Protecting cislunar space: securing strategic stability through 2030

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1. ABSTRACT

Cislunar space, a critical arena for scientific, technological, economic, and strategic activities, necessitates a expanding and augmenting Space Domain Awareness (SDA), including Space Situational Awareness (SSA) ensure the protection of assets and strategic stability. This paper explores the imperatives of extending SSA/SDA beyond geosynchronous orbit, highlighting vulnerabilities in legacy frameworks through the disintegration of the Intelsat 33e satellite on October 19th, 2024. Detected by Kratos's Radio Frequency (RF) network before traditional systems, this incident underscores the need for real-time cyber Indications and Warnings (I&W) and the integration of commercial RF data to enhance anomaly detection and resilience. The report proposes to leverage Design of Experiments (DOE) methodologies and test and evaluation (T&E) frameworks to address technical challenges, such as cislunar orbital instability, cyber threats, and space weather events, while advancing sensor development, orbital analysis, and Communication and Positioning, Navigation, and Timing (C&PNT) services.

The Department of Defense (DOD) is identified as a pivotal leader in fostering international collaboration through initiatives like the Artemis Accords and partnerships with industry stakeholders, including Intuitive Machines, Quantum Space, and NASA. The report emphasizes the importance of secure-by-design Lunar PNT constellations as the backbone of civil-military operations and future economic activity on the Moon and beyond. Public-private partnerships, exemplified by the Space Information Sharing and Analysis Center (Space ISAC)'s Cislunar affinity group, are highlighted as essential for cooperative planning and resilience in this contested domain. The paper also envisions a long-term trajectory toward Mars and deeper space, where these technologies and alliances will support sustained human presence and economic viability.

2. INTRODUCTION

Cislunar space, defined as the region beyond geosynchronous orbit and within the gravitational influence of Earth and the Moon, represents a frontier of extraordinary scientific, technological, economic, and strategic value. The DoD has been assigned to lead several Cislunar initiatives in the areas of SSA and Communication and Position, Navigation, and Timing (C&PNT) due to their critical impact on national security interests. These key DoD equities drive four major use cases: orbital analysis, sensor development and testing, cybersecurity, and C&PNT services. There is also value in exploring best practices and lessons learned in SSA and SDA in terrestrial orbits through incidents such as Intelsat 33e disintegration. However, the Cislunar environment presents unique challenges compared to Earth-centric missions driven by its complex orbital dynamics and large distances for operation and transmission. This new regime necessitates innovative test and evaluation (T&E) approaches that account for the interplay of these challenges. Efforts to establish an extensive presence in Cislunar space are still in their early stages; therefore, now is the time to perform preliminary design space exploration studies in order to guide the DoD in effectively allocating its energy, time, and commitment toward areas where data collection and analysis will be most valuable. These analyses will help identify high-value architectures, systems, and capabilities while highlighting potential challenges, such as edge cases requiring design refinement. An immediate next step to support this endeavor is the adaptation of existing prototype tools for modeling and evaluating Cislunar architectures, with a particular focus on the orbital trade space. Medium term, it is recommended to develop test scenarios that are aligned with needs and gaps in the Cislunar region. Finally, for long-term efforts, the focus should shift toward developing integrated T&E environments that accurately represent the Cislunar operational environment and can validate system performance in this challenging regime. Collaboration will be essential across all timelines. In the short term, coordination and secure information sharing with commercial and international partners is key. In the medium term, efforts should prioritize understanding the evolving threat landscape to determine what means of protection and security will be needed. Ultimately, the long-term goal is to foster open communication and partnerships with minimal classification or proprietary restrictions, enabling seamless collaboration with commercial and international stakeholders.

3. CASE STUDY: INTELSAT 33E, CISLUNAR RISKS, AND THE MADCAP FRAMEWORK

3.1 Lessons from Intelsat 33e in GEO

The breakup of Intelsat 33e in October 2024 revealed both technical and institutional vulnerabilities in SSA. Commercial RF networks detected telemetry loss nearly 20 minutes before U.S. Space Command's optical confirmation, underscoring the lag in official detection and notification cycles (Kratos Defense, 2024). By the time status updates reached operators, aviation and maritime sectors were already experiencing ripple effects from lost connectivity, with cumulative losses estimated in the tens of millions of dollars (Hale, 2024) (Intelsat 33e suffers catastrophic breakup; hundreds of fragments detected. , 2024). This sequence highlights how reliance on traditional SSA channels and fragmented data sharing can create cascading economic impacts from a single failure event.

3.2 Amplified Risks in Cislunar Space

The vulnerabilities evident in GEO become magnified in cislunar environments. Unlike Earth orbit, where the DoD maintains a comprehensive catalog of tracked objects, no such passive tracking capability exists in lunar or Martian space. Instead, safety depends on voluntary ephemeris sharing by mission teams—a process highly sensitive to data accuracy, transparency, and trust (National Aeronautic and Space Administration, 2023). This Cislunar T&E study emphasizes that current frameworks cannot replicate the compounded stresses of lunar gravitational perturbations, communication delays, and cyber vulnerabilities, leaving operators "blind" to anomalies until after they occur. A disruption akin to Intelsat 33e—if it involved a lunar communications relay or navigation satellite—could halt Artemis supply chains, compromise international science missions, and destabilize emerging lunar economic activity.

3.3 MADCAP and the Reliance on Operator Cooperation

NASA's Multi-Mission Automated Deep-Space Conjunction Assessment Process (MADCAP) is currently the only operational framework screening for conjunctions in cislunar and deep-space environments (Smith, 2025). Unlike its Earth-orbit counterparts, MADCAP cannot draw on a passive debris catalog. Instead, it relies on self-reported trajectory and uncertainty data submitted by participating missions through the Deep Space Network or cloud-based servers. This dependence elevates the importance of operator cooperation: without timely and accurate submissions, the system cannot generate reliable risk assessments.

The challenges are illustrated by uneven international participation. Chinese missions provide ephemerides for Mars but not for lunar orbit, leaving blind spots in an increasingly congested environment. In Low Lunar Orbit (LLO), where the available volume is only 2% that of LEO, repeated conjunctions occur among orbiters clustered in popular "frozen" orbits. A NASA–Aerospace Corporation analysis of a near-miss between the Lunar Reconnaissance Orbiter and Chandrayaan-2 showed that, had a collision occurred, debris from a quasi-stable orbit would persist for years, elevating daily collision risk for nearby missions by an order of magnitude above baseline.

3.4 Integrated Human–Technical Vulnerabilities

MADCAP's operational realities also expose structural limitations. The system is staffed by only a small team, communicates primarily through email, and lacks a real-time dashboard, leaving emergency notifications dependent on direct phone calls. These constraints place heavy cognitive and procedural burdens on operators. Without robust fatigue risk management, standardized reporting protocols, and international agreements mandating participation, MADCAP remains vulnerable to the very coordination failures it is designed to prevent.

3.5 Implications

The Intelsat 33e case demonstrates how SSA delays translate into immediate financial losses on Earth. The Cislunar T&E findings and MADCAP's reliance on voluntary participation show that, without reforms, the same vulnerabilities could trigger more severe consequences beyond Earth orbit. A single collision in a lunar frozen orbit could generate persistent debris clouds that threaten both orbital and surface operations, magnifying risks to astronauts, scientific missions, and commercial ventures.

To prevent such outcomes, a multi-pronged approach is required: integrating commercial RF data into SSA, establishing international norms for ephemeris sharing, funding robust cislunar T&E environments, and embedding MADCAP within a broader Space Information Sharing Ecosystem (SISE). Without these steps, the economic and safety lessons of Intelsat 33e may be replayed in cislunar space at exponentially greater scale.

4. WHY CISLUNAR SPACE IS IMPORTANT

Cislunar space is defined by the space that is beyond geosynchronous orbit (GEO) and is within the gravitational influence of Earth and/or the Moon (National Science & Technology Council, 2022), as illustrated in Fig. 1.

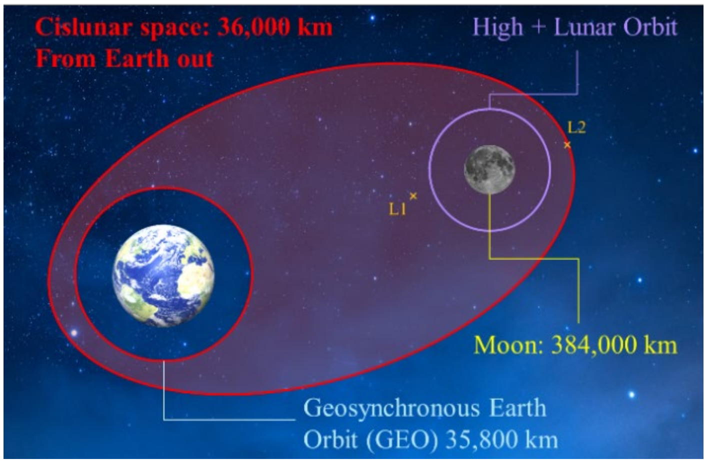


Fig. 1 Cislunar space as defined by the White House Office of Science and Technology Policy (OSTP) (National Science & Technology Council, 2022)

Since the publication of the Space Policy Directives (SPDs) in 2019, including SPD-1 that "The United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations" (White House, 2017), and the launch of the Artemis Accords by the National Aeronautic and Space Administration (NASA) in 2020 (National Aeronautics and Space Administration, 2020), the Moon is of high interest to the world. The White House Office of Science and Technology Policy (OSTP) has since published two major documents pertaining to the United States' strategy in Cislunar space: a Cislunar Science and Technology (S&T) Strategy (National Science & Technology Council, 2022), and a Cislunar S&T Action Plan (White House , 2024), the later describing key equities in Cislunar space and their lead government agency.

4.1 What are the Drivers?

Why is the Moon attractive? First and foremost, the Moon is Earth's only natural satellite, and as such, has been integral to many religious beliefs, cultural traditions, and even civilizations, but most importantly, the Moon has been the object of humanity's curiosity for centuries. There are numerous reasons why the U.S. is going back to the Moon, which can be divided into four categories: scientific interest, technological challenges, economic drivers, and strategic drivers.

4.1.1 Scientific Interest

The Moon represents billions of years of solar system history and preserved geological processes, such as impact cratering and crust evolution. With an extremely thin atmosphere and no plate tectonics to rapidly erase major geological features, the Moon is a unique object to study planetary formation and differentiation, in addition to solar system phenomena that continue to be mostly preserved at the surface of the Moon (Space Study Board, National Research Council, National Academy of Science, 2007). Furthermore, the far side of the Moon provides a radio-quiet zone for astronomical studies of the universe, heliophysical research, and much more.

4.1.2 Technology Challenges

The technological challenges to arrive to the surface of the Moon were NASA's primary mission in the 60s, and with Artemis, the Nation has set an even more difficult goal that includes building a base camp at the South Pole, as a stepping stone towards deep space destinations, such as Mars (National Aeronautics and Space Administration, 2022). The technological challenges are numerous, and include, but are not limited to, building a communication system, excavating life-support resources (water), and overall, establishing a sustained presence on the Moon. Implementing the Artemis Plan before China builds its Lunar Base would undoubtedly maintain the U.S. as the uncontested leader in the space domain.

4.1.3 Economic Drivers

The Moon has resources, starting with water ice that NASA plans to use to produce life support compounds and fuel for sustained human presence on the Moon (National Aeronautics and Space Administration, 2020). Beyond water, the Moon is believed to have other resources, including critical minerals (defined as minerals that are essential to the U.S. economy and national security but present a high risk of supply chain disruption) such as Rare Earth Elements (REEs) (Hedrick, 2023). There is also Helium 3, which is a promising resource for energy production, in abundance on the Moon. Even though additional ground data are needed to better characterize distribution of minerals, the Moon shows potential for mining beyond water ice, and while it is not believed that resources will create a return on investment in the next two decades, it is important to continue investing and developing technology towards lunar mining to develop such economic viability (Borowitz, Noonan, & Ghazal, 2023). Moreover, many have made the comparison with maritime trade routes protected by the Navy, and the need to do the same with our commercial traffic that could be generated by the exploitation of lunar resources.

4.1.4 Strategic Drivers

Adversary nations are also targeting the Moon to establish sustained human presence. China and its partners (including Russia and Iran) already launched their own collaborative agreement for an International Lunar Research Station (ILRS) (Jones, 2023) at the South Pole of the Moon (which is where NASA plans to establish the Artemis Base Camp). This is very much a space race 2.0, and the first to arrive at the final line will collect the advantages of the winning position, such as establishing precedence, standards, best practices, and norms of behavior (Borowitz, Noonan, & Ghazal, 2023). It is indeed important to consider the prestige and soft power that goes with being first to arrive at Cislunar space and the Moon, with the added strategic value of going after resources. Whichever great power establishes sustained presence first could shape the future of the Cislunar ecosystem and position themselves as a leader in the space domain with long lasting impact on the geopolitical theater. In addition, Cislunar space could be leveraged to launch attacks on terrestrial systems, using the Moon's gravity to target GEO satellites (and below). This is valid for both like-minded nations and adversaries, who could also take advantage of Cislunar operations for terrestrial purposes (Glabreath, 2024).

4.2 Who is Involved?

Unlike the Apollo missions, the Artemis Era goes beyond NASA alone, beyond the U.S., and beyond government. The new space landscape is characterized by the prominence of commercial stakeholders and international partnership, which is even more pronounced in the Cislunar environment (Fig. 2). NASA launched the Artemis Accords (National Aeronautics and Space Administration, 2020), which are signed by 53 countries; the agency has awarded multiple contracts to industry to build capabilities in Cislunar space, with Intuitive Machines being the first commercial spacecraft to land on the lunar surface (Foust, 2024) and marking the return of the U.S. to the Moon.

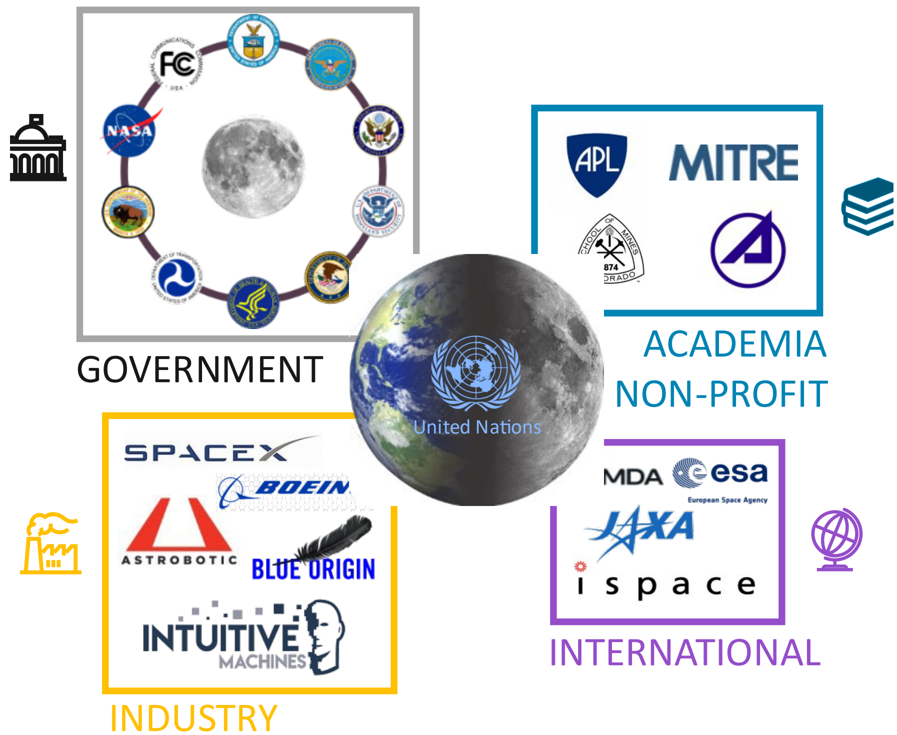


Fig. 2. Players in the Cislunar region include U.S. government, industry, academia, non-profit and international partners, commercial, civil, and military alike

Beyond the involvement of industry and the international community, missions to Cislunar space encompass a whole-of-government perspective. Because the landscape has changed and space has evolved to be more open to the general public, there are implications for the U.S. government in Cislunar space. This is a whole-of-government effort, with various agencies having a role in the commercial return to the Moon. In addition to those traditionally involved in space and those identified by the Space Policy Directives, there are considerations for a role for other parts of government that are not traditionally space-oriented, such as the Federal Bureau of Investigation (FBI) and the Department of Health and Human Services (DHHS). A summary of agencies and their current and potential role is laid out in Table 1.

Table 1. U.S. Government Agencies and their role in Cislunar Space

AGENCY	CURRENT AND POTENTIAL ROLE
Federal Aviation Administration	Launch and reentry licensing; commercial human spaceflight
Department of Commerce	Traffic coordination, space situational awareness (SSA)
Department of State	International coordination and collaboration
Department of Defense	Protection of assets; space domain awareness (SDA); reference frame (time and coordinate systems); standards
National Aeronautics and Space Administration	Scientific exploration, communication system
Department of Interior	Mapping, geology
Department of Justice	Law enforcement
Department of Homeland Security	Critical infrastructure protection; border protection; cybersecurity
Federal Communication Commission	Frequency spectrum licensing
Department of Health and Human Services	Space health
Department of Labor	Worker’s safety (e.g., lunar mining)

Cislunar SSA and Communication and Position, Navigation, and Timing (C&PNT) are key areas of focus as humanity's interest and presence in Cislunar space continues to expand. There are several existing efforts in support of these capabilities, led by NASA, the Department of Defense (DoD), and commercial companies. Tables 2, 3, 4, and 5 provide descriptions of the major efforts undertaken by NASA, the DoD, industry, and collaborative initiatives, respectively. It also includes the Artemis Base Camp, which is an effort to establish sustained human presence at the South Pole of the Moon and will inevitably generate a need for SSA and C&PNT services.

Table 2. NASA SSA and C&PNT efforts in Cislunar Space and other initiatives that will generate a need for SSA and C&PNT services

EFFORT	MISSION	DATES	LOCATION
CARA (Conjunction Assessment Risk Analysis)	Risk analysis for NASA missions and risk mitigation services for NASA assets	2009 – current	
MADCAP (Multi-mission Automated Deep-space Conjunction Assessment Process)	Part of CARA that screens provided ephemerides from the Deep Space Network against each other in space beyond Earth orbit (Moon and Mars)	2015 – current	
CAPSTONE (Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment)	Part of a lunar peer-to-peer navigation and communication project aiming to respond to the need for tracking capabilities	2022 – current	
Nokia 5G Network	First cellular network delivered to the Moon via Intuitive Machine’s lander	March 2025	
LunaNet	Interoperable communication and navigation network that can be leveraged for tracking	By 2030	
LCRNS (Lunar Communications Relay and Navigation Systems)	Initiative aimed at enabling a robust communication and navigation infrastructure around the Moon	Initial capability by 2028 Enhanced capability by 2030	
Artemis Base Camp	Sustained human presence at the South Pole of the Moon	Mid-2030s	

Table 3. DoD SSA and C&PNT efforts in Cislunar Space

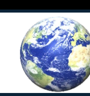
EFFORT	MISSION	YEAR	LOCATION
VLBA (Very Long Base Array)	Detected Resident Space Objects (RSO) via bistatic radar	2021	
GOLLD (Ground-Based Object Localization at Long Distance)	Maintain a catalog of objects at lunar distance	2021	
ORACLE (CHPS)	Provide on-orbit tracking and cataloging capabilities for objects in Cislunar space	2027 or later	
ORACLE-H (CDAS) (Hosted)	Demonstrate Earth-Moon corridor search as a hosted payload and on-board image processing	After 2025	
ORACLE-M (D2S2) (Mobility)	Assess orbits and custody of known Cislunar objects	After 2025	
Lunar reference frame	Establish a lunar coordinate and timing reference frame for PNT and communication	Ongoing	N/A

Table 4. Industry efforts in Cislunar Space

EFFORT	GOAL	YEAR	LOCATION
Quantum Space	First commercial SSA mission	2024	
Quantum Radar	Improve tracking accuracy by positioning a quantum radar at Earth-Moon Lagrange points	Research ongoing	

Table 5. Overarching efforts in Cislunar SSA and C&PNT

EFFORT	GOAL	YEAR
Sensing	Study sensing needs in Cislunar space to track and predict maneuvers	Ongoing
Track Custody	Overcome the challenge of unstable dynamics in the Cislunar orbital regime	Ongoing
Deconfliction, policy	Comprehensive SSA framework (SSA, SDA, space traffic coordination [STC], conjunction analysis, sustainability, debris and environmental awareness)	Ongoing
International Cooperation	Enable safe operations, including coordinating infrastructure implementation for SSA and STC services	Ongoing

Additionally, adversary nations are also advancing their capabilities, with China having launched a series of successful mission to the Moon (Chang'e missions). Table 6 summarizes recent and upcoming missions that demonstrates the success of the Chinese Space Program, and that will require the U.S. and its partners to establish resilient SSA services. This includes awareness of China's own base camp at the South Pole of the Moon that will trigger traffic between Earth and the Moon and around the Moon.

Table 6. Adversary efforts that will generate additional needs for SSA and C&PNT

EFFORT	GOAL	YEAR	LOCATION
Chang'e 5	Lunar sample return	2020	
Chang'e 6	South Pole-Aitken (SPA) Basin exploration mission	2024	
Chang'e 7 & 8	Resource exploration at the SPA Basin	2027	
International Lunar Research Station	Lunar base at the South Pole	Mid-2030s	

Industry, government, and adversary efforts are summarized in a timeline in Fig. 3.

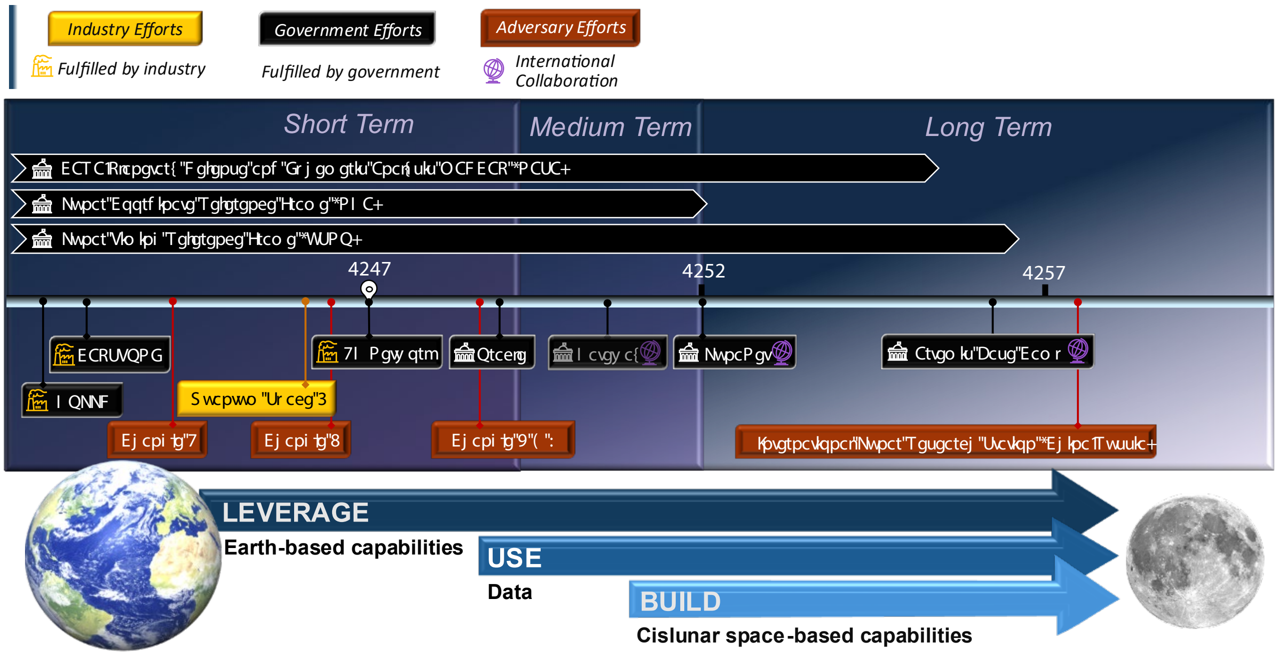


Fig. 3. Timeline of initiatives and missions for the U.S. government, its commercial and international partners, and adversary nations.

4.3 What are the Challenges?

The Cislunar environment presents unique challenges compared to Earth due to the complex orbital regime and large distances for operation and transmission. These can make it difficult to navigate and track spacecraft, maintain stability, operate effectively, and communicate with other spacecraft and Earth.

The Cislunar orbital dynamics environment is particularly challenging due to the influence of third-body effects and irregular gravity field. In the Cislunar regime, two-body dynamics and assumptions break down due to the interaction of three bodies: Earth, the Moon, and the spacecraft. Orbits are no longer geometric shapes such as ellipses, circles, parabolas, and hyperbolas, and very few trajectories repeat. In the three-body problem, Keplerian elements do not accurately represent orbits in the long-term, and Two-Line Elements (TLEs), which are commonly used to describe orbits are no longer useful (Holzinger, Chow, & Garretson, 2021). A set of Keplerian elements can be used as a starting point but will significantly change over time, which is why the rate of change of elements is important. In Cislunar space, the three-body problem lacks an analytic solution, necessitating numerical integration. The Circular Restricted Three-Body Problem (CR3BP) is a simplification of the three-body problem that is commonly used to model the Earth-Moon system, but it is still complex and requires numerical techniques to solve (Peterson & Scheeres, 2023).

The lunar gravity field is very irregular. The most significant factor is the presence of lunar mass concentrations, or mascons, which are high-density regions below the lunar surface formed by large asteroids or comet impacts during the Late Heavy Bombardment era. These mascons exert a higher gravity pull than other areas of the lunar surface, causing perturbations to the orbits of spacecraft (Muller & Sjogren, 1968) (Melosh, et al., 2013). Lunar topography and albedo also contribute to the irregular lunar gravity. Lunar terrain such as mountains and craters can induce minor orbit perturbations, especially if a spacecraft passes nearby. The Moon's non-uniform albedo results in uneven radiation pressure force on spacecraft, leading to small perturbations of their orbits.

The complexity of the lunar orbital environment makes it difficult to identify suitable orbits and trajectories, plan to operate in the Cislunar environment, and maintain SSA. Overall, there is a lot of instability in the Cislunar regime. Many orbits are unstable and prone to divergence or potential collision with the lunar surface, making station-keeping crucial. Disposed spacecraft placed in lunar graveyard orbits may drift into undesirable positions and after time may pose a threat to the lunar surface, Cislunar space, and even Earth-centric orbits such as GEO. In addition, predicting the long-term positions of adversary assets can be particularly challenging. Large precession rates of orbital elements mean that a spacecraft will drift in its orbit. This may impact a mission, such as by affecting its ability to view certain areas at a specific time or provide C&PNT services. When designing or testing a Cislunar system that will be operational for several months or years, experiments must be performed for a large mission duration to capture the orbit changes expected during the mission timeframe. For the modeling and simulation of orbits, this can substantially increase computational cost.

Cislunar space encompasses a very large volume, exceeding the entire region of geosynchronous orbits by more than 2,000 times, as well as involves vast distances that extend over 12 times the distance between geosynchronous orbits and Earth. This expansive region presents significant challenges for maintaining SSA, as it requires constant monitoring of a vast area. Providing communication and navigation services to this domain is particularly challenging due to its size. Communication with Earth is especially complicated by the great distances involved and the fact that lunar bases and satellites on the far side of the Moon lack direct line-of-sight with Earth. In addition, increased distances necessitate a great reliance on autonomy, which in turn increases the risk of cybersecurity threats. This underscores the importance of building secure systems to ensure the integrity and reliability of operations in Cislunar space.

4.4 Test & Evaluation in Cislunar Space

There are multiple concurrent efforts to understand challenges associated with Cislunar space. However, it is impossible to physically test and evaluate space capabilities with all the challenges of the environment together, and very few simulated environments exist to do virtual T&E. Instead, many T&E initiatives for Cislunar space focus on one aspect of the space environment. For example, in human spaceflight research for missions to the Moon, there are efforts associated with construction material for the habitat itself; work looking at protecting the astronauts from radiation by using lava tubes; simulated missions such as HERA (Human Exploration Research Analog) and CHAPEA (Crew Health and Performance Exploration Analog) to assess the human factor in long-term missions; and many others. While the latter looks at the human factor, it does not account for weightlessness; and living in lava tubes could solve the radiation problem but is not considering the psychological effects of living underground. Space, and in particular, Cislunar space, is unique because it combines all factors that are typically not simulated or reproduced together, and current efforts do not have a way to model and simulate all factors at once.

5. KEY DOD EQUITIES

The National Cislunar Science & Technology Action Plan published in December 2024 establishes actions to advance U.S. government scientific, exploration, and economic development activities in Cislunar space (White House , 2024). The DoD has been identified as a leader of several initiatives in the areas of SSA and C&PNT due to their critical impact on national security interests. These include exploring novel orbits, advancing research and development to extend U.S. SSA capabilities into Cislunar space, driving the design and development of key technologies, and ensuring scalable and interoperable infrastructures. Furthermore, the DoD should support efforts to expand international science and technology cooperation in Cislunar space.

5.1 Space Situational Awareness

Maintaining SSA is critical to ensuring U.S. leadership in Cislunar space and beyond. The irregular Cislunar orbital dynamics can cause spacecraft to deviate from their intended trajectories, posing risks not only to other Cislunar missions but also those in GEO and other high-altitude, Earth-centric orbits. The Action Plan directs the DoD to identify and prioritize research and development needs, as well as evaluate current efforts and technology gaps, to support extension of U.S. SSA capabilities. Essential SSA capabilities include, but are not limited to, analyzing the performance of satellites in specific orbits over time, including potential degradation and operational longevity; tracking the presence and activities of commercial and international entities; and understanding the trajectories and potential future positions of other nations' assets to maintain awareness and infer their strategic intentions.

5.1.1 Sensor Development

Sensors are a critical technology for enabling Cislunar SSA goals, and the Action Plan identifies the DoD as a lead for several related initiatives. These include identifying current efforts and technology gaps of commercial and international contributors, assessing the capabilities of existing government SSA sensors to determine if modifications or upgrades are needed, and identifying the best use of satellites in novel orbits to complement existing ground and space-based SSA sensors.

5.1.2 Cislunar Object Catalog

To support SSA efforts, the Action Plan calls for the development of a comprehensive catalog of natural and artificial objects across the Cislunar regimes. Collaboration of government, industry, and international partners is particularly important for establishing such a database. The DoD will help lead the identification of technical resources required to integrate applicable data sources, including data from spacecraft owners and operators, DoD, NASA, and commercial and academic sources.

5.1.3 Data Sharing in Cislunar Space

Data and information sharing is critical to maintaining comprehensive situational awareness. Due to the limited infrastructure in Cislunar space, it is especially essential to ensure data sharing among stakeholders. The DoD will help lead the development of procedures for publicly sharing Cislunar SSA data and support spaceflight safety. A key aspect of this includes developing best practices for post-mission disposal and debris mitigation, as well as developing conjunction assessment and mitigation processes. It is to be noted that part of SSA is cyber SSA, which includes maintaining awareness of cyber activities in Cislunar space. There are organizations that exist with the sole purpose of information sharing among stakeholders, such as the Space ISAC, which focuses primarily on cyber threats awareness and analysis with an operational Watch Center. While the Watch Center is not yet operational in Cislunar space, the Space ISAC has a Cislunar focused group that discusses needs and gaps in the Cislunar region.

There are, however, concerns over data sharing for industry due to proprietary considerations. It is crucial that these challenges be overcome through solutions such as anonymized information sharing. Such processes exist in other domains, as illustrated with example such as Aviation Safety Information Analysis & Sharing (ASIAS) which anonymizes data for further analysis and sharing for safety improvement purposes.

5.2 Communication and Position, Navigation, and Timing

The implementation of Cislunar C&PNT capabilities is of paramount importance due to its impact on spacecraft missions within Cislunar space, including on the Lunar surface. The DoD will be involved in establishing foundational capabilities for enabling a flexible Cislunar architecture and ensuring capabilities are scalable and interoperable with private and international actors. The Cislunar environment poses unique challenges for C&PNT, particularly due to large orbital precession rates that affect constellation geometry and degrade performance. Preserving optimal constellation geometry for a long-standing C&PNT system will likely require creativity and in-depth analyses for selecting orbits and establishing a viable station-keeping approach. Other key challenges include supporting vast areas in space and on the lunar surface, transmitting data over long distances back to Earth, and maintaining collaboration and consistency among a diverse array of organizations and countries. In addition, developing an infrastructure that is interoperable and scalable with both current and future systems and technologies – some of which are yet to be realized – presents a significant challenge.

5.2.1 Establish Foundational Capabilities

The DoD will support efforts to establish foundational capabilities that enable a flexible Cislunar architecture. This entails the establishment of an interagency coalition responsible for coordinating, developing, and overseeing the National Cislunar C&PNT Architecture, identifying overlapping and differing needs across various agencies for Cislunar C&PNT, and providing updates to the Moon to Mars Architecture. There is a significant emphasis on a long-term and adaptable infrastructure that will provide a robust and secure framework that can be scaled as presence in Cislunar space and beyond increases.

5.2.2 Ensure Scalability and Interoperability of Capabilities

The DoD has been assigned to lead the identification of priority technology demonstrations to enable modernized and expanded sensing, ranging, and timing technologies, as well as techniques that enable integration of new space-based operations with existing infrastructure. Furthermore, the DoD will support the development and implementation of standards and identification of primary C&PNT topics for international consultation or coordination, in particular those related to security.

5.3 International Collaboration

As previously mentioned, infrastructure on and around the Moon is both sparse and multi-national. Given that space is inherently a shared domain, it is necessary for the U.S. to lead and foster strong international collaboration to achieve SSA goals and ensure a safe Cislunar environment for all. The Action Plan identifies two specific areas of opportunity where international cooperation is crucial: the establishment of an International Lunar Year (ILY) and the global development of technical foundations that support best practices for safe and sustainable Cislunar operations. These efforts will build on the principles of the Artemis Accords and Outer Space Treaty. Recognizing the importance of international collaboration in space, documentation should remain unclassified when possible, allowing all key stakeholders to stay informed, aligned, and able to share data and information freely. It also highlights the importance of information sharing and the need to limit the urge to retain important information even if unclassified, as aforementioned.

6. DRIVING USE CASES AND ENABLING TOOLS

The DoD can take several actions to begin addressing the strategic objectives set forth in the National Cislunar Science & Technology Action Plan. Efforts to establish an extensive presence in Cislunar space are still in their early stages; therefore, now is the time to perform preliminary design space exploration studies in order to guide the DoD in effectively allocating its energy, time, and commitment toward areas where data collection and analysis will be most valuable. These analyses will help identify promising areas within the design space, such as architectures, systems, and capabilities that are worthwhile investments. Additionally, they will highlight areas of potential challenges, including recognizing T&E edge cases where systems, designs, or architectures may struggle to meet requirements, thus necessitating further design refinement. The DoD equities drive relevant use cases and the identification of tools to facilitate preliminary analysis in these areas. The four use cases that will be presented are orbital analysis, sensor development and testing, cybersecurity, and C&PNT services.

6.1 Driving use case

6.1.1 Orbital Analysis

A comprehensive understanding of the complex Cislunar orbital dynamics environment is critical for addressing the key DoD priorities, as it will enhance the protection and advancement of U.S. interests in the Cislunar regime. This expertise will improve the DoD's ability to identify optimal orbits and trajectories and maintain SSA in this increasingly contested domain. Different orbits and trajectories offer unique advantages for applications within SSA and C&PNT, a summary of which is shown in **Error! Reference source not found.**. Specific actions related to orbital dynamics that will strengthen the position of the U.S. include leveraging orbits and trajectories to gain a competitive edge, such as by minimizing fuel consumption or transfer time, in order to maintain desired positions for extended durations; identifying the most optimal orbits and trajectories for specific spacecraft and missions; and evaluating potential challenges that spacecraft and satellite constellations may encounter in different orbits and proposing associated mitigation strategies. Future conflicts in space may be won through superior orbital strategies that will enable prolonged asset presence with minimal resource expenditure, making a deep understanding of Cislunar orbital dynamics critical to success in this regime. Orbital analysis is a precursor to addressing the DoD equities and driving use cases. The selection of viable orbits and development of reliable Cislunar orbital M&S environments are necessary before being able to assess system performance in areas such as SSA, C&PNT, sensor development, and cybersecurity. Preliminary orbital analysis allows analysts to hone in on promising areas of the design space for each of the various applications, as well as identify areas to avoid. Design space analysis and trade studies can enable decision makers to identify characteristics of optimal architectures and make informed decisions for areas of further analysis. This orbital information can inform design analyses of SSA architectures, C&PNT systems, and Cislunar sensors, as well as support T&E efforts of these areas.

6.1.2 Sensors

Sensor development is a driving use case and key enabler for addressing the DoD priorities pertaining to SSA and C&PNT. The proposed efforts focus on assessing current sensors, identifying gaps, and implementing necessary improvements, as well as recommending technology investments tailored for the Cislunar environment. For example, traditional SSA sensors rely on TLE formats which are inadequate for extended use in the Cislunar region and therefore require upgrades. Additionally, the inherent instability of the Cislunar environment means that even small perturbations can cause significant changes to spacecraft trajectories. As a result, frequent observations are required in order to maintain SSA of objects in this domain. System design and T&E methodologies are needed to support the design, test, and validation of Cislunar sensors.

6.1.3 Cybersecurity

The Action Plan places a strong emphasis on the security of current and future systems that will support Cislunar SSA and C&PNT applications. Existing cybersecurity T&E methodologies are inadequate for the Cislunar design space due to the aforementioned unique challenges and differences from Earth-centric environments. Approaches that can adequately represent all the aspects of Cislunar space are needed to ensure robust and secure infrastructures. In particular, obstacles such as distance make Cislunar space cybersecurity more challenging than Earth orbit cybersecurity. Command and control suffer from delays between terrestrial-based control and the spacecraft, which would also affect any real-time response to a cybersecurity threat to vehicles. In addition, natural phenomena such as space weather can also increase the difficulty of protecting assets in Cislunar space, including the fact that threats can be disguised as natural space weather phenomena. Moreover, due to the current limited infrastructure in Cislunar space, it is crucial to consider interoperability with actors in that space, increase access to key infrastructure such as communication, and optimize situational awareness, in addition to ensuring reception of data by terrestrial control. This would also limit the number of interfaces and therefore increase cyber resilience.

6.1.4 C&PNT Services

Addressing the DoD equity of Cislunar C&PNT is a multifaceted effort that must incorporate exploring viable orbits for C&PNT applications, designing and testing sensors that will enable these services, and performing T&E of the security and resiliency of these systems. Orbit selection will be key to ensuring the longevity of a proposed C&PNT architecture due to the irregular Cislunar dynamics. Preliminary orbital analysis can help to identify suitable orbits and constellation configurations for providing consistent services over a long operational lifetime. Sensors that support communication and PNT capabilities must be developed and tested in scenarios analogous to the expected operational environment. Candidate systems must undergo rigorous T&E that measure system performance, robustness, and security in the presence of both natural and manmade threats.

6.2 Enabling Tools

Preliminary analyses that support the DoD equities can be performed, particularly in the areas of orbital analysis, sensor development, cybersecurity, and C&PNT services. Design of experiment (DOE) methodologies are well-suited to support these efforts by enabling comprehensive trade studies of alternative designs and rigorous T&E. Systematically varying factors and levels of system characteristics allows exploration of a large design space and identification of promising areas of the design space. Honing in on these areas can help inform future investment decisions and ensure resources are being used where they will provide the most value. For the T&E scenario, DOEs prove useful for testing and evaluating a system under the various conditions to which it may be exposed. Such rigorous and systematic methodologies help ensure the efficiency and completeness of testing, as well as make certain that all evaluation criteria and requirements are being properly addressed. Performing preliminary T&E analyses can facilitate the early identification of challenging areas of the design space, specifically conditions under which a system may struggle to meet requirements. This can help inform where resources should be invested to overcome such challenges while still in the early design stages. As previously mentioned, it is difficult to test and evaluate space capabilities with all the challenges of the Cislunar environment together. DOE methodologies systematically vary factors and levels for a comprehensive exploration of the design space. To effectively analyze and simulate a system's performance in this complex environment, advanced modeling and simulation (M&S) environments are needed that can accommodate the DOE conditions. For the Cislunar environment, critical M&S capabilities include high-fidelity modeling of third-body orbital dynamics, satellite and sensor characteristics, and communication and navigation capabilities. A key challenge for Cislunar M&S is the orbital drift and irregular behavior of spacecraft. Unlike Earth or Keplerian dynamics, Cislunar orbits do not repeat predictably, necessitating extended propagation durations to accurately assess long-term system behavior.

6.3 Exemplar

The objective of this exemplar is to identify design trade studies and T&E scenarios for a lunar constellation that provides C&PNT services to spacecraft operating in the Cislunar regime. Many orbit and satellite design factors impact the constellation characteristics, enabling trade studies of alternative architectures. Types of orbits may include Frozen, Halo, Low Lunar Orbits (LLOs), Distant Retrograde Orbits (DROs), and Lagrange Point Orbits. The number of satellites is another design decision, and each satellite may be of the same or a different orbit family. Specific orbital elements for each satellite can be varied based on the selected orbital family. Satellite design characteristics may include the range for communication and navigation capabilities, which is a particularly significant factor when in the vast operational area of Cislunar space, as well as the satellite field of view (FOV). A graphical depiction of these design choices is shown in Fig. 4.

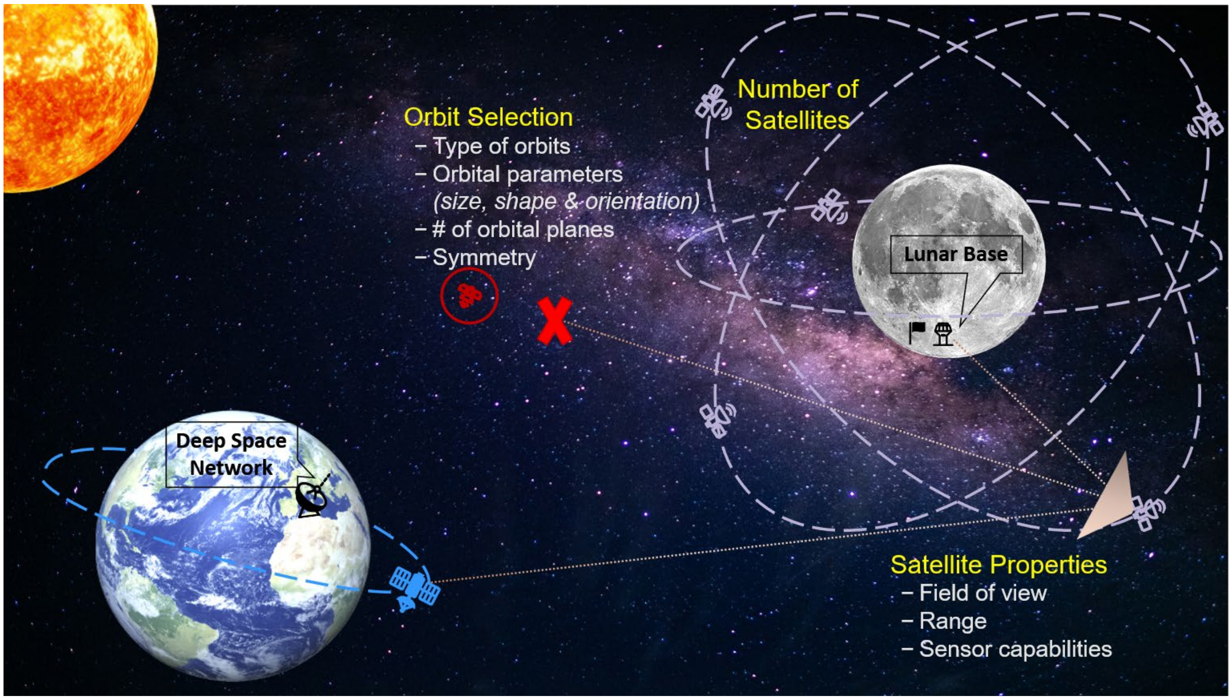


Fig. 4. Cislunar design matrix to consider, including orbits, number of satellites, and satellite properties. Due to large distances, threats could be out of range for some satellites on some orbital planes; the Cislunar region is vast and maintaining situational awareness everywhere is a challenge.

Data, cyber, and environmental factors are key T&E operational conditions to which the architecture may be exposed. Data factors may include the type of data, such as text, video, or voice, and the volume of data that the system is expected to handle. Cyber factors describe potential attributes of a cyber-attack, including the vector, power level, segment, and threat actor. Vectors of cyber-attacks may include jamming, spoofing, malware, denial of service, command intrusion, hacking, or high-jacking. Impacted segments may include the ground segment, space segment, user segment, or link segment. The cyber-attacker power may range from low to high. The threat actor describes the identify and location of the cyber attacker, such as an enemy on the Earth, in Earth orbit, in Cislunar space, or on the lunar surface. Environmental considerations may include factors such as space weather, micrometeorites, and space traffic. Combinations of these threats will be executed to evaluate system performance under these conditions. A morphological matrix of the design T&E factors divided into orbit design, satellite design, data, cyber, and environmental is shown in Table 7.

Table 7. C&PNT system test and evaluation morphological matrix

	FACTORS	LEVELS
Orbit Design	Orbit characteristics	Frozen, Halo, LLO, DRO, Lagrange (L1, L2, L4, L5)
	Orbital elements	*Ranges dependent on orbit family*
	Number of satellites	X_1 to X_2 satellites
Satellite Design	Satellite Range	Y_1 to Y_2 kilometers
	Satellite FOV	Z_1 to Z_2 degrees
Data	Data Type	Data, Video, Voice
	Data Volume	Mega to Tera
Cyber	Cyber-attack Vector	Jamming, Spoofing, Malware, etc.
	Cyber-attack Power	Low, Medium, High, None
	Cyber-attack Segment	Ground, Space, User, Link
	Threat Actor	Identity and location of cyber attacker
Environ mental	Space weather	Adverse, benign
	Micrometeorites	Low, Medium, High
	Space Traffic	Low, Medium, High

Key performance parameters based on system requirements are needed in order to evaluate and compare alternative designs, as well as evaluate system robustness to the operational environment. These metrics should directly correspond to system requirements and align with stakeholder interests regarding the system's intended use. A sample set of evaluation criteria, their descriptions, and unique challenges in Cislunar space for a C&PNT system are shown in

Table 8. Data rate describes the amount of data transmitted during a specific time period. Service availability and coverage provide measures of the areas a system can service and the system's overall accessibility to users. Metrics such as Geometric Dilution of Precision (GDOP) and one-sigma position and time errors indicate the system's navigation accuracy. Latency describes the delay between an instruction to transfer data and it actually being transferred. Due to the large areas of Cislunar space and sparsity of resources, at least initially, these performance metric values will be much lower than typical Earth-based PNT systems. The next set of metrics are specific to the system response to a cyber-attack. The probability of cyber-attack detection measures the likelihood a system will successfully identify and flag the presence of a cyber-attack attempt. The cyber attacker location accuracy specifies how accurately a system can determine the location of a cyber attacker. The cyber-attack detection time measures the time to successfully detect an attack. These are metrics used for Earth-based systems, but the act of detecting an attack and identifying an actor is more complex due to the aforementioned challenges of Cislunar space. Delta-V and system cost provide measures of how expensive the system is to build and maintain. Delta-V measures the fuel costs needed for station-keeping for the satellite constellation, which is a significant factor when operating in the Cislunar orbital environment, as Delta-V requirements are likely to be much higher for maintaining performance than for typical Earth-based systems. A measure of system cost can be calculated that scales with factors such as the number of assets and number of orbital planes in order to capture the increased costs of certain constellations.

Table 8. Communication system cyber resilience and design evaluation criteria

METRIC	DESCRIPTION	CHALLENGES
Data Rate	Amount of data transmitted during a specified period	Availability of the Deep Space Network (DSN) for large data rate
Service Availability	Percentage of time the C&PNT system is operational and accessible to users	Orbital dynamics and distances
Coverage	Volume where the system can deliver C&PNT services	Very large volume of space
GDOP	Measures the effect of satellite system geometry on positional measurement accuracy	Sparsity of resources and large areas
One-Sigma Position & Time Errors	Indicators of the navigation accuracy of satellite-based systems	Lack of standards in coordinate and timing systems
Latency	Delay between an instruction to transfer data and it being transferred	Long distances lead to delays
Probability of Cyber-attack Detection	Likelihood a system will successfully identify and flag the presence of cyber-attack attempt	Long distances and sparse infrastructure to detect attacks
Cyber Attacker Location Accuracy	Accuracy with which a system can determine the location of a cyber-attack that is interfering with C&PNT services	
Cyber-attack Detection Time	Time to successfully detect a cyber-attack	Latency, especially in deep areas of Cislunar space
Station-keeping Delta-V	Fuel costs to perform station-keeping for the satellite constellation	Complex Cislunar orbital dynamics
System Cost	Cost of the PNT system. May be a nondimensionalized number that scales with number of assets, number of orbital planes, etc.	Significant launch costs

An experimental environment must be developed to simulate and analyze lunar constellations, accommodating a variety of orbit types, spacecraft characteristics, operating conditions, and cybersecurity threats. This may include M&S tools, as well as hardware in the loop test apparatuses. Statistical analysis and data visualization techniques may be used to interpret results and convey findings to decision makers and key stakeholders. A visualization dashboard can support real-time decision making and assist in identifying optimal systems with respect to the specified evaluation criteria. Performing largescale trade studies early in the process allows for the identification of candidate architectures and promising areas of the design space, which can inform future investment decisions. This analysis can also illuminate challenging areas of the design space where architectures may struggle to meet requirements. Performing T&E throughout the design process enables these areas to be identified early so that resources can be put toward addressing them, either through design or requirement updates.

7. FUTURE TEST AND EVALUATION NEED AREAS AND RECOMMENDATIONS FOR NEXT STEPS

7.1 Near Term Need Areas

Near-term objectives to prepare the DoD to effectively support the initiatives outlined in the Action Plan include defining test scenarios, establishing design metrics, and conducting preliminary analysis of the orbital architecture trade space. Key test scenarios include the design of a C&PNT system and the development of an SSA architecture, which may be evaluated using performance, cost, and robustness metrics. Performing design space analysis to identify promising areas for further exploration and refinement will facilitate the identification of optimal solutions within the design space and guide development efforts. This will help with scoping down to the best relevant use cases and inform resource planning.

An immediate next step to support this endeavor is the development of a prototype tool for modeling and evaluating Cislunar architectures. This tool will enable preliminary analyses to demonstrate its utility and begin identifying promising areas within the design space, with a particular focus on the orbital trade space. Orbital analyses are the foundation for Cislunar architectures and must therefore be prioritized in the early stages of development.
Fig. 5 outlines the proposed process for developing this prototype tool. The first step involves defining relevant test scenarios where orbital trade studies will provide valuable insights, such as the C&PNT exemplar. The next step is to develop a M&S environment capable of conducting orbital and design trade studies. This environment must address the unique challenges of Cislunar space, such as large precession rates and significant station-keeping requirements. To perform a comprehensive exploration of the design space, factors and levels can be systematically varied, potentially using a design of experiments approach. Data analysis can then be performed to profile the design space, identify candidate architectures, and highlight their key characteristics for further consideration.

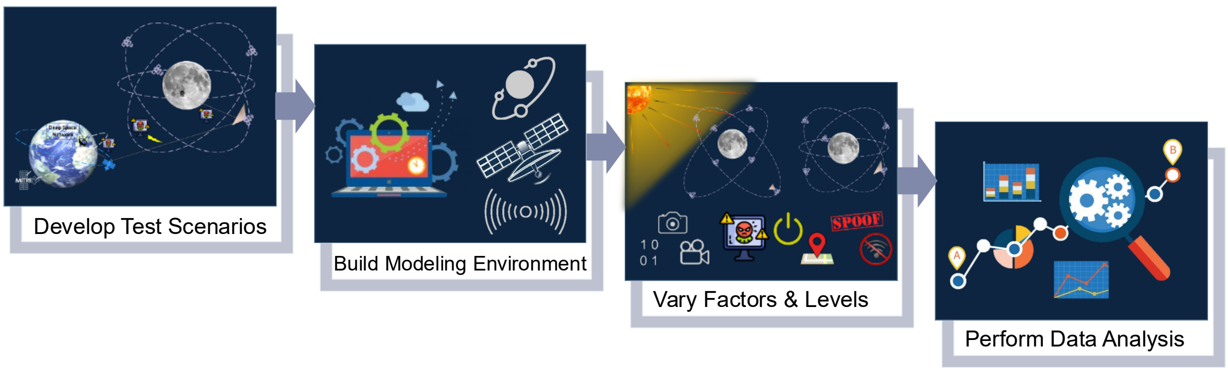


Fig. 5. High-level development process for the proposed prototype tool

7.2 Long Term Need Areas

Long-term objectives for advancing Cislunar capabilities involve the development of integrated Cislunar T&E environments that accurately represent the expected operational conditions in Cislunar space. These environments are critical for validating the performance of Cislunar architectures, systems, and technologies under realistic conditions. One key scenario is the testing long-range sensors, which represent a critical equity that the DoD will lead. Heritage sensors designed for Earth-centric operations are likely insufficient for the unique challenges of the Cislunar regime, necessitating the upgrading and validating of novel sensors. Another key scenario involves testing PNT solutions, which are essential for ensuring reliable operations in this complex environment.
Developing T&E environments that account for the unique and diverse challenges of Cislunar space is a significant undertaking, as they must address factors such as large precession rates, extended communication distances, large station-keeping requirements, and the influence of multiple gravitational bodies. Without accurately representing these factors, proposed systems cannot be effectively validated to ensure they will perform as intended in all operational scenarios. Long-term efforts must ensure that these environments are comprehensive and robust to enable thorough test and evaluation efforts.

7.3 Key Challenges

In Cislunar space, there are key orbital dynamics challenges that lead to difficulties with station keeping, SSA, object tracking, and custody maintenance. Long distances create latency, making it challenging to operate in real time, observe the whole of Cislunar space, and communicate effectively. The operational environment is highly complex, containing both natural and manmade threats, and associated T&E scenarios have high dimensionality. Due to the number of stakeholders and vast areas of operation, effective design and T&E will rely on coordination and collaboration with commercial and international partners.

7.4 Key Recommendations

Key recommendations can be organized in two main categories and are summarized in Table 9:

- Recommendations relevant to an integrated Cislunar T&E environment
- Recommendations relevant to collaboration to advance Cislunar space exploration

Table 9. Key recommendations for short, medium, and long-term

	INTEGRATED CISLUNAR T&E ENVIRONMENT	COLLABORATION
Short Term	Definition of test scenarios and design metrics for current Cislunar challenges	Coordination and secure information sharing with commercial and international partners
Medium Term	Preliminary analysis of the orbital architecture trade space	Understanding of the threat landscape
Long Term	Accurate representation of the operational environment T&E of key technologies, e.g., Cislunar-based sensors and PNT solutions, including cybersecurity threats, vulnerability and responses to attacks	Minimal to no classification and/or proprietary level

8. CONCLUSION

Cislunar space has emerged as a critical area of interest due to a combination of scientific, strategic, technological, and economic drivers. This has attracted a diverse array of stakeholders, including government agencies, commercial industries, and international organizations, which have undertaken significant efforts in the areas of Cislunar SSA and C&PNT. Fundamentally, Cislunar space differs from Earth in large part due to its complex orbital dynamics, and as a result, existing Earth-centric architectures, technologies, modeling environments, and T&E approaches cannot be directly applied.

The DoD was assigned to lead several initiatives outlined in the Cislunar S&T Action Plan, from which four driving use cases were derived: SSA, sensors, cybersecurity, and C&PNT. Support is needed to ensure the readiness of DoD test infrastructure for design and T&E in these key areas. A proposed immediate next step is the development of a prototype tool to conduct preliminary Cislunar orbital design trade studies. Over the longer term, efforts should focus on developing integrated T&E environments capable of accurately representing the Cislunar operational environment and validating system performance in this challenging regime.

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