact.

**Table 2. Mid-Term AI-Driven Developments in the Cislunar Domain (2030–2040)**

Area	Projected Development (2030–2040)	Description & Rationale
<b>Autonomous Navigation</b>	<b>Lunar GPS and AI-guided trajectories:</b> Constellations of lunar-orbit satellites (e.g. NASA's LunaNet, ESA's Moonlight) providing navigation signals, augmented by onboard AI for real-time orbit determination and hazard avoidance	Space agencies plan to deploy lunar communication and navigation networks by the late 2020s. By the 2030s, spacecraft will use AI to seamlessly fuse signals, star-tracker data, and perhaps vision-based landmark recognition for pinpoint navigation in cislunar space. This will enable <b>routine transit between Earth and Moon with minimal ground support</b> , as well as autonomous station-keeping in unstable orbits (e.g. Gateway's NRHO). <sup>173</sup>
<b>Space Domain Awareness &amp; Traffic</b>	<b>AI-managed Space Traffic Control:</b> Integrated monitoring of thousands of objects from LEO through lunar orbit, using	With the anticipated surge in lunar missions and megaconstellations, manual tracking will be infeasible. By mid-2030s, AI systems could aggregate data from ground telescopes, lunar orbit sensors, and

169 Franchesca Conner, "AFRL's Oracle developing nation's 1st Cislunar Space Situational Awareness capabilities," *Air Force Research Laboratory News*, Dec 11, 2023, <https://breakingdefense.com/2022/11/oracles-vision-understanding-cislunar-satellite-images-poses-afrls-biggest-challenge/#:~:text=match%20at%20L294%20Oracle%20has,number%20of%20spacecraft%2C%20he%20explained>

170 Rocamora, "Multi-robot cooperation," 1-23,

171 NASA, "Overview: In-Situ Resource Utilization," *NASA* (web page), accessed May 1, 2025, [https://www.cat.com/en\\_US/blog/nasa-using-caterpillar-technology.html#:~:text=technology%20to%20develop%20its%20own,part%20of%20the%20Artemis%20mission](https://www.cat.com/en_US/blog/nasa-using-caterpillar-technology.html#:~:text=technology%20to%20develop%20its%20own,part%20of%20the%20Artemis%20mission).

172 Rocamora, Multi-robot cooperation for lunar"

173 Clark P. Newman et al., "Stationkeeping, Orbit Determination, and Attitude Control for Spacecraft in Near Rectilinear Halo Orbits" (paper presented at the AAS Astrodynamics Specialists Conference, Snowbird, UT, August 19–23, 2018), NASA Technical Reports Server (Document ID 20180006800), 17, <https://ntrs.nasa.gov/citations/20180006800> (accessed May 2, 2025).

Area	Projected Development (2030–2040)	Description & Rationale
<b>Management</b>	distributed sensors and AI analytics to predict conjunctions and orchestrate avoidance maneuvers	perhaps <b>Moon-based observatories</b> , to maintain a space catalog. AI would continuously update orbital trajectories in the complex Earth-Moon gravitational environment and issue collision warnings or maneuver commands autonomously. This extends today’s SSA into a <b>comprehensive cislunar traffic management system</b> . <sup>174</sup> The U.S. Space Force’s early cislunar SSA experiments (Oracle-M/P) in 2025–27 are first steps toward this goal. <sup>175</sup>
<b>Robotic Operations &amp; ISRU</b>	<b>Autonomous Lunar Base Operations:</b> AI control of mining facilities, power systems, and habitats on the Moon with human supervisors largely “on the loop” rather than on site	By the late 2030s, a permanent lunar outpost is envisioned. Given the expense and risk of continuous human presence, much of the base’s routine functions may be handed over to AI: fleets of mining robots could dig and process regolith for water/oxygen extraction, guided by AI planners that allocate tasks and handle contingencies (e.g. robot failures). <sup>176</sup> AI would also regulate life support and power distribution in habitats when crew are Earthside. This concept builds on autonomy technologies proven earlier – for example, multi-robot coordination algorithms, like those from NASA’s 2022 challenge (Figure 1), scaled up to real operations. <b>Mining and construction robots from commercial partners (e.g. Caterpillar)</b> would by then have extensive operational data, making autonomous lunar mining by 2040 a tangible reality.
<b>Launch &amp; Space Logistics</b>	<b>AI-optimized launch and supply chain:</b> Global launch scheduling and in-space cargo routing managed by AI, plus <b>intelligent spacecraft design</b> via generative AI	As cislunar commerce grows, timely delivery of payloads (satellites, supplies, propellant, etc.) becomes critical. By 2040, AI could be coordinating launch windows and orbits across multiple spaceports and providers to maximize efficiency and minimize conflicts, essentially acting as an air-traffic control for space launches. In spacecraft manufacturing, mid-2030s should see wider use of AI-driven generative design to produce lighter, more reliable spacecraft and landers. <sup>177</sup> AI may also manage on-orbit servicing depots and tug routes, determining the best way to ferry cargo between Earth orbit, Gateway, and lunar surface. The result would be a <b>highly autonomous Earth-Moon supply chain</b> , with reduced cost and latency for projects.
<b>Human Missions</b>	<b>Advanced Crew Assistance &amp; Autonomy:</b> Human crews work with AI copilots for deep-space travel; AI systems handle more spacecraft control under human oversight. Crew vehicles and habitats incorporate “fail-operational” autonomy (can continue safe function even if crew become incapacitated)	For missions deeper into the solar system (e.g. Mars), which may be underway by late 2030s, AI will be indispensable. Technologies proven in cislunar space can be transferred. By this stage, even Moon missions might use an “ <b>AI Commander</b> ” in a limited capacity – for instance, Orion or a lunar lander’s guidance AI could execute an entire mission profile if needed, with astronauts intervening only if something deviates. Crew will have AI assistants far more capable than today’s Siri/Alexa, integrated with vehicle systems. NASA is already examining how to increase crew autonomy with trusted AI for long-duration missions. <sup>178</sup> By 2040, the balance may shift such that <i>most routine decisions are left to AI</i> , allowing astronauts to focus on exploration and responding to the unexpected. That said, final

<sup>174</sup> Stephanie Doster, “UArizona Researchers Develop AI-Powered Methods to Improve Safety in Space,” *Space4 Center News* (University of Arizona), September 7, 2023, <https://s4.arizona.edu/news/uarizona-researchers-develop-ai-powered-methods-improve-safety-space> (accessed May 2, 2025).

<sup>175</sup> Franchesca Conner, “AFRL’s Oracle Developing Nation’s 1st Cislunar Space Situational Awareness Capabilities,” *Air Force Research Laboratory News*, December 11, 2023, <https://afresearchlab.com/news/afrls-oracle-family-of-systems-developing-nations-1st-cislunar-space-situational-awareness-capabilities/> (accessed May 2, 2025).

<sup>176</sup> Rocamora, “Multi-robot Cooperation.”

<sup>177</sup> Manchau, “How Rocket Lab is Using AI.”

<sup>178</sup> NASA, “The Role of Trust and Usability in Enabling Spaceflight Crew Autonomy,” presentation at AIAA ASCEND 2022, [https://humansystems.arc.nasa.gov/publications/AIAA\\_ASCEND\\_2022\\_Trust\\_Usability\\_Experimental\\_Results.pdf](https://humansystems.arc.nasa.gov/publications/AIAA_ASCEND_2022_Trust_Usability_Experimental_Results.pdf); NASA, “The Role of Trust; Fernando Figueroa, “Trusted Autonomy and the NASA Platform for Autonomous Systems (NPAS)” (presentation, Space Trusted Autonomy Working Group Technical Talk, virtual, May 19, 2022), NASA Technical Reports Server (Document ID 20220008322),

Area	Projected Development (2030–2040)	Description & Rationale
		critical decisions (dockings, landings) may still involve human judgment as an extra safeguard, as discussed next.

The progression of AI in cislunar operations represents a shift from isolated applications to integrated systems that work in concert across multiple domains. What begins as individual technology demonstrations this decade will gradually coalesce into a more comprehensive autonomous ecosystem supporting sustained lunar presence. This evolution mirrors previous technological transitions in spaceflight, where capabilities once considered extraordinary eventually become standard operational practice.

As these systems mature, we'll likely see a transition from Earth-dependent operations to increasingly self-sufficient lunar activities, with AI serving as the connective tissue between various mission elements. The implications extend beyond technical feasibility to fundamentally reshape mission planning, resource allocation, and even organizational structures supporting cislunar development.

In essence, the mid-term vision positions AI as an integral component woven throughout every dimension of cislunar operations—from subterranean mining activities to orbital satellite constellations to strategic traffic management and mission planning. Autonomy fundamentally enables scalability: as we work toward establishing a sustainable lunar presence and eventually Mars expeditions, AI serves as the crucial force multiplier allowing a limited number of ground controllers or astronauts to oversee an extensive, intricate system of systems.

This trajectory is clearly reflected in both industry roadmaps and government strategies. NASA's 2024 AI Strategic Plan emphasizes the expansion of autonomous space operations, highlighting successes like the Mars Perseverance rover's AI navigation capabilities while outlining plans for greater AI implementation in lunar exploration efforts.<sup>179</sup> Similarly, the European Space Agency is investing in research focused on AI for onboard data processing and spacecraft health management to develop more self-reliant missions.<sup>180</sup>

By 2040, we can reasonably expect typical lunar missions to feature spacecraft that primarily navigate themselves, ground systems that intelligently prioritize thousands of tracking assignments, and robotic assistants that prepare lunar sites for human arrival or maintain equipment during periods without human presence. This progression reflects not just technological advancement but a fundamental shift in how we conceptualize and execute space operations beyond Earth orbit.

Yet, amid this optimistic outlook, space agencies maintain a pragmatic perspective regarding the risks and limitations of AI systems. The final section addresses these important counterpoints—providing essential context for understanding why AI, despite its considerable advantages, will not entirely supplant human control in the most critical operational scenarios for the foreseeable future.

This balanced approach acknowledges both the transformative potential of autonomous

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<sup>179</sup> Kate Halloran, “NASA’s AI Use Cases: Advancing Space Exploration with Responsibility,” *NASA*, January 7, 2025, <https://www.nasa.gov/organizations/ocio/dt/ai/2024-ai-use-cases/#:~:text=NASA%E2%80%99s%202024%20AI%20Use%20Case,as%20navigation%20for%20the%20Perseverance>.

<sup>180</sup> European Space Agency (ESA), “Using AI for More Reliable Space Missions,” *Enabling & Support – Discovery and Preparation*, January 30, 2025, [https://www.esa.int/Enabling\\_Support/Preparing\\_for\\_the\\_Future/Discovery\\_and\\_Preparation/Using\\_AI\\_for\\_more\\_reliable\\_space\\_missions](https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/Using_AI_for_more_reliable_space_missions) (accessed May 1, 2025).

systems and the prudent caution that characterizes space mission planning. The tension between increasing autonomy and maintaining appropriate human oversight represents one of the central challenges in advancing cislunar operations. By examining specific limitations and risks, we gain a more nuanced understanding of how AI will likely be integrated into space systems—not as a wholesale replacement for human judgment, but as a sophisticated tool that extends human capabilities while preserving critical decision authority where it matters most.

### **Counterarguments: Why Humans Still Matter in High-Stakes Missions**

Despite AI's growing capabilities, compelling arguments exist against fully embracing autonomous systems in crewed spacecraft or high-value missions where recovery isn't possible. Space leaves no room for error—mistakes can cost lives or destroy billion-dollar assets. Historically, mission managers have viewed novel, unproven AI as "an unacceptable source of risk," often choosing not to deploy these systems on critical missions.<sup>181</sup> Several considerations underpin this cautious approach:

- First, advanced AI systems—particularly machine learning models—present challenges in thorough testing and verification. Their decision-making processes often lack transparency, making it difficult for engineers to trust their responses in anomalous situations. As one NASA study on autonomy noted, intelligent control software is "hard to understand and inspect, and thus hard to evaluate."<sup>182</sup> While traditional spacecraft software follows deterministic rules and undergoes exhaustive testing, AI systems that "learn" or adapt might behave unpredictably when facing conditions outside their training data. In the harsh realities of space, unexpected scenarios emerge frequently, and human creativity or intuition has often been the saving grace when missions go awry.
- Second, high-reliability aerospace systems demand proven performance records. AI systems lack the decades of flight heritage that simpler guidance and control algorithms possess. One of the few attempts to grant an AI full spacecraft control—NASA's Remote Agent experiment on Deep Space 1 (1999)—was restricted to a limited two-week, non-critical window rather than the entire mission due to these trust concerns.<sup>183</sup> Mission teams typically only embrace new technology after it demonstrates extensive failure-free operation. For AI, building such a record presents a paradox: it's difficult to accumulate without flight experience, yet flying without this record introduces substantial risk.<sup>184</sup> By 2025, we've seen measured progress (automated docking of spacecraft like SpaceX's Crew Dragon has become routine, but only following rigorous certification). Nevertheless, fully autonomous decision-making in life-or-death situations—such as an AI aborting a crewed landing due to sensor anomalies—remains difficult to justify.
- Third, astronauts and ground controllers provide qualitative judgment and adaptability that current AI cannot match. Humans integrate complex cues, sense anomalies intuitively, and develop creative solutions to unforeseen problems. During Apollo 11's lunar descent, when the onboard computer became overwhelmed with alarms, Neil Armstrong's decision to take manual control and navigate around a boulder field likely saved the mission—a split-second judgment that pre-programmed systems might have

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181 Michael Freed, Pete Bonasso, Mitch Ingham, David Kortenkamp, Barney Pell, and John Penix, "Trusted Autonomy for Space Flight Systems" (paper presented at the AIAA 1st Space Exploration Conference, Orlando, FL, January 29–February 1, 2005), NASA Technical Reports Server (Document ID 20050156644), 1, <https://ntrs.nasa.gov/api/citations/20050156644/downloads/20050156644.pdf> (accessed May 2, 2025).

182 Freed, "Trusted Autonomy for Space Flight", 1.

183 Freed, "Trusted Autonomy for Space Flight", 1.

184 Freed, "Trusted Autonomy for Space Flight", 1-3.

missed. While modern AI would handle such scenarios better than 1969 software, human intuition remains an invaluable safety net. As one commentary observes, "while AI can streamline processes, the stakes in space missions are far higher than on Earth... human intuition remains irreplaceable for navigating the unknown."<sup>185</sup> Consequently, high-stakes missions typically employ AI in an advisory capacity with human supervision (known as "human-on-the-loop" control) rather than granting AI complete autonomy.

- Fourth, crewed spacecraft incorporate redundant systems and fail-safe modes for all critical functions. Introducing AI raises important questions: Can humans override poor AI decisions in time? Designing interfaces for seamless control transfer between AI and humans presents significant challenges. Ethical and legal questions also arise—who bears responsibility if an AI decision leads to an accident? These concerns drive conservative approaches. NASA's guidelines for autonomy emphasize "trusted autonomy," requiring systems to explain their reasoning and permit human intervention.<sup>186</sup> Until AI becomes transparent, predictable, and demonstrably safe across all anticipated conditions, it won't receive sole authority over critical crew or payload functions.
- Finally, AI systems may be vulnerable to cyberattacks or manipulation. Sophisticated adversaries could potentially spoof sensors or introduce malicious inputs to cause AI misbehavior (known as adversarial attacks). National security space systems remain hesitant to rely on AI for this reason.<sup>187</sup> Robust fault-detection mechanisms and cybersecurity measures must evolve alongside AI capabilities.

Given these considerations, we anticipate a hybrid approach will continue: AI handling routine or data-intensive tasks while humans maintain strategic oversight and final authority during critical moments. Even by 2040, with significantly advanced AI, crewed spacecraft will likely include manual override capabilities, with mission control monitoring AI decisions. For unmanned missions with higher risk tolerance, AI may assume more ambitious roles—a fully AI-managed lunar mining operation might be acceptable, whereas an AI-managed crew landing would require extensive successful uncrewed demonstrations first.

These counterarguments don't aim to impede AI progress but rather ensure responsible deployment. They've driven research into "trusted AI" frameworks—NASA and aerospace companies are actively investigating certification and verification methods for AI, developing explainable algorithms, and incrementally increasing autonomy to build confidence.<sup>188</sup> Future spacecraft might incorporate redundant AI systems or parallel AI and traditional software configurations that cross-verify each other. Another approach involves extensive simulations and analog missions (like NASA's Earth-based habitats where crew-AI interactions undergo months of testing) before committing to deep-space autonomous operations.<sup>189</sup>

While AI represents a key enabler for expanding human presence beyond Earth, the space

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185 Ilaria Cinelli, "Will AI Redefine Human Roles in Space Exploration?," *SpaceNews*, January 28, 2025, <https://spacenews.com/will-ai-redefine-human-roles-in-space-exploration/> (accessed May 2, 2025).

186 Freed, "Trusted Autonomy for Space Flight", 1.

187 Michael Freed, Pete Bonasso, Mitch Ingham, David Kortenkamp, Barney Pell, and John Penix, "Trusted Autonomy for Space Flight Systems" (paper presented at the AIAA 1st Space Exploration Conference, Orlando, FL, January 29–February 1, 2005), NASA Technical Reports Server (Document ID 20050156644), 1, <https://ntrs.nasa.gov/api/citations/20050156644/downloads/20050156644.pdf> (accessed May 2, 2025).

188 Freed, "Trusted Autonomy for Space Flight", 1-2.

189 NASA, "The Role of Trust; Figueroa, "Trusted Autonomy." <https://ntrs.nasa.gov/api/citations/20220008322/downloads/NPAS%20for%20Space%20Trusted%20Autonomy%20%2005-19-2022.pdf> (accessed May 2, 2025).

industry recognizes that not every function should be delegated to AI, particularly where human lives hang in the balance. The ideal strategy leverages complementary strengths: using AI for data processing, optimization, and rapid response, while keeping humans involved for creative thinking, judgment, and ensuring ethical and safety standards. As AI technology and reliability improve throughout the 2020s and 2030s, its role will naturally expand, but always with appropriate checks and balances.

### Conclusion

Artificial intelligence is fueling a fundamental shift in how we approach cislunar operations. From autonomous lunar navigation to robotic resource extraction, AI technologies deliver efficiencies and capabilities that seemed out of reach just ten years ago. Current missions are already reaping benefits from AI applications in navigation (as demonstrated by CAPSTONE's self-positioning system) and mission operations (through automated anomaly detection in launch vehicles), establishing foundations for more ambitious applications in the coming decades. By the 2030s, AI is likely to become essential in managing the growing complexity of cislunar activities, serving as the intelligence behind lunar traffic management, orchestrating teams of robots constructing lunar infrastructure, and potentially even contributing to the design of next-generation spacecraft.

Nevertheless, this appendix emphasizes a crucial principle: progress in space development is evolutionary rather than revolutionary. The integration of AI will proceed methodically and cautiously, particularly where mission-critical functions are concerned. Human expertise remains indispensable to the process, with rigorous testing and validation protocols ensuring that AI earns its place in operational systems. In essence, the space sector is embracing AI as a powerful complement to human capability, not as an infallible replacement.

AI's significance in cislunar operations will undoubtedly continue to grow, enabling sustainable exploration and development of the Moon and its surrounding environment. Success will ultimately depend on effectively combining artificial and human intelligence—leveraging the strengths of each to compensate for the limitations of the other. The decades ahead promise a dynamic collaboration between astronauts, mission controllers, robotic systems, and AI, working in harmony from Earth to the Moon and beyond. This partnership, if properly realized, will unlock cislunar space's full potential for scientific discovery, commercial development, and humanity's expansion into the solar system, while maintaining mission safety and effectiveness throughout.”

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Output:

#### Appendix B Artificial Intelligence in Cislunar Operations — Streamlined (≈ 980 words)

Artificial intelligence (AI) has moved from niche augmentation to the connective tissue of every serious cislunar concept of operations. Vast Earth–Moon distances, three-body orbital mechanics, light-second latencies, and a still-immature ground network force spacecraft, habitats, and logistics chains to think for themselves far more than traditional low-Earth-orbit missions. Machine-learning pipelines now steer navigation, space-domain awareness (SDA), surface robotics, and crew decision aids, providing civil agencies, defense planners, and commercial ventures a common technology path to a durable lunar presence.

**Why AI Matters Between Earth and Moon** Cislunar traffic—NASA projects more than thirty active lunar missions by 2030—must cope with intermittent line-of-sight, multi-minute command loops, and unfamiliar gravitational regimes. AI mitigates three critical pain points:

- **Self-reliant navigation.** Sensor-fusion algorithms blend optical, star-tracker, range-and-bearing,

and environmental cues, allowing spacecraft such as CAPSTONE to station-keep in Near-Rectilinear Halo Orbit (NRHO) with minimal ground intervention.

- **Persistent detection.** Computer-vision models filter faint satellites from star-rich backdrops, extending SDA beyond geosynchronous orbit and into Earth-Moon Lagrange points.
- **Hands-off surface operations.** Robotic excavators and additive-construction systems must perceive, plan, and recover from faults two light-seconds from Earth without constant human oversight.

### Current Capability Snapshot (2025)

#### Capability Area Representative Demonstrations & Metrics

Navigation & Guidance	CAPSTONE's Cislunar Autonomous Positioning System proved peer-to-peer ranging and onboard orbit determination; commercial terrain-relative navigation achieves <100 m landing error.
Cislunar SDA	The U.S. Space Force/AFRL <b>Oracle</b> pathfinder (launch 2025) will test on-board object classification at Earth-Moon L1; physics-informed ML cuts trajectory-propagation error by an order of magnitude.
Launch & Mission Ops	SpaceX telemetry classifiers reduce Falcon 9 aborts; Rocket Lab applies ML to additive-manufactured engine QA and weather-constrained launch windows.
In-Situ Resource Utilization	NASA's VIPER rover employs autonomous path-planning to map south-pole ice; a 2022 Centennial Challenge showcased multi-robot excavation managed by a central AI scheduler.
Crew Support	The ISS <b>CIMON</b> assistant enables context-aware voice interaction; Orion and Starship integrate AI caution-and-warning systems to rank alarms and propose corrective actions.

### Near-Term Trajectory (2025 – 2030)

Forthcoming Milestone	Operational Effect
<b>LunaNet / Moonlight</b> cooperative navigation constellation	Offers global lunar positioning, navigation, and timing (PNT), freeing landers from Earth-based Doppler tracking.
First AI-driven traffic-management prototypes	Oracle-seeded catalogs will generate conjunction alerts within minutes, accelerating maneuver coordination across actors.
Autonomous surface campaigns	Reinforcement-learning (RL) schedulers will orchestrate regolith excavation, electrolysis, and 3-D printing while balancing power margins and eclipse periods.

### Mid-Term Vision (2030 – 2040)

- **Autonomous lunar base.** Multi-agent planners dispatch haulers, excavators, and additive-manufacturing rigs while adapting to tool wear, dust adherence, and crew absence.
- **Space logistics network.** Generative-design engines co-optimize depot architectures and tanker routes; marketplace algorithms price delta-v, cryogenic boil-off, and launch manifests in real time.
- **Fail-operational crew vehicles.** AI flight directors will handle nominal burns, safe-mode entries, and contingency landings, leaving astronauts with ultimate veto authority but far less routine workload.

### Risks and Limitations

Risk Vector	Challenge	Emerging Mitigation
Verification & Trust	Adaptive models resist traditional test-as-you-fly certification.	"Bounded autonomy" modes and post-hoc interpretability layers mandated by NASA and ESA.

Sparse Training Data	Few real lunar datasets exist; sim-to-real gaps persist.	Physics-augmented networks and domain-randomization to harden models.
Dual-Use Ambiguity	Servicing arms and proximity sensors can repair—or disable—satellites.	Greater transparency, intent broadcasting, and interoperable SDA data exchanges.
Cyber-Physical Threats	Radiation upsets and cyber intrusions target shared AI stacks.	Triplicated fault-tolerant processors and formal-methods hardening.

**Human Oversight Still Matters** Historic rescues—from Apollo 14’s manual re-entry to JWST sunshield troubleshooting—underscore the value of intuitive human judgment when sensors lie or dynamics change. For at least the next decade, crews and mission controllers will remain **on-the-loop** for abort calls, crew-rated landings, and unmodeled contingencies. AI shifts workload, not ultimate accountability.

**Strategic Implications**

- AI multiplies a lean operations cadre, an essential advantage as lunar sortie rates grow tenfold.
- Early U.S. deployments—Oracle, Gateway autonomy—shape data-exchange norms before rival models become de facto standards.
- Successes in navigation, mining, and logistics feed terrestrial spin-offs (edge-AI, resilient autonomy), creating an economic flywheel for further exploration.

**Priority Recommendations**

Recommendation	Rationale
Expand open lunar datasets.	Rich, labeled telemetry and imagery accelerate community model training and validation.
Deploy a Cislunar Autonomy Testbed.	Radiation-hardened edge-compute boards on CLPS landers let updates fly in situ and de-risk later crewed missions.
Codify traffic-management APIs within the Artemis Accords.	Machine-readable, cryptographically signed state vectors enable rapid, trusted maneuver adjudication.
Invest in formal-methods / ML-assurance research.	Blending mathematical proofs with runtime anomaly detection paves a path to certifiable adaptive systems.

**Conclusion** AI is transforming cislunar operations from episodic, Earth-dependent sorties into a resilient, scalable ecosystem. Demonstrations this decade will mature into integrated autonomy in the 2030s, unlocking affordable lunar logistics, continuous surface industry, and safer human journeys to Mars. That future rests on transparent early deployments, rigorous validation, and balanced human-machine teaming today.