Cislunar Security National Technical VISION

JOHNS HOPKINS
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CISLUNAR SECURITY NATIONAL TECHNICAL VISION

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1. INTRODUCTION

Steve Parr

This document describes a technology vision for cislunar security: the technology developments needed to ensure free access to, transit to, and use of the Earth–Moon system beyond geosynchronous orbit (GEO).

The Johns Hopkins University Applied Physics Laboratory (APL) established and hosted the Cislunar Security Conference (CLSC) in 2020 and 2021.[1] CLSC encourages national-level discourse on the technology, policy, and strategy implications of increased cislunar activity for national security. Over the first two years of the conference, APL hosted 700+ attendees (on-site and virtually) from more than 150 organizations, including the U.S. government and military, University Affiliated Research Centers, Federally Funded Research and Development Centers, the commercial space industry, and academia.

The recommendations in this document are based on presentations and discussions that occurred at the first two CLSCs as well as discussions internal to APL and those with the external cislunar community, including the Office of Science and Technology Policy, Aerospace Corporation, Air Force Research Laboratory, and others.

Importance of the Moon and Cislunar Space

The Moon has been a focus of deep space missions since the early days of the Space Age. From 1958 to 1976, approximately 90 lunar missions were attempted by the United States and the Soviet Union, culminating in the successful Apollo 11–17 missions.[2] After a 14-year gap, new missions launched to the Moon beginning in 1990. In the 1990s, the United States and Japan launched several lunar missions. Since 2003, approximately 20 lunar missions were launched by a broad range of nations and space agencies, including the United States, Europe, Japan, China, India, Luxembourg, Israel, and South Korea.

More than 100 lunar missions are expected in the next decade.[3]

The primary reasons for going to the Moon have been exploration, scientific inquiry, and national prestige. The National Aeronautics and Space Administration (NASA) plans to return to the Moon with its Artemis program,[4] with the aims of establishing a lunar space station (Gateway), establishing a sustainable presence on the lunar surface,[5] and conducting necessary research to enable future human missions to Mars. This will include in-situ resource utilization (ISRU) for extracting materials such as water and oxygen. China is also planning (with Russia)

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[1] Agendas from CLSCs can be found at https://cislunar.jhuapl.edu.
[2] NASA Science: Earth's Moon. https://moon.nasa.gov/exploration/moon-missions/.
[3] Olson, J., Butow, S., Felt, E., Cooley, T., & Mozer, J. (2021). *State of the Space Industrial Base 2021: Infrastructure & Services for Economic Growth & National Security*. Ed. P. Garretson. U.S. Department of Defense. https://assets.ctfassets.net/3nanhbfkr0pc/43TeQTAmdYrym5DTDrhjd3/a37eb4fac2bf9add1ab9f71299392043/Space_Industrial_Base_Workshop_2021_Summary_Report_-_Final_15_Nov_2021c.pdf.
[4] NASA Artemis. https://www.nasa.gov/specials/artemis/.
[5] Executive Order No. 13914, The National Space Policy, 85 *Fed. Reg.* 81755 (2020). https://www.federalregister.gov/documents/2020/12/16/2020-27892/the-national-space-policy.

to establish a crewed lunar research station. In recent years, the economic potential of the Moon and cislunar space have also come to the forefront. There is great interest in the Moon within the booming commercial space industry, both for providing launch and other services to NASA and government customers and for the potential value of lunar ISRU products.

Definition of Cislunar

A prescriptive dictionary definition of cislunar is "lying between the Earth and the Moon or the Moon's orbit."[6] This document uses "cislunar" to mean the region of space in the Earth–Moon system beyond GEO, including the Moon's orbit and all of the Earth-Moon Lagrange points.[7] This is the descriptive definition of cislunar typically used at present within the space community[8,9,10]. In addition to cislunar, the term "xGEO" is also used, primarily within the national security space community, to similarly describe the region of space beyond GEO. We use "cislunar" in this document because it is the term with the broadest use across all communities with interests in the cislunar domain.

This anticipated increase in activity at the Moon and in cislunar space brings security concerns and a need for increased situational awareness in the cislunar domain. These have been outlined in multiple U.S. government documents, including the National Space Council's *A New Era for Deep Space Exploration and Development*,[11] the Memorandum of Understanding (MOU) between NASA and the United States Space Force (USSF),[9] the Space Force Space Capstone Publication (*Spacepower*),[10] and the 2021 State of the Space Industrial Base Report.[3] The unique orbital characteristics of the cislunar regime—complex, generally unstable orbits with quasi-stable halo orbits available around Lagrange points—present a challenge for situational awareness. The ease of moving from orbit to orbit within cislunar space, as well as from cislunar space to GEO or to the Sun–Earth Lagrange points, presents both challenges for situational awareness and opportunities for novel mission design. In this document, we describe the mission types that are of primary importance for cislunar security, with a focus on technology gaps and needs, and recommend specific policy and technology development needed at the national level to ensure security of U.S. interests in the cislunar domain.

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[6] Merriam-Webster. Cislunar. In *Merriam-Webster.com Dictionary*. https://www.merriam-webster.com/dictionary/cislunar.

[7] A Lagrange point is a position in space where gravitational forces of a two-body system, like the Earth–Moon system, are in balance. See https://solarsystem.nasa.gov/resources/754/what-is-a-lagrange-point/.

[8] Holzinger, M. J., Chow, C. C., & Garretson, P. (2021). *A Primer on Cislunar Space*. AFRL 2021-1271. Air Force Research Laboratory. https://www.afrl.af.mil/Portals/90/Documents/RV/A%20Primer%20on%20Cislunar%20Space_Dist%20A_PA2021-1271.pdf?ver=vs6e0sE4PuJ51QC-15DEfg%3D%3D.

[9] Memorandum of Understanding Between the National Aeronautics and Space Administration and the United States Space Force (2020). https://www.nasa.gov/sites/default/files/atoms/files/nasa_ussf_mou_21_sep_20.pdf.

[10] United States Space Force. (2020). *Spacepower: Doctrine for Space Forces*. Space Capstone Publication. https://www.space-force.mil/Portals/1/Space%20Capstone%20Publication_10%20Aug%202020.pdf.

[11] White House National Space Council. (2020). *A New Era for Deep Space Exploration and Development*. https://csps.aero-space.org/sites/default/files/2021-08/NSpC%20New%20Era%20for%20Space%2023Jul20.pdf.

Low Cost of Navigating Cislunar Space Once Off the Earth

Figure 1 is a representative change in velocity (delta-v) chart that shows navigation in near-Earth and cislunar space. The chart shows delta-v in kilometers per second based on energy transfer between different orbits in near-Earth and cislunar space. The low delta-v cost for moving around once off the surface of the Earth provides interesting opportunities in cislunar space.

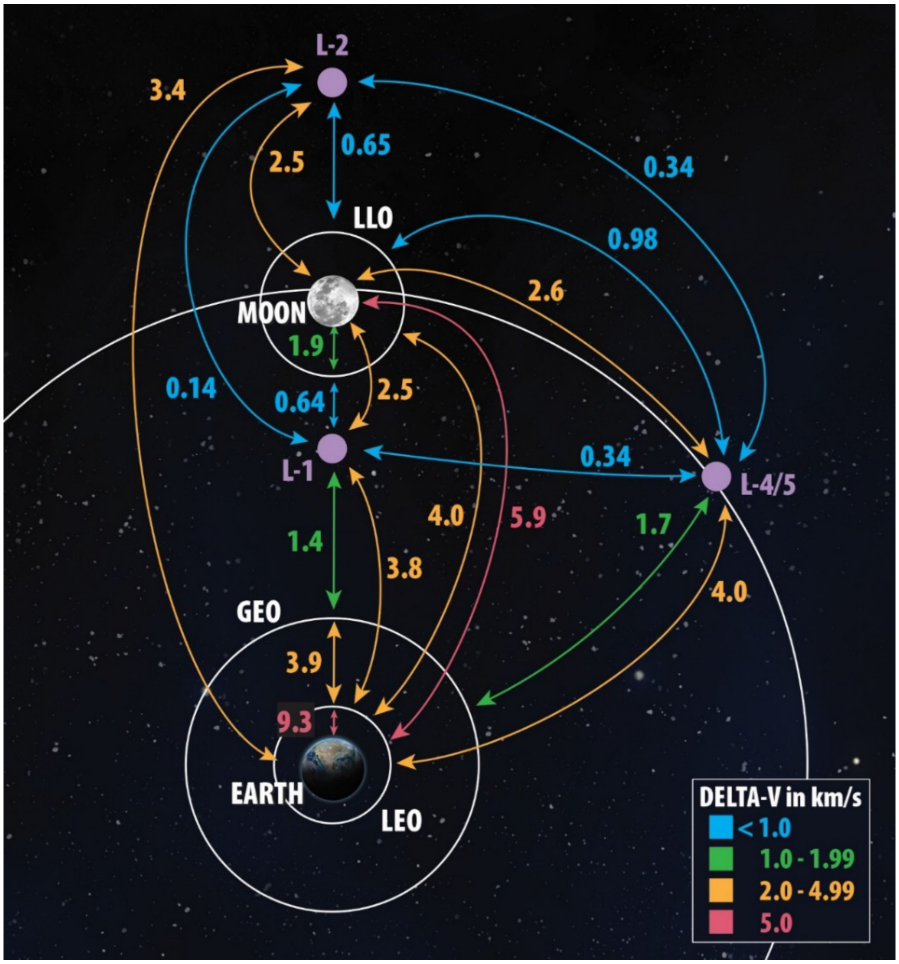

Figure 1. Representative delta-v values based on energy transfer. This chart of representative delta-v values for transition between different cislunar orbital regimes is based on the energy transfer needed to move from one regime to another. To get actual values, specific orbits need to be considered.[12,13] *Also note.*[14,15]

[12] Delta-v budget. In *Wikipedia*. https://en.wikipedia.org/wiki/Delta-v_budget.
[13] Delta-v image. In *Wikipedia*. https://it.m.wikipedia.org/wiki/File: Delta_V_Earth_Moon_Mars.png.
[14] Lower-energy transition options might exist that would take substantially longer than a conventional transition.
[15] Not shown in this diagram, the Moon can be used as a gravity assist to help reduce the energy of some of these transitions.

In navigating cislunar space, the following delta-v comparisons can be surprising:

- It takes less delta-v to get to low Earth orbit (LEO) from the surface of the Moon than from the surface of the Earth.
  - Earth to LEO 9.3 km/s delta-v
  - Moon to LEO 5.9 km/s
    - Moon to low lunar orbit (LLO) 1.9 km/s
    - LLO to LEO 4.0 km/s
- LEO to the cislunar Lagrange points is about the same as LEO to GEO: 3.4–4.0 km/s delta-v.
  - LEO to GEO 3.9 km/s
  - LEO to L2 3.4 km/s
  - LEO to L1 3.8 km/s
  - LEO to L4/L5 4.0 km/s
- Moving between Lagrange points requires small amounts of delta-v.
  - L1 to L2 140 m/s
  - L1 to L4/L5 340 m/s
  - L2 to L4/L5 340 m/s
- Moon to GEO is the same as LEO to GEO
  - Moon to GEO 3.9 km/s
  - LEO to GEO 3.9 km/s
  - Earth to GEO 13.2 km/s

Also note that the 9.3 km/s to get from Earth to LEO dwarfs all other delta-v values shown in this chart. It's cheaper in delta-v to get from the surface of the Moon to LEO than from the Earth to LEO because the Moon's gravity well is substantially shallower than the Earth's gravity well when measured in delta-v. So, when ISRU on the Moon generates sufficient quantities of fuel, providing that fuel from the Moon to LEO is cheaper in delta-v than providing it from Earth.

The further away from Earth, the more these delta-v values favor non-Earth sources. For instance, from the Moon to GEO is 3.9 km/s compared with 13.2 km/s from the Earth to GEO.

U.S. Cislunar Security Needs

Following the presentations and discussions at the 2020 and 2021 CLSC, APL identified two broad needs for U.S. cislunar security. The first is a national strategy and policy that ensures U.S. leadership in the cislunar domain and enables the United States, its allies, and its partners to set norms of behavior and establish rules-based order in cislunar space and on the Moon. The second is the development of technical capabilities required for the United States, its allies, and its partners to ensure safety, stability, and transparency for space operations in the cislunar domain. This document describes capabilities identified as foundational to cislunar security: space situational awareness (SSA); reconstitution of space-based capabilities from cislunar space; position, navigation, and timing (PNT); and communications. Specific technology developments that are required to support each of these missions are included.[16]

Stakeholders and Other Efforts

There are many stakeholders with interests in cislunar space and cislunar security, including the international science community, commercial industry, international allies and partners, the National Space Council, the National Security Council, NASA, the defense community, including the United States Space Command (USSPACECOM) and Space Force, and the United States Intelligence Community.[17] Other entities, programs, and forums have examined the use of cislunar space and its security implications, and some have developed or are developing recommendations for U.S. cislunar strategy and technology development. A few examples are the United States Space Priorities Framework,[18] NASA's Artemis Program,[19] the Lunar Surface Innovation Initiative,[20] the Lunar Surface Innovation Consortium,[21] the Air Force Research Laboratory's Cislunar Summits, the Aerospace Corporation's Cislunar Technical Exchange Meetings and Workshops, and the Advanced Maui Optical and Space Surveillance Technologies Conference's[22] cislunar SSA sessions. In addition, the White House Office of Science and Technology Policy put out a Request for Information in July 2022 soliciting input to help inform development of a national science and technology strategy for U.S. activities in cislunar space.[23] This document is meant to add to the national discourse on cislunar security strategy and complement other efforts by providing viewpoints both presented and discussed at the 2020 and 2021 CLSCs as well as discussed internally at APL and externally with the stakeholders above.

Scope

This document describes current national needs in cislunar strategy, policy, and technology, with a focus on technology to enable the missions mentioned above (SSA, reconstitution, PNT, and communications). It defines current technology needs and challenges for cislunar operations, identifies critical technology gaps, and provides recommendations for near- and long-term technology development at the national level to execute these missions. Technology areas that are specific to a particular mission are discussed in the section for that mission type. Several space technologies needed for all cislunar mission types that would benefit from maturation include

[16] Mike Griffin's keynote address at the 2021 CLSC also identified many of these mission needs.
[17] An interesting question is which U.S. government agency is responsible for lunar exploitation? NASA is an exploration agency. The DoD defends. Does the Department of Commerce own lunar development and exploitation? Should the Department of the Interior? Or is a new organization needed to foster the cislunar economy? Perhaps the Department of the Exterior?
[18] White House. (2021). *United States Space Priorities Framework*. https://www.whitehouse.gov/wp-content/uploads/2021/12/united-states-space-priorities-framework-_-december-1-2021.pdf.
[19] NASA Artemis Program. https://www.nasa.gov/artemisprogram.
[20] NASA Space Technology Mission Directorate, Lunar Surface Innovation Initiative. https://www.nasa.gov/directorates/spacetech/Lunar_Surface_Innovation_Initiative.
[21] Lunar Surface Innovation Consortium. https://lsic.jhuapl.edu/.
[22] Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference. https://amostech.com/.
[23] Request for Information; Cislunar Science and Technology Subcommittee, 87 *Fed. Reg*. 128 (July 6, 2022). https://www.govinfo.gov/content/pkg/FR-2022-07-06/pdf/2022-14316.pdf.

mission design, propulsion (high- and low-thrust), guidance and control, power, thermal, structures, communications and data handling, and autonomy.

This technology vision does not address the entirety of technology development needed for cislunar security. For one, it is focused on the specific capabilities of SSA, reconstitution, PNT, and communications and does not address technology development required for pursuits such as human exploration and economic development that, although they have important implications for cislunar security, do not fall within the purview of the defense community. Furthermore, this technology vision is focused on in-space components and does not address topics such as ground systems or launch capabilities.

Other technologies not addressed in this document include: nuclear power (such as surface kilopower)[24] and nuclear thermal or electric propulsion (such as DRACO),[25] ISRU technologies,[26] autonomous manufacturing, and autonomous construction.[27]

This technology vision also does not address who should be responsible for developing and implementing the recommended strategy, policy, and technology solutions. It is expected that, to achieve the national-level cislunar vision, partnerships and collaboration across multiple agencies will be required. This was recognized in the MOU between NASA and the Space Force:

> "As NASA's human presence extends beyond ISS to the lunar surface, cislunar, and interplanetary destinations, and as USSF organizes, trains, and equips to provide the resources necessary to protect and defend vital U.S. interests in and beyond Earth-orbit, new collaborations will be key to operating safely and securely on these distant frontiers."[9]

Outline of the Cislunar Security National Technical Vision

There are three points worth emphasizing in this cislunar security vision. The United States needs the following:

1. An international policy that establishes norms of behavior[28]
2. SSA to identify when norms have been violated
3. The ability to address norm violations

This document consists of six sections (including this Introduction) describing needs for cislunar security and associated recommendations that address policy, SSA, the cislunar reconstitution option, and PNT and Communications infrastructure.

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[24] NASA Space Technology Mission Directorate. https://www.nasa.gov/mission_pages/tdm/fission-surface-power/index.html.
[25] DARPA DRACO. https://www.darpa.mil/program/demonstration-rocket-for-agile-cislunar-operations.
[26] LSIC In Situ Resource Utilization Focus Area. https://lsic.jhuapl.edu/Our-Work/Focus-Areas/index.php?fg=In-Situ-Resource-Utilization.
[27] In-Space Servicing, Assembly, and Manufacturing Interagency Working Group of the National Science & Technology Council. (April 2022). *In-Space Servicing, Assembly, and Manufacturing National Strategy.* https://www.whitehouse.gov/wp-content/uploads/2022/04/04-2022-ISAM-National-Strategy-Final.pdf.
[28] While out of scope of the cislunar vision, these norms of behavior would also be useful in GEO and LEO.

In “Formulating a National Cislunar Strategy and Policy,” Susanne Wirwille and Bruce MacDonald describe the history and trajectory of cislunar activity, the urgent need for a cislunar security strategy and policy, threats to cislunar security, cislunar opportunities and challenges, and a recommended national approach for cislunar security and prosperity through cooperative, economic, and stability threads.

In “Cislunar Situational Awareness,” Erin Fowler and Ben Schmachtenberger describe the need for situational awareness in cislunar space for identifying norm violations, enabling space traffic management, enhancing safety, and avoiding hazards. Technological needs and challenges, critical technology gaps, and recommendations for technology development in support of cislunar SSA are identified.

In “Use of Cislunar Space for Reconstitution of Space-Based Capabilities,” Brian Bauer and Eric Klatt cover the missions and priority for a cislunar reconstitution option, several approaches to building a capability for reconstitution, and considerations for reconstitution using cislunar space-based assets.

In “Cislunar Position, Navigation, and Timing,” Ryan Mitch describes the PNT services and technology needed in cislunar space, heritage systems, emergent architectures, and recommendations for Department of Defense and NASA collaborations.

In “Cislunar Communications,” Ed Birrane and Sarah Heiner give an overview of network communications, networking as an enabler, evolving and defining a cislunar network architecture, and recommendations for cislunar communications systems.

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2. FORMULATING A NATIONAL CISLUNAR STRATEGY AND POLICY

Susanne Wirwille and Bruce MacDonald

The United States Needs a Cislunar Security Strategy and Policy Now

The United States needs a long-term cislunar strategy and policy to strengthen leadership in the space domain; expand our economic zone into cislunar; fortify our science, technology, engineering, and mathematics (STEM) base; develop our cislunar industrial base; and enhance space security and stability from the Earth to the Moon. Such a strategy and policy require uniting our government agencies, attracting allies and partners with common visions, establishing norms of behavior, shaping the foundational investments, and propelling our expansive and talented space industry into cislunar. The longer that the United States delays in producing such a strategy and policy, the further we fall behind in global leadership and competitive advantage. The lack of a cislunar strategy and policy reduces our national purpose for space, and fails to inspire young scientists and engineers to pursue related studies and careers in space exploration, development, and operation. Building a cislunar enterprise on a foundation of universities and international partnerships will ensure transparency of space activities, contributing to the overall security and stability of cislunar space and our nation.

In this section, we lay out key factors to consider for a national cislunar strategy and policy, highlighting the value that cislunar development offers to our nation, allies, and partners.

Cislunar—The Newest Frontier

History of Cislunar Activity

From the earliest days of the space race, U.S. and Soviet competition embraced cislunar and other deep space missions. This competition was driven by a common desire for scientific knowledge plus intense competition for international prestige between the two countries, which resulted in multiple missions to the Moon and planets, with the United States quickly pulling ahead in the competition after an early Soviet lead. The Moon was the chief focus of cislunar missions, with more than 100 spacecraft sent there, though not all successfully. The U.S. Apollo program sent humans to the Moon between 1968 and 1972 with nine missions to the Moon and six landings. Russia's last Moon mission was Luna 24 in 1976. It had planned to send a Luna 25 mission to the Moon in 2022, but underperformance during testing of a key instrument, coupled with the withdrawal of the European Space Agency (ESA) from the project over Russia's invasion of Ukraine, has postponed these plans to no earlier than 2023. Plans for Luna 26 and 27 missions are likely uncertain at best.[1]

[1] Vardhan, H. (Sept. 8, 2022). Russia's space chief confirms the launch of Luna 25 Moon mission postponed to 2023. RepublicWorld.com. https://www.republicworld.com/science/space/russias-space-chief-confirms-the-launch-of-luna-25-moon-mission-postponed-to-2023-articleshow.html.

In the last few decades, China has replaced Russia as the Unites States' chief competitor. Bringing advanced technology and greater resources to its program, China has achieved important milestones, such as putting humans into space, landing a spacecraft on the far side of the Moon, putting a communications relay at L2, building a space station in Earth's orbit—Tiangong, to be completed at the end of 2022—and landing and operating a rover on the surface of Mars. More ambitiously, China plans to establish a crewed research base on the Moon, dubbed the International Lunar Research Station, which is scheduled to become operational after 2035. Russia has signed an agreement to collaborate with China on this mission, though Russia's role in the partnership is currently unclear, particularly given recent events in Ukraine. As of 2021, China was engaged in negotiations with ESA, Thailand, the UAE, and Saudi Arabia.[2] Notably, the UAE just signed on to fly a rover on Chang'e-7, which makes them the first to formally participate.[3]

The United States has its own program for lunar exploration and research, Artemis, which aims to return American astronauts to the Moon by 2025 and ultimately establish a sustained human presence there. Through the Artemis Accords, the United States has invited other countries to become partners in this project, to which the European Union and 21 other countries have signed on as of July 2022.

It appears that cislunar space activity is not a question of "if," but rather "when, to what extent, and to what end?" If so, the question becomes "how should the Unites States address this oncoming future chapter in space?"

Current Situation and Trajectory

In addition to the United States' and China's national plans, a variety of other countries are planning to explore and exploit cislunar space.[4] From a policy perspective, the cislunar region represents a new frontier for more intensive exploration and economic development. The 1967 Outer Space Treaty (OST)[5] was a good start, but this 55-year-old treaty could not be expected to address the issues of the modern space era. It lacks the policy, regulatory authorizations and restrictions, and even norms guidance necessary to support cislunar activities. However, the United States now has both the OST and lessons learned in Earth's orbits to provide guidance and highlight past mistakes, giving us the chance to avoid making those mistakes again in the future. This experience provides an opportunity to bring a more organized system into the process, particularly where the economic exploitation of new opportunities by the international commercial sector can lead to a disorderly environment without appropriate oversight.

In an encouraging recent development, the past several years have seen a rapid emergence of reinvigorated discussion around space governance, particularly as it applies to novel, private activi-

[2] Stimers, P., & Jammes, A. (Oct. 18, 2021). The Artemis Accords after one year of international progress. *The Space Review.* https://www.thespacereview.com/article/4267/1.
[3] Jones, A. (Sept. 19, 2022). UAE rover to fly on China's Chang'e-7 lunar south pole mission. *SpaceNews*. https://spacenews.com/uae-rover-to-fly-on-chinas-change-7-lunar-south-pole-mission/
[4] Johnson, K. (2022). *Fly Me to the Moon: Worldwide Cislunar and Lunar Missions*. Center for Strategic and International Studies. http://aerospace.csis.org/wp-content/uploads/2022/02/220215_Johnson_FlyMe_Moon_WEB.pdf.
[5] United Nations Office for Outer Space Affairs, OST. https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html.

ties and increasingly congested space. This discussion, which has been characterized by the formation of new fora for international discussions on appropriate norms of behavior in space and new mechanisms for the U.S. government, particularly, to collaborate with its space industry actors, is beginning to shape a new era of space policy. These mechanisms have the potential to form a strong foundation for the evolution of responsible and peaceful cislunar space and lunar surface governance; however, such conversations have so far been eclipsed by more pressing needs in Earth's orbits. Increasingly, considerations unique to cislunar space and the lunar surface will need to be acknowledged.

United States

The United States Artemis program seeks to establish a sustainable, human-robotic presence on the Moon as early as 2025 or 2026[6] to prepare for missions to Mars. To accomplish this, NASA is collaborating with commercial and international partners. U.S. agencies are already preparing for greater activity in the cislunar region, as evidenced by the joint Defense Advanced Research Projects Agency (DARPA)–NASA nuclear thermal propulsion program that envisages traversing vast distances in cislunar space with 2–5 times the efficiency of chemical propulsion[7] with a flight demonstration in fiscal year (FY) 2026. DARPA has also initiated a program, Novel Orbital Moon Manufacturing, Materials, and Mass-efficient Design (NOM4D), to enable production of future space structures on-orbit without the volume constraints imposed by launching limitations.[8]

NASA's overall budget request for FY2023 is almost $26 billion, of which the Artemis Program request is $7.5 billion, a $1.1 billion increase over FY2022's $6.4 billion.[9] U.S. government and commercial organizations have invested on the order of $7–10 billion in 2022 in cislunar infrastructure, though these funds are not being spent in a coordinated manner.[10]

NASA cislunar efforts in addition to Artemis include LunaNet,[11] Commercial Lunar Payload Services (CLPS),[12] and Gateway.[13] LunaNet is a proposed data network to provide a lunar internet for cislunar spacecraft and installations. It will avoid needing to preschedule data communications back to Earth, making it easier for lunar devices to communicate with each other and with Earth. CLPS relies on commercial companies for landed lunar payload delivery with 14

[6] Howell, E. (March 1, 2022). NASA's 1st Artemis moon landing will likely slip another year to 2026. Space.com. https://www.space.com/artemis-moon-landing-likely-slip-to-2026.
[7] Erwin, S. (May 4, 2022). DARPA moving forward with development of nuclear powered spacecraft. *SpaceNews*. https://spacenews.com/darpa-moving-forward-with-development-of-nuclear-powered-spacecraft/.
[8] DARPA. (March 23, 2022). *DARPA Kicks Off Program to Explore Space-Based Manufacturing* [press release]. https://www.darpa.mil/news-events/2022-03-23.
[9] Harwood, W. (March 28, 2022). Biden's 2023 budget request gives boost to NASA's Artemis moon program. *CBS News*. https://www.cbsnews.com/news/nasa-artemis-moon-program-biden-budget-2023/.
[10] Guidi, C., Birk, R. J., Rathjen, T. W., & Radcliffe, T. O. (June 2022). *Charting a Course Through Cislunar Master Planning*. Aerospace Corporation.
[11] NASA. (Oct. 6, 2021). LunaNet: Empowering Artemis with communications and navigation interoperability. https://www.nasa.gov/feature/goddard/2021/lunanet-empowering-artemis-with-communications-and-navigation-interoperability.
[12] NASA Commercial Lunar Payload Services Overview. https://www.nasa.gov/content/commercial-lunar-payload-services-overview.
[13] NASA Gateway. https://www.nasa.gov/gateway/overview.

identified eligible providers. Gateway is a lunar Near Rectilinear Halo Orbit (NRHO) space station intended for astronaut docking on the way to and from the lunar surface. In addition, more than 60 companies and 10 U.S. government organizations are involved with work for investing for deploying one or more foundational layers of a sustainable cislunar ecosystem.[10]

China

China released its latest space white paper in January of 2022. “China’s vision for space is to strengthen its space presence in an all-round manner: to enhance its capacity to better understand, freely access, efficiently use, and effectively manage space; to defend national security, lead self-reliance and self-improvement efforts in science and technology, and promote high-quality economic and social development; to advocate sound and efficient governance of outer space, and pioneer human progress; and to make a positive contribution to China’s socialist modernization and to peace and progress for all humanity.”[14]

China advertises plans[15] to become a global leader in space technology by 2045 and to establish a space economic zone in cislunar space by 2050—an economy they estimate at $10 trillion a year for China. This also corresponds with the 100th anniversary of the establishment of the People’s Republic of China (PRC) in 1949, an important landmark for China.

The PRC’s space enterprise continues to mature rapidly, and Beijing has devoted significant resources to growing all aspects of its space program, from military space applications to civil applications such as profit-generating launches, scientific endeavors, and space exploration. The PRC is employing more sophisticated satellite operations and is probably testing dual-use technologies in space that could be applied to counter-space missions.[16]

Overall Chinese funding on its space program is estimated at $8.9 billion in 2020.[17] In many ways, China’s civil space program, the China National Space Administration, is a wholly owned subsidiary of the PLA Rocket forces. It is much more closely aligned than NASA and the U.S. national security establishment.[18]

In the next five years, China will continue with lunar and planetary exploration.[14] It will:

- Launch the Chang'e-6 lunar probe to collect and bring back samples from the polar regions of the Moon;
- Launch the Chang'e-7 lunar probe to perform a precise landing in the Moon’s south polar region and deploy a mini flying probe into a permanently shadowed lunar area;

[14] The State Council Information Office of the People’s Republic of China. (January 2022). *China’s Space Program: A 2021 Perspective*, White Paper.
[15] China Daily, Nov. 17, 2017; CXTech News, Caixinglobal.com, Nov. 1, 2019.
[16] Office of the Secretary of Defense. (2020). *Military and Security Developments Involving the People’s Republic of China 2020*, Annual Report to Congress.
[17] GW News Desk. (Dec. 15, 2020). Euroconsult’s flagship research shows government space program budgets have maintained growth trajectories. *Geospatial World*. https://www.geospatialworld.net/news/euroconsults-flagship-research-shows-government-space-program-budgets-have-maintained-growth-trajectories/.
[18] China Power Team. (Dec. 7, 2016). What’s driving China’s race to build a space station? *China Power*. Updated April 21, 2021. https://chinapower.csis.org/chinese-space-station.

- Complete research and development on the key technology of Chang'e-8 and work with other countries, international organizations, and partners to build an international research station on the Moon;
- Launch asteroid probes to sample near-Earth asteroids and probe main-belt comets;
- Study plans for boundary exploration of the solar system, beyond the cislunar region.

China and Russia have agreed to work together on the Chinese International Lunar Research Station. They are presenting this agreement as being open to all interested countries and international partners, particularly India.

The Threat of Complacency

Threats to cislunar security could easily reach maturity and domination simply due to U.S. complacency. Competitors, such as China, aim to develop a Cislunar Economic Zone which will prioritize their own national interests, establishing themselves and the rule-set first.

China has set out to gain the first-mover advantage by accelerating their space program, to include cislunar space. They aim to dominate with a Cislunar Economic Zone by 2050. Such a future is not consistent with the interests of U.S., our allies, and our partners.

Standardized Norms

An "open ended working group"[19] was established by the U.N. General Assembly in December 2021 to address space security issues. It held its first session May 9–13, 2022, at the United Nations Office in Geneva. The goal of these talks is to make "recommendations on possible norms, rules and principles of responsible behaviors relating to threats by states to space systems."[19] This working group is the result of a resolution put forth by the United Kingdom with U.S. backing, and supported by 163 nations. Twelve countries voted against it, including Russia, China, Iran, Syria, North Korea, Cuba, and Venezuela. The resolution put forward by the United Kingdom also expressed concern about "the fragility of the space environment and the challenges to the long-term sustainability of outer space activities, in particular the impact of space debris." It is expected to meet twice in 2022 and twice more in 2023. China will show up, though Russian participation is especially uncertain. Under likely consideration will be a moratorium on destructive direct-assent anti-satellite (ASAT) missile testing, much as the United States unilaterally announced in 2022.[20] Other related measures, such as space debris mitigation and disposal, are likely to come up. The expectation is that despite voting against the measure, China will participate. The working group met again in September 2022 to focus on "current and future threats by states to space systems, and actions activities and omissions that could be considered irresponsible." All this is prelude for the working group in 2023 to prepare its recommendations to the U.N. General Assembly.[21]

[19] United Nations. Open-Ended Working Group on Reducing Space Threats. https://meetings.unoda.org/meeting/oewg-space-2022/.
[20] The White House. (April 18, 2022). *Fact Sheet: Vice President Harris Advances National Security Norms in Space*. https://www.whitehouse.gov/briefing-room/statements-releases/2022/04/18/fact-sheet-vice-president-harris-advances-national-security-norms-in-space/.
[21] Kimball, D. (June 2022). Space Security Working Group meets. *Arms Control Today*.

History is replete with examples of sustained first mover advantages, not just in the venture capital arena but also in international endeavors, particularly in scientific and technological exploration. For example, in World War II, the cost of developing atomic weapons deterred all the major powers from pursuing a successful program to develop them given the financial demands of conventional conflict, except for the United States, which allocated funding to both develop atomic weaponry and prosecute conventional conflict. Similarly, the Soviet Union gained important international acclaim for its space prowess when it jumped to an early lead in the space race in the late ’50s and early ’60s, and it was only overtaken by a determined and sustained U.S. effort that reached 4.5% of the federal budget in the mid-1960s.

In an earlier era, countries that explored new realms gained important geopolitical advantages over countries that failed to explore. Perhaps just as important, nations that “get there first” are generally able to dominate in the setting of norms of behavior. Setting space norms of behavior is an important objective that the United States should not cede to a rival space power that embraces a political philosophy of autocratic government. Given sustained worldwide interest in space exploration, the U.S. should not allow its reputation in the space domain to be diminished by China or any other nation. This does not rule out possible cooperation with China or Russia in cislunar exploration, a la Apollo-Soyuz Project and other confidence-building steps, but it should be done from a U.S. position of strength and technological leadership. The choice is not between the United States setting norms for cislunar space and pure U.S. freedom of action. There is a trade-off between United States leadership in setting norms in cooperation with other countries, and the U.S. asserting the right to do as it sees fit in space. The latter is a prescription for failure in international cooperation. It would cede the leadership ground to China to set those norms and rules of the road and lead the way to greater practical cooperation in cislunar space. The choice is stark: China will dominate the setting of space norms of behavior if they predominate in cislunar exploration and exploitation. An emergency cislunar program is not needed, but a sustained effort is.

China is not hesitating. Its most recent white paper[14] on space devotes an entire section to the global governance of space. In this section, it states that China will “speed up the formulation of a national space law and establish this law at the core” and “include studying and formulating regulations on the management of satellite frequency and orbit resources,” among other governance tasks. In our view, China wants to have an important seat at the table when space governance is being discussed at the United Nations and in other fora. They see an opportunity to take a leadership position.

The latest Defense Intelligence Agency (DIA) assessment of China and Russia space activity[22] includes special attention on Chinese and Russian Moon and Mars exploration, and potential threats from the increased use of cislunar space for exploration and potential economic exploitation.

“Deep-space operations beyond Earth orbit, sometimes called xGEO, are focused on scientific missions and exploration of the Moon and other celestial bodies. Spacecraft in xGEO are much

[22] DIA. (2022). *Challenges to Security in Space: Space Reliance in an Era of Competition and Expansion*. https://www.dia.mil/Portals/110/Documents/News/Military_Power_Publications/Challenges_Security_Space_2022.pdf.

harder to track and characterize, and could threaten U.S. or allied high-value satellites. Adversaries could also place operational or reserve satellites in deep space so they are much harder to monitor for later use in lower orbits," DIA states.

> "The United States still requires a **whole-of-nation vision and strategy for economic and industrial space development** to unite all elements of national power and to attract like-minded allies and partners to a common wealth-creation framework. Central to this is the establishment of **a clear vision of a cislunar economy** by bringing the Moon into Earth's economic sphere with clear production goals for in-space and Lunar industrial facilities. Such a vision and strategy **must be relevant to the global agenda**, consonant with the spacefaring ambitions of the electorate, and have sufficient bipartisan support to endure multiple administrations. This is America's better answer to China's Belt and Road Initiative."
>
> – *State of the Space Industrial Base 2021*, November 2021, p. 37 (emphasis added)[23,24]

National Strengths and Values

Deep within our national psyche is the strong desire to push boundaries, explore the unknown, and advance knowledge and understanding. From the very depths of the oceans or outer space, pursuing these desires with vigor and passion is what enables us to advance confidently into cislunar space.

As a nation, we value rules-based order, transparency, confidence-building measures, and the continual advancement of security and prosperity. Within the space domain, our strengths include active technical and operational collaboration with like-minded allies and partners around the globe. The United States also enjoys both significant launch capability and a thriving commercial space ecosystem. Uniting our national values, passions, and strengths positions us at this time and place to chart a responsible course for the exploration and advancement of cislunar space, while maintaining stability and security for all, through the establishment of "norms" of responsible behavior.

Cislunar Opportunities and Challenges

There are significant potential opportunities in cislunar space. Some are already known and others are yet to be discovered. For the near-term, most organizations see their business cases tied to government funded space-oriented agencies, especially NASA, and in particular the Artemis program and human activities on the Moon.

One major uncertainty is the extent to which national security requirements will further boost the demand for goods and services in space. The Department of Defense's demand for goods and services in cislunar space, if and when it materializes, may be greater than that of NASA, but this is conjecture, not fact. Relatively few companies have plans independent of government space agencies that tie into their vision of settling the Moon; most companies count on funding from the government. Issues of property rights and legal uncertainties, such as those related to mining

[23] Olson, J., Butow, S., Felt, E., Cooley, T., & Mozer, J. (2021). *State of the Space Industrial Base 2021: Infrastructure & Services for Economic Growth & National Security*. Ed. P. Garretson. U.S. Department of Defense. https://assets.ctfassets.net/3nanhbfkr0pc/43TeQTAmdYrym5DTDrhjd3/a37eb4fac2bf9add1ab9f71299392043/Space_Industrial_Base_Workshop_2021_Summary_Report_-_Final_15_Nov_2021c.pdf.

[24] State of Space Industrial Base 2022 is in development, building on the 2022 SSIB workshop (May 31–June 3, 2022).

on the surface of the Moon, did not seem to be central challenges to the business plans for these companies.

The transformation of the near-Earth economic landscape alone is testimony to the potential of unforeseen opportunities. There is certainly commercial interest in cislunar space. One private company, Quantum Space, has already been formed to establish a private outpost in cislunar space to take advantage of the opportunities presented by Artemis, commercial lunar payload services, and the needs of the national security community. Quantum plans to operate a space tug to move payloads from near Earth to its outpost near the Earth–Moon L1 Lagrange point.

The United Launch Alliance has started a project, CisLunar-1000, which foresees lunar bases, lunar mining, stations between the Earth and Moon, and asteroid mining operations.[25] This approach would reduce the cost of boosting satellites from temporary LEO orbits up to GEO orbits. One recent Institute for Defense Analyses (IDA) study[26] found that there are more than 80 organizations in 12 countries that offer or aspire to offer services and products on the Moon or in cislunar space. While most are U.S.-based, several are in allied countries such as Germany, the United Kingdom, Japan, and Luxembourg. Many are commercially oriented. Two private stakeholders in developing the cislunar economy, SpaceX and Blue Origin, are investing heavily in lowering the cost of transportation services to the Moon. Most companies focus on transportation or structures and habitats, two areas of derived demand where there are likely to be stable long-term government contracts. This frees government to focus on higher value activities, while letting industry handle services. For household products and services in the near term, there may be markets for lunar tourism, lunar rocks, lunar artifacts, and burials on the Moon.[27] Other than advertising, it isn't clear what goods or services purchased by businesses will be economically viable in the next 20 years. Of course, it is worth noting that 20 years ago few predicted that the current space economy would be anything like it is today.

The potential is great, but the road ahead for cislunar space is hazy at best. This is much like the potential of the Louisiana Territory must have appeared in the immediate aftermath of the Louisiana Purchase in 1803. The answer then, as it appears to be now, was a further exploration of the potential of this new frontier, to shed light on this hazy and dim future and allow better-informed decisions to be made on the path forward. Perhaps the U.S. needs to identify the cislunar Lewis and Clark expedition.

Future Vision

Humanity is gaining access to a new frontier, one that could benefit from previous lessons about what works. Could the United States create a vision for cislunar space that is embraced by all nations, delivering stability, security, and prosperity that comes through living in harmony?

Many of the sound principles for cislunar space parallel the safety and security principles exercised in the maritime environment today. Those maritime principles are many, but several stand

[25] David, L. (June 29, 2016). Inside ULA's plan to have 1,000 people working in space by 2045. Space.com. https://www.space.com/33297-satellite-refueling-business-proposal-ula.html.
[26] Colvin, T. J., Crane, K. W., Lindbergh, R., & Lal, B. (April 2020). *Demand Drivers of the Lunar and Cislunar Economy*, IDA Document D-13219. IDA Science & Technology Policy Institute.
[27] https://elysiumspace.com/.

out as foundational: international maritime organization (IMO) for safety and security under the United Nations, international agreed rules for safety (United Nations Convention on the Law of the Sea), notification of hazards (Notice to Mariners, NTM or NOTMAR), safe routes of transit (sea lines of communication), collision avoidance, emergency communications, at-sea and in-port replenishment, infrastructure for loading/unloading and services, and cargo declaration/bill of lading. While cargo transport is the main activity in the maritime domain, there are a multitude of other activities which could also occur in cislunar space, to include cooperative business enterprises, natural resource extraction, research and exploration, and tourism. In the maritime domain, these activities are conducted with the underlying agreement to preserve the environment and minimize pollution and debris. We could certainly embrace similar principles for cislunar space, enabling security and economic prosperity.

A National Approach

A national approach to cislunar development, safety, and security should be firmly rooted in our core national tenets: establish through cooperation with global partners standardized norms of behavior, enable the U.S. commercial enterprise to thrive, and ensure stability and security for the United States, its allies, and its partners. As such, there are three strategic threads to follow when developing a cislunar strategy:

1. **Cooperative activities** undertaken with allies, partners, and industry that build transparency and strengthen relations;
2. **Economic activities**, which create an environment for the United States and free world commercial enterprises to thrive; and
3. **Stability activities**, in which security is achieved through internationally-agreed rules, international governance, and enforcement.[28]

Cooperative strategic thread activities and services follow OST principles by enabling an environment of non-interference, and emphasize building understanding and basic infrastructure for activity in cislunar space. The United States can accelerate learning and trust through transparency. This thread includes missions such as scientific discovery, communications and networking, PNT, space weather, and SSA. Standards should be agreed cooperatively, and these capabilities developed and fielded in cooperation with allied and partner nations, industry, as well as through university consortiums.

Economic strategic thread activities support and accelerate commercial development in cislunar. Economic activities include prospecting, resources, manufacturing structures, standardizing transit corridors and orbits supported by fuel stations and services, and development of cislunar-sustainable power and propulsion. As the foundational infrastructure capabilities are cooperatively developed, nations can unilaterally, bilaterally, and multilaterally develop commercial capabilities for economic activities in cislunar space.

[28] Falk, T., Wirwille, S., & Brothers, S. (November 2021). *The Future Cislunar Economy: Strategy and Plan for Achieving a "Tipping Point" for Industrialization of Space.* The Johns Hopkins University Applied Physics Laboratory, Laurel, MD.

Rules and governance should be co-developed and established early to ensure stability and security of cislunar space. Stability strategic thread missions include space safety coordination, guardianship, and regulation and international governance coordination. The proposed space safety coordination body should be a strategic entity that ensures the transparency of activities to support safe cislunar transits, sharing SSA, alerts, and warnings, particularly related to space weather, conjunctions, debris, and other potential hazards. The proposed guardianship body should be an operational entity, mandated by an international body to provide safety and security in cislunar by rendering assistance to humans or critical infrastructure in distress, as well as conduct general policing functions. The proposed regulation and international governance coordination body should review and update laws and regulations required to accommodate new and envisioned activities in cislunar and deep space. In the Stability thread, the aim is to establish laws, governing behavior, monitor and coordinate activity for safety, and render assistance through an operational entity.

Conclusion

Space exploration has historically been beneficial to our nation, fueling innovation and industry. To boldly advance in this new frontier of cislunar space, we need a national strategy and policy, with government foundational investments and clear paths for space industrial enterprise activities. Our nation, allies, and partners should be at the heart of our national strategy and policy, bolstering our collaborative STEM base—composed of scientists, industrial engineers, service providers, and more—and inspiring our future astronauts. Strong national leadership will guide and orchestrate the foundational activities, and maintain a keen eye on future possibilities—in space, on the Moon, and beyond cislunar. Our decisions, or lack of decisions, set the course for the future of our nation's activities in cislunar space. We cannot afford to endlessly study the potential of cislunar space—we need a strategy and policy now to set the course for stability, security, and prosperity for our nation, allies, and partners.

3. CISLUNAR SITUATIONAL AWARENESS

Erin Fowler and Ben Schmachtenberger

Why Do We Need Cislunar Situational Awareness?

The need for cislunar situational awareness is motivated by the recent increase in cislunar activities and a multitude of near-term planned activities on the Moon and in cislunar space. On December 11, 2017, President Donald Trump issued a presidential memorandum known as Space Policy Directive 1 (SPD-1), which amended President Barack Obama's Presidential Policy Directive 4 by incorporating the following paragraph:[1]

> Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, 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.

Lieutenant General John Shaw, Deputy Commander of United States Space Command since 2020, wrote with co-authors in *Aether: A Journal of Strategic Airpower and Spacepower*, about the logic behind the founding of the United State Space Force in 2019: "With its organize, train, and equip responsibilities, the newly formed service will usher in an era of space-based capabilities focused on ex-geosynchronous [also known as cislunar] operations that would not have proliferated otherwise."[2]

Asked [in 2021] by *Air & Space Forces Magazine* whether the United States would be able to detect a kinetic weapon launched at Earth from the Moon, Lt. Gen. Shaw answered: "We need to get our capabilities to the point where we can easily see it." China has launched an object from the Moon and accurately landed it back on Earth, placed a lander on the far side of the Moon in 2019, and used its lunar orbiter that was part of the sample return mission to demonstrate the ability to traverse cislunar and Sun-Earth space.[3]

The Memorandum of Understanding (MOU) between the National Aeronautics and Space Administration (NASA) and the Space Force states:[4]

[1] Presidential Memorandum on Reinvigorating America's Human Space Exploration Program (Dec. 11, 2017). https://trumpwhitehouse.archives.gov/presidential-actions/presidential-memorandum-reinvigorating-americas-human-space-exploration-program/.
[2] Shaw, J. E., Purgason, J., & Soileau, A. S. (Spring 2022). Sailing the new wine-dark sea: Space as a military area of responsibility. *Aether*, 1(1), 35–44.
[3] Miller, A. (Oct. 7, 2021). Cislunar space. *Air & Space Forces Magazine*. https://www.airforcemag.com/article/cislunar-space/.
[4] Memorandum of Understanding Between the National Aeronautics and Space Administration and the United States Space Force. (2020). https://www.nasa.gov/sites/default/files/atoms/files/nasa_ussf_mou_21_sep_20.pdf.

> With new U.S. public and private sector operations extending into cislunar space, the reach of USSF's sphere of interest will extend to 272,000 miles and beyond—more than a tenfold increase in range and 1,000-fold expansion in service volume. USSF now has an even greater surveillance task for space domain awareness (SDA) in that region, but its current capabilities and architecture are limited by technologies and an architecture designed for a legacy mission.

As mentioned above in the Policy section, the United States benefits from international policy that establishes norms of behavior in cislunar space. Space situational awareness (SSA) is an enabler in making international norms of behavior possible, by identifying when those norms have been violated. Without sufficient SSA, norm violations cannot be detected, which could make norms unenforceable. In addition to using SSA to identify norm violations, a third component of international policy is the mechanisms to address norm violations.

Space traffic management (STM) is distinct from SSA, although it relies on the availability of SSA. STM can be defined as safe access to space, operations in space, and return from space. Most commonly, it involves the prediction and avoidance of potential collisions (also known as conjunctions) between space objects, but it can also include other aspects, such as management of electromagnetic spectrum emissions. Additional published definitions are listed by Lal et al. (2018, Appendix B).[5] Automatic identification systems (AISs), such as are used in the maritime domain, may be useful for STM if hosted on cooperative vehicles to facilitate identification, location, and collision avoidance. SSA will be needed to support robust STM in cislunar space.

The need for cislunar situational awareness will also extend to the lunar surface. Note that while cislunar space is very big, high-value regions on the lunar surface are small and limited in number. In addition to other lunar surface activities worth monitoring, both the United States and China are planning to establish stations on the lunar surface to test and demonstrate technologies for in-situ resource utilization (ISRU). Various commercial companies see a future business case for ISRU and plan to mine the Moon and use the resulting material to manufacture life support, propellants, construction materials, and other items. Situational awareness, both on the lunar surface and in cislunar space, will be critical to logistics and safety for these future applications. Lunar surface awareness will be required to maintain safety, security, and transparency of activities on the Moon. It will likely take advantage of currently available technology applied in new systems. Outside of SSA, there are investments needed in lunar surface technology (e.g., landing pads, precision navigation, etc.), which NASA is pursuing under the Lunar Surface Innovation Initiative (LSII)[6] focus areas.

In this section, we focus on the component of cislunar situational awareness that requires significant investment in enabling technologies: cislunar SSA.

[5] Lal, B., et al. (April 2018). *Global Trends in Space Situational Awareness (SSA) and Space Traffic Management (STM)*, IDA Document D-9074. IDA Science & Technology Policy Institute.

[6] LSII Status. https://www.nasa.gov/sites/default/files/atoms/files/nwerkheiser_lsii_status_0.pdf.

Space Situational Awareness Definitions and Background

SSA is the study and monitoring of satellites, and it involves the detection, tracking, cataloging, and identification of artificial objects (e.g., active or inactive satellites, spent rocket bodies, or fragmentation debris). The term was first used in the Long Range Plan presented by General Howell M. Estes III, United States Space Command, in March of 1998, when he stated "near real-time space situational awareness, enabled by Surveillance of Space, is the key contributor to the Control of Space and enabling freedom of operations within it."[7] On October 4, 2019, Maj. Gen. John Shaw, then Deputy Commander of Air Force Space Command, introduced the concept of "Space Domain Awareness" to replace the legacy definition of SSA for the purpose of the U.S. Department of Defense, leaving SSA to civil and commercial space applications.[8,9]

Various elements are required to achieve effective SSA: reliable sensors capable of detection and measurement of space objects, algorithms for scheduling the use of these sensors, and filters to transform measurements into state estimates and uncertainties that are digestible by and maintained in a catalog. Commonly published catalogs for Earth-orbiting objects use two-line elements (TLEs) based on the Simplified General Perturbations model SGP4[10] and vector covariance messages (VCMs) based on the Special Perturbations model (SP).[11] The SGP4 model predicts the effect of perturbations caused by the Earth's shape, drag, radiation, and gravitation effects from other bodies such as the Sun and the Moon. SGP4 assumes a two-body (Keplerian) orbit solution, in which the resulting trajectory can only be elliptical, and updates the parameters defining the ellipse according to the effects of estimated perturbations.[12] SP contains higher order theory models than SGP4.[13]

Cislunar space situational awareness constitutes the incorporation of the states of objects significantly beyond GEO into a catalog of space objects. Cislunar SSA requires collection of observations of cislunar objects and maintenance of a catalog using data formats compatible with the trajectories of these objects. Custody entails maintaining state knowledge of an object accurate enough that when the object's position is propagated forward in time through a dynamic model and a sensor is tasked to collect another observation of that object at that time, the object is still within the sensor's field of view as expected. Custody is lost when a sensor is tasked to collect an observation of the object, but the object is not within the field of view of the sensor at collection time.

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[7] Sturdevant, R. W. (Winter 2008). From satellite tracking to space situational awareness: The USAF and space surveillance, 1957-2007. *Air Power History,* 55(4), 4–23.
[8] Shaw, J. E., Maj. Gen., USAF. (Oct. 4, 2019). Space Domain Awareness (SDA) [Memorandum]. Peterson AFB, CO: Air Force Space Command.
[9] Note that this document uses the broader SSA to represent both the civil uses of SSA and the DoD uses of SDA.
[10] Hoots, F. R., & Roehrich, R. L. (1980). *Models for Propagation of NORAD Element Sets*, Spacetrack Report No. 3. http://celestrak.org/NORAD/documentation/spacetrk.pdf.
[11] National Research Council. (2012). *Continuing Kepler's Quest: Assessing Air Force Space Command's Astrodynamics Standards*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13456.
[12] Hoots, F. R., et al. (March–April 2004). A history of analytical orbit modeling in the United States space surveillance system. *Journal of Guidance, Control, and Dynamics*, 27(2), 174–185.
[13] NASA. (December 2020). *NASA Spacecraft Conjunction Assessment and Collision Avoidance Best Practices Handbook.* https://nodis3.gsfc.nasa.gov/OCE_docs/OCE_50.pdf.

Loss of custody could be caused by insufficiently accurate prior observations or long periods of time during which observations cannot be made (for whatever reason) or oversimplified dynamic modeling (which would also encompass any unknown maneuvers made by the target object since these forces would not have been included in the dynamic model assumed by the observer) or the specific algorithms for combining prior observations with dynamic state propagation to estimate the future position of the target object. In the future, detailed and comprehensive SSA data may be used to determine violations of norms of behavior.

Current Activities in Cislunar SSA

In 2022, the Combined Space Operations Center (CSpOC), a U.S.-led multinational space operations center located at Vandenberg Space Force Base, is responsible for managing the space and missile defense sensor network, setting prioritization for monitoring more than 23,000 objects in Earth orbit and retasking sensors in real time during contingencies while ensuring adequate missile warning for national defense.[14]

The 18th Space Defense Squadron (18 SDS), also located at Vandenberg, is a component of Space Delta 2, the Space Force's Space Domain Awareness delta, and provides and advances a continuous, comprehensive, and combat-relevant understanding of the space situation and provides tracking data of resident space objects to the U.S. Department of Defense, interagency, commercial, international, and academic partners.[15]

The 19th Space Defense Squadron (19 SDS), located in Dahlgren, Virginia, provides SDA products and services in support of various missions under U.S. Space Command, which include expanding cislunar and extra-geosynchronous (xGEO) awareness via the current space surveillance network, and commercial capabilities.[16] In 2014, Analytical Graphics, Inc. (AGI, renamed Ansys Government Initiatives in 2022) introduced a Commercial Space Operations Center (COMSPOC), and in 2020 COMSPOC became a separate company independent of AGI. COMSPOC has an international space situational awareness system, including the world's first commercial deep space radar tracking system, and maintains a catalog.[17]

Cislunar SSA Challenges

TLEs fundamentally describe space object trajectories as conic sections (predominantly ellipses) and are not appropriate for cislunar SSA. In the cislunar regime, motion is best represented by three-body dynamics rather than by two-body dynamics, so the resulting trajectories are not conic sections. In special cases these trajectories are periodic or quasi-periodic in the three-body system, or they may be completely chaotic. These trajectories can be fitted to TLEs for short periods of time for the purpose of tasking sensors to collect observations of cislunar space objects, but the TLEs are not valid for very long. Heritage SSA sensors that only accept tasking in TLE

[14] https://www.space-track.org/.
[15] https://www.spacebasedelta1.spaceforce.mil/About-Us/Fact-Sheets/Display/Article/3155838/18th-space-defense-squadron-detachment-1/.
[16] https://www.spacebasedelta1.spaceforce.mil/About-Us/Fact-Sheets/Display/Article/1060278/19th-space-defense-squadron/.
[17] https://celestrak.com/.

formats will need to be upgraded for cislunar SSA. Due to the chaotic nature of the dynamic system, small perturbations can cause dramatic changes in cislunar trajectories, causing SSA systems to lose custody of objects in these trajectories. When artificial objects appear in the cislunar regime, existing TLE processes are not valid for maintaining custody of these objects.

Challenges to cislunar SSA include the need for highly accurate object observations at large distances and through obscuration, exclusion zones, and periods when the target object may be unlit (via various sensor phenomenologies); sufficiently detailed dynamic modeling (maintaining nonlinearities); and appropriate algorithms (filters) for combining expectation with observation and incorporating domain knowledge to produce successful predictions of future object states.

Tracking cislunar objects will require a paradigm change when compared to tracking objects in lower Earth orbits.

In the current paradigm, every user generates an ephemeris on-demand locally by receiving a distributed model and states (SGP/TLE or SP/VCM). This paradigm has been good enough for most SSA activities in near-Earth space. The models rarely need to be updated, and the state data in TLE format requires very little communications bandwidth. With only previous states, and modest computer resources a user can generate the ephemeris locally.

In a new paradigm, because of the intrinsic issues with the dynamic sensitivities and variability of cislunar objects described above, the originator maintains the states and model and distributes the ephemeris. This paradigm is used by the Planetary Data System and the deep-space community to deal with the issue that TLEs are only useful in a two-body situation. Ephemeris information is passed in Spacecraft, Planet, Instruments, C-matrix, and Events (SPICE) format.[18] Besides some computational inefficiencies, SPICE has made data exchange and downstream processing (e.g., sensor tasking, conjunction assessment), all viable and reliable.

We recommend the use of SPICE or similar formats for cislunar propagation and object tracking.

National Technical Vision and Current Technological Needs and Challenges

For effective cislunar situational awareness, multiple technologies must be developed for or transplanted from traditional spaces into the cislunar domain. This section details the technologies that need to be developed to effectively monitor the cislunar domain, with a deeper treatment given to the primary technological enablers. These enabling technologies include electro-optical and infrared (EOIR) and radar sensors, orbit determination methodologies, mission autonomy capabilities, and low-thrust propulsion. As mentioned previously, systems to maintain situational awareness on the lunar surface will also be required; however, the specific technology required to enable this may not be distinct from what is currently used for Earth surface monitoring. Enabling infrastructure (communications and position, navigation, and timing) are addressed in other sections of this document.

[18] Navigation and Ancillary Information Facility (NAIF), The SPICE Concept. https://naif.jpl.nasa.gov/naif/spiceconcept.html.

Electro-optical/Infrared and Radar Sensors

To enable the detection, identification, and tracking of objects in cislunar space, sensors used in modern satellite detection must be reevaluated to determine the ideal type, placement, and combination. Any sensor that is capable of sensing objects in simple Keplerian orbits around Earth can be applied to the cislunar domain and can be effective if leveraged correctly.

Every sensor type has effectiveness limitations, both in traditional SSA as well as cislunar SSA. These include the maximum range the sensor can detect, the wavelengths it is sensitive to, and the way natural exclusion zones degrade detection capabilities. Exclusion zones in the cislunar domain include eclipse (target is shadowed), the solar exclusion zone (cannot sense within a certain angle of the Sun), the lunar exclusion zone (cannot sense within a certain angle of the illuminated part of the Moon), and the Earth exclusion zone (cannot sense within a certain angle of the illuminated part of the Earth). Different sensor modalities and designs can effectively mitigate some of these while being vulnerable to others.

Electro-optical sensors that can detect visible wavelengths (300nm to 700nm) are extremely effective in observing the cislunar domain, and this is the ideal waveband to extensively leverage for cislunar observations. These sensors rely on reflections from the Sun, which is extremely energetic in this spectrum compared to IR wavelengths. These sensors are also effective from the Earth's surface, in orbit around the Earth, on and around the Moon, or even in cislunar orbits themselves. Studies have shown how to maximize the amount of information that can be gained from optical observations of deep sky objects,[19] technology which would be vital to cislunar SSA.

Beyond the visible spectrum lie the infrared wavelengths, which are typically broken up into the mid-wave infrared (3–5µm, MWIR) and the long-wave infrared (8–14µm, LWIR). Infrared sensing provides multiple advantages compared to visible sensors for SSA. First, MWIR and LWIR sensors rely on self-emission from thermal radiation of the target due to internal warming or solar heating. This allows for detection of hot spacecraft in the shadow of the Earth or the Moon.[20] Second, since the Sun is much dimmer in the MWIR and LWIR bands compared to the visible spectrum, the solar exclusion zone is much smaller. However, these characteristics are not without their drawbacks.

LWIR sensors rely almost entirely on the thermal radiation from the spacecraft itself, and are not particularly useful when deployed on the surface of the Earth due to atmospheric attenuation. Radiation from the Sun in this band is negligible as well, and as such LWIR reflections cannot be relied upon for detections. However, space-based and lunar-based LWIR sensors could prove effective at monitoring the nearby space.

MWIR sensors are a compromise between LWIR and visible sensors, neither excelling at detecting solar reflections, as the Sun is still somewhat dim, nor at detecting self-emission, which is lower in this part of the spectrum for the typical temperature range of satellites. However, MWIR

[19] Shahzad Virani, M. H. (2021). *Sequential Multi-Target Detection & Tracking of Space Objects in Cislunar Domain* [conference presentation]. Cislunar Security Conference, Laurel, MD.
[20] Cantella, M. (1988). Space surveillance with medium-wave infrared sensors. *Lincoln Laboratory Journal*, 1, 75–88.

sensors can be deployed wherever visible sensors can be placed, including the Earth's surface, and still remain effective.[20]

Radar is traditionally a powerful tool for detecting and tracking objects on the Earth and above. However, when it comes to cislunar space, even altitudes as low as geosynchronous orbits become taxing for active radar systems to generate enough power to make consistent detections. These systems suffer from a quartic power drop-off, as they need to produce a beam powerful enough to reach the target such that reflections back toward the system are detectable. This could be mitigated by placing sensors on the lunar surface itself, dramatically reducing the distance between the radar and any objects orbiting around the Lagrange points L1 or L2. However, to detect objects near L3, L4, and L5, an active radar would need to be placed near these Lagrange points to be effective.

Very Long Baseline Interferometry (VLBI) allows us to combine collections from multiple radio telescopes into a single measurement, emulating a telescope the size of the maximum separation between telescopes. Ground systems like the Very Long Baseline Array (VLBA) use this technique for science and astronomy, and the technique is also applicable for cislunar space situational awareness.[21] Adding a space-based radio telescope to a ground-based network of sensors using VLBI algorithms may greatly improve its observations for improved SSA for radio frequency emitting targets.

Sensor Placement

Another challenge in cislunar domain sensing is not just what type of sensor to use, but where to place it. No single location in cislunar space will be able to monitor the entirety of the space. First, the range across the entire domain is massive, and will tax even the best sensors looking out with ideal lighting conditions. Second, exclusion zones will hamper any individual sensor from making detections across the entire domain. For these reasons alone, multiple sensors must be employed to effectively monitor the entire cislunar domain, placed with enough geometric diversity to ensure effective coverage over the cislunar domain.

Any cislunar SSA system does not, however, necessarily need to be able to cover all 4π steradians of the cislunar sphere, a massive volume. Due to the structure and physics of the system, there exist "dynamical choke points" where spacecraft are more likely to pass through. Phillips and Schlei[22] showed that ingress from L1 and L5 periodic orbits typically pass through a smaller, more easily surveilled choke point, limiting the amount of space that needs to be monitored for potential objects. Further study in this area should be undertaken to identify locations outside the lunar orbital plane, as well as where other periodic orbit families pass through easily observed space.

There are three different choices for where to place any sensor. The first, and easiest, is using Earth-based sensors that already exist. EOIR sensors can be used to observe cislunar objects under ideal lighting and astronomic conditions from the Earth. This would include sensors that are

[21] National Radio Astronomy Observator, Very Long Baseline Array. https://public.nrao.edu/telescopes/vlba/.
[22] Phillips, S., & Schlei, W. (2020). Monitoring Advantages in the Cislunar Battlespace [conference presentation]. Cislunar Security Conference, Laurel, MD.

already in orbit around the Earth as well. Viable ground-based sensors would, by necessity, observe in visible and MWIR bands.[20] Space-based sensors, however, could be deployed to make observation in the visible, MWIR and LWIR bands, allowing for detection in traditionally hard-to-observe spaces such as shadows.

The second choice is to place optical sensors on[23] and around the Moon. They would be much closer than Earth-based sensors to objects in periodic orbits around L1 and L2, offering better performance for detecting these objects. IR sensors could also be employed on the lunar surface, as there is no atmosphere to scatter and degrade the radiation before entering the telescope's optics. It has been shown that by combining lunar observers and Earth-based sensors, large-scale catalog maintenance can be achieved.[24] However, further study is still needed to determine the ideal sensors to optimize SSA for orbits around L1 and L2, or in other near orbit families that come within close proximity to the Moon. It's also worth noting that the cost of putting sensors on the Moon would be extremely high, even when compared to lunar orbit. They likely won't be cost effective until there is a robust human presence on the Moon.

The third option is to place sensors in cislunar periodic orbits themselves. Since these orbits can span the entire space, a carefully considered constellation would be effective at monitoring the entire domain, in multiple different spectral regimes, and would be effective for any sensor type, such as radar. L1 and L2 halo orbits are effective at monitoring the entire Earth-Moon ingress corridor, while geo-cyclers (cislunar periodic orbits that intersect with GEO) combined with L4 and L5 periodic orbits would allow for more coverage of the other regions in the domain.

Mission Autonomy

Cislunar platforms must be capable of performing common spacecraft tasks on their own at the least, if not completely capable of decision-making and cooperation without human interference. Primarily, there are parts of cislunar space where communication from Earth with a spacecraft might not be possible. Any spacecraft must be capable of effectively carrying out its mission without any human intervention in these nodes. A secondary reason is that, in the case of large constellations, managing every aspect of individual systems might not be the most efficient or effective way to operate constellations.

As such, an operator must be able to give a goal, or a heuristic, to a collection of satellites, and the system itself should be capable of determining the best course of action. This involves empowering the computers to design their own trajectories on the fly, as well as to communicate and collaborate with similar systems. Each node could be equipped with different sensor or communication technologies and effective collaboration is required for the SSA mission to be optimized.

[23] Note that placing sensors on the Moon will require technology development to survive the 2-week lunar night (outside the polar regions) and thermal management between lunar day and night.
[24] Fedeler, S., & Holzinger, M. (2021). *Observational Utility of Lunar Optical Sensors Across Periodic Orbit Families* [conference presentation]. Cislunar Security Conference, Laurel, MD.

Low-Thrust Propulsion

Low-thrust propulsion is an enabling technology for a multitude of cislunar trajectories and constellations. Low-thrust propulsion allows for more efficient and precise movement around the cislunar domain. By thrusting continuously, one can move between different orbit family members to maximize mission performance.

Low-thrust technologies are also good for orbiting around artificial equilibrium points. By applying constant thrust, a spacecraft does not necessarily need to orbit around the five traditional equilibrium points, but could make its own to orbit about wherever is convenient.[25] This opens up a lot of mission utility, as spacecraft positioning and navigation would no longer be bound by the dynamics of the system, and could be optimized to get the most return on investment for whatever mission is being performed.

Conversely, detecting low-thrusting spacecraft presents a challenge for SSA as low-thrust maneuvers are difficult to distinguish from other perturbations. Low-thrust spacecraft have the potential to become prevalent in cislunar space not only for monitoring missions but also as tugs, pulling and pushing large amounts of resources to and from the Moon. This potentially saves the cost of rockets that otherwise need to perform from launch all the way through delivery. One could imagine launching a payload to geosynchronous transfer orbit (GTO) and having a tug spacecraft pick it up and deliver it to its final destination. Such a spacecraft would quickly become a reusable and invaluable resource.

Orbit Determination

SSA includes activities related to the detection, tracking, and characterization of resident space objects (RSOs). Orbit determination for two-body motion in the vicinity of the Earth involves the use of filtering techniques and least squares estimation to fit observations with a conic section that is a solution to the two-body equations of motion in a Keplerian dynamic environment where non-gravitational accelerations may be treated as perturbations. These techniques result in an estimated orbit as well as a covariance matrix associated with each RSO. The covariance is essentially a measure of confidence in the estimated orbit, so objects with larger covariance may need more regular observations for custody to be maintained. Tracking is the regular updating of an RSO's estimated orbit by combining the propagation of that orbit in a dynamic model that approximates reality to some level of fidelity with observations of the RSO. When the detection step reveals an object that does not seem to be associated with an existing track, initial orbit determination (IOD) methods must be used to initiate an uncorrelated track (UCT), and UCT association methods are used to determine which, if any, catalogued object is most likely represented by the UCT. Sensor tasking and scheduling algorithms are used to balance priorities like collecting observations of an RSO whose covariance is growing, collecting observations of a high-value

[25] Cox, A. (2016). *Transfers to a Gravitational Saddle Point: An Extended Mission Design Option for LISA Pathfinder*, Thesis for Master of Science in Aeronautical and Astronautical Engineering, Advisor: Kathleen Howell, West Lafayette: Purdue University.

asset to maintain a low covariance for that asset, spending long periods of time observing a single object in order to characterize that object and develop knowledge about that object's patterns of life, and spending time on search for new objects.

When an RSO's orbit seems to have changed in a way that is not attributable to the usual perturbations expected in Earth orbits (e.g., effects from the Earth's atmospheric drag, solar radiation pressure, Earth oblateness, ocean tides), techniques can be used to determine the size and direction of the force that created the orbit change, as well as the time of the change, by making the generally applicable assumption that the force was applied instantaneously. For instance, a sudden explosion or breakup of an old satellite in orbit, contact between two satellites, or a thruster firing could cause such an essentially instantaneous change in an RSO's orbit. On the other hand, vehicles using finite- and low-thrust propulsion (which cannot be readily approximated as instantaneous) are difficult to track even in Earth orbits, and low-thrust propulsion is likely to be very commonly used in the cislunar regime due to its high specific impulse. Reachability manifold calculation, which finds volumes in state-space that could be reached given an integration constraint such as a time horizon and an estimate of the propulsion available on an RSO, could be used to track maneuvering RSOs in cislunar space, including objects using finite- and low-thrust propulsion.[26]

Beyond geosynchronous orbit, the Moon's gravity contributes to the dynamics of the system to an extent that can no longer be accurately modeled as merely a perturbing force. For instance, the Earth–Moon Lagrange points, around which an object can complete a closed orbit despite the lack of a gravitating body at these points, do not exist in a two-body dynamic model. To properly model the dynamics, propagate trajectories, and track objects near Lagrange points, one must use at least a three-body dynamic model, which does not have a closed-form analytical solution and does not result in the trajectories shaped like conic sections that are familiar trajectories followed by Earth-orbiting satellites. Whereas the two-body, Keplerian dynamics governing motion in the vicinity of the Earth result in deterministic, predictable circular or elliptical orbits, the three-body system including both Earth and Moon gravity as significant influences results in unstable equilibrium points and chaotic motion, meaning that very small changes in initial conditions of an object may result in very large changes in the trajectory of that object as it is propagated forward in time. The chaotic nature of the dynamics in much of the cislunar regime requires higher-resolution sensing, a requirement which is complicated by the large distances between Earth and Moon and Lagrange points. New algorithms and filters may be required to track RSOs through the chaos of the Earth–Moon system. Machine learning could be applied to estimate which of various families of infinite possible periodic, quasiperiodic, and chaotic trajectories in the Earth–Moon system an observed RSO might be following.

Whereas precise orbit determination for an RSO in Earth orbit depends on a detailed knowledge of the physics affecting the RSO, precise orbit determination for an RSO in cislunar space may depend more heavily on an understanding of the desired behavior and operations of the RSO. For instance a good estimate of the reference trajectory for the RSO allows an analyst to predict how

[26] Holzinger, M. J., Scheeres, D. J., & Alfriend, K. T. (2012). Object correlation, maneuver detection, and characterization using control-distance metrics. *Journal of Guidance, Control, and Dynamics*, 35(4), July–August. doi:10.2514/1.53245.

that RSO may be station-keeping to maintain the reference trajectory, even if the natural chaotic dynamics would cause a departure from that trajectory.

Critical Technology Gaps and Recommendations

This section presents a list of gaps in the enabling technologies for cislunar SSA that were described in the previous section. We recommend investment in each of these as an integral part of the development of a robust and effective cislunar SSA system.

Orbit Determination and Catalog

The chaotic nature of the dynamics in much of the cislunar regime require higher-resolution sensing, a requirement which is often complicated by the large distances between Earth and Moon and Lagrange points. New algorithms and filters may be required to track RSOs through the chaos of the Earth–Moon system. Reachability manifold calculation, which finds volumes in state-space that could be reached given an integration constraint such as a time horizon and an estimate of the propulsion available on an RSO, could be used to track maneuvering RSOs in cislunar space, including objects using finite- and low-thrust propulsion. Machine learning could be applied to estimate which families of infinite possible periodic and quasiperiodic trajectories in the Earth–Moon system an observed RSO might be following. Clever tasking algorithms will likely be required to make appropriate use of available sensing resources for search and discovery in the very large volume of cislunar space. These algorithms will need to maintain custody of objects in the chaotic system and especially objects performing finite maneuvers. Further, these algorithms will be needed for long dwell or coordinated multi-sensor collections against objects of interest for detailed characterization and pattern of life determination. A catalog maintaining the latest information on cislunar RSOs will need to use a data type that does not presuppose a Keplerian orbit and will likely need to hold characterization information about these RSOs (e.g., size, shape, materials, estimated fuel type and amount, intended use, etc.) along with information about their trajectories.

Sensor-Related Recommendations

Current sensor technology, especially visible sensors, are capable of monitoring cislunar space given the right constellation, management and post-processing algorithms. Cislunar space is so vast, that a constellation of electro-optical sensors will be required to observe enough space for a coherent SSA picture, as well as provide enough diversity to overcome exclusion zone limitations. These concepts, when considered alone and together, imply the following recommendations.

First, autonomous and collaborative constellation management and direction should be researched. This would allow a constellation, of varying size, to manage itself (position, pointing, and communication) and optimize an objective set by the invested parties. The goal of the constellation can be flexible depending on the capabilities of the payloads and the number of spacecraft available. This would allow for continuous and effective SSA operations, and similar concepts have been developed and implemented in other domains, such as ground surveillance with unmanned aerial vehicles (UAVs).

Second, post-processing algorithms will need to be researched and integrated into any SSA products. Objects with low signal-to-noise ratios (SNRs) in ground based optical images have been detected with effective post-processing techniques.[19] While effective post-processing algorithms do currently exist, they are effective only with certain foreknowledge of objects present in the arena. Other algorithms, perhaps leveraging machine learning and neural networks, might be more effective with less information available. Given this, it is recommended that post-processing algorithms on products of sensors in any spectrum should be investigated.

In summary, these two recommendations do not require significant investment in new sensing technologies, but rather thought and research into how to best leverage the resources that could be available.

Low-Thrust Capabilities

As noted above, low-thrust capabilities would provide for multiple new mission design paradigms, allowing for further optimization and tweaking of any cislunar SSA solution. By allowing for resources to move freely through the space, as well as orbit artificial equilibrium points, any SSA constellation could be enhanced. This effort would go hand-in-hand with detection, monitoring, and tracking of friendly and non-cooperative low-thrust objects as well.

Algorithm Development for Autonomous Mission Design

Creating an effective cislunar SSA system requires determining not just the number of spacecraft, the sensors, and the cost, but also how to use them most effectively. Flying as many sensors as possible is not cost effective. It is vital to develop mathematical algorithms that allow operators to effectively tell the sensors how to behave, as well as algorithms that allow the platforms to make effective decisions on their own to enhance the performance of the entire constellation.

Many of these problems are combinatorial in nature. Optimization is typically not computationally tractable, and a global optimum is not always able to be found or verified. As such, algorithms used to solve these problems are typically heuristic in nature. Examples include ant colony[27] and wasp swarm optimization,[28] two algorithm archetypes that should be investigated to see how well the solutions they produce perform.

Reinforcement learning algorithms are another class that remains largely unexplored for solving the cislunar SSA problem. Reinforcement learning algorithms are an active area of research, and have shown great promise at solving problems once thought to be too computationally challenging. One relevant example is mapping out an unknown city with self-driving, communicative, and cooperative cars.[29] By using reinforcement learning, these vehicles are capable of completely mapping an unknown environment, controlling for traffic conditions, and evaluating whether revisiting a certain area is necessary, all while optimizing over the entire network. A

[27] Awan-Ur-Rahman. (April 25, 2020). Introduction to Ant colony optimization (ACO): A probabilistic technique for finding optimal paths. *Medium*. https://towardsdatascience.com/the-inspiration-of-an-ant-colony-optimization-f377568ea03f.
[28] Runkler, T. (2008). Wasp swarm optimization of the c-means clustering model. *International Journal of Intelligent Systems*, 23, 269–285. 10.1002/int.20266.
[29] Sykora, Q., Ren, M., & Urtasun, R. (2020). Multi-agent routing value iteration network. https://arxiv.org/abs/2007.05096.

similar approach could monitor cislunar space with low-thrust, agile vehicles. Instead of traffic conditions, there are the physical dynamics of the space and limitations of the vehicles. Instead of mapping a city, the network is attempting to maximize continuous coverage of areas an object is most likely to reside.

These are a few examples of algorithms, outside of orbit determination and tracking, which must be developed to effectively leverage any SSA constellation in cislunar space.

Cislunar Computing Resources

Another limitation of operating in cislunar space is the lack of local computational resources. Computational equipment that is designed with the space environment in mind will be necessary. The algorithms that are required for running a constellation that can effectively monitor cislunar space will need to run on capable hardware, so minimum computing requirements should be developed. The data collected by any individual node will likely be too dense, or too incomplete, for it to process effectively on its own. One could transport all the data to Earth, but this would require expensive transmission equipment on each node, or a centralization of the data in any case. As such, a central computational node will likely be necessary. This could reside in a periodic orbit in cislunar space, or be stationed on the lunar surface, and could work in cooperation with computational resources on the Earth. However, there are no capable computational resources, such as GPUs and CPUs, available that are able to effectively operate in the lunar or deep space environment.

Typically, “hardware systems designed for advanced, intelligent decision making are not suited for space.”[30] The radiation, difficulty in temperature control, and other events make modern, powerful computing equipment not capable of performing in this environment. Further, the software written for terrestrial-based processing does not have the necessary logic or capabilities to tolerate hardware faults resultant from the space environment. Computational equipment currently deployed to space environments have been rad-hardened, a process that diminishes the computational capability and increases the size, weight, power, and cost (SWaP-C) requirements of the host platform.[30]

Visualization Utilities

Due to the nature of cislunar missions, it is not always immediately intuitive for decision-makers or end users to understand the mission design. The presentation of trajectories in a rotational reference frame, as well as temporal considerations, can be confusing, especially in comparison to traditional, Earth-centric orbits. Due to this, significant development in building an intuitive, easy to use visualization suite for presenting cislunar missions should be considered. There are a multitude of tools that could be further developed for this purpose, each with their pros and cons. Options include JavaFX, VTK, and Paraview, or Unity, an interactive physics engine capable of creating applications. Significant expertise in both multibody dynamics, mission design and familiarity with these software tools would be necessary for success in this endeavor.

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[30] Smith, R., Bekker, D., Chen, M., Gifford, C., Schmachtenberger, B., & Steiger, I. (2021). *AI in Space Pathfinder Study*. The Johns Hopkins University Applied Physics Laboratory, Laurel, MD.

Any visualization software must also allow for real-time mission design and analytics. This would make any end user or operator capable of understanding exactly how objects in the domain behave, as well as how to effectively leverage resources available. By allowing for interactive and intuitive mission design, SSA missions could be rapidly engineered, analyzed and considered, allowing for multiple iterations before settling on a final solution. Additionally, this software could be used to display the current perceived state of objects in cislunar space, a vital piece of the puzzle for SSA. This could further be extended by allowing for exporting of data to software like STK and AFSIM, which could then be incorporated into assisting other missions, or bringing cislunar capabilities into wargames.

4. USE OF CISLUNAR SPACE FOR RECONSTITUTION OF SPACE-BASED CAPABILITIES

Brian Bauer and Eric Klatt

Introduction

Space assets are integral for several functions that are crucial to U.S. interests: satellite communications; position, navigation, and timing (PNT); missile warning; intelligence, surveillance, and reconnaissance (ISR); weather monitoring; space domain awareness; and space control. To maintain resiliency of mission capability throughout a conflict, consideration must be given to the timelines under which assets must be replaced if their functionality is lost. Interim capabilities may be needed to maintain mission capability while replacement assets are assembled, launched, and/or inserted into the necessary mission orbits.

Reconstitution is one option for resiliency, along with capability proliferation. Cislunar is ideally suited for reconstitution due to its size for storing spares undetected, and the favorable energy transfer between orbits. Reconstitution and capability proliferation are non-escalatory, by removing a perceived first mover advantage. They can also facilitate attribution, since a successful hostile action would need to be repeated several times.

This section discusses strategies and considerations for establishing an interim or full replacement capability using cislunar assets.

Options for Resiliency Through Reconstitution

Two options for resiliency include resiliency through reconstitution and resiliency through capability proliferation.

Resiliency through reconstitution has several general options for capability replenishment: ground storage with launch on demand, space storage in safe orbits, and repurposing assets in place.

Capability proliferation provides another approach for reconstitution. A capability distributed over a proliferated constellation is resilient through the number of nodes that contribute to perform the mission. A mission capability proliferated over a low Earth orbit (LEO) constellation, for example, requires a significant degradation of the constellation before the mission capability significantly degrades.

In resiliency through reconstitution, ground-based storage with launch on demand requires dedicated assets and long-term contracts to integrate and maintain the replenishment units on the ground. To keep these units ready for rapid deployment, a team would need to perform regular checkouts, similar to any other military capability drills. Since the spacecraft are stored on the ground, modernization efforts can be employed to keep the hardware up to date. A responsive launch capability is required with rapid integration into the fairing and deployment. Depending on the number of launches required, several launch vehicles must be stored at the launch facilities ready for rapid deployment. Finally, replenishment depends on the ability to launch and deploy these spacecraft in the midst of combat, so typical communication capabilities should not be assumed, and systems would need to create necessary redundancies to account for this.

Space storage in safe orbits requires the up-front investment to build and launch these systems into their storage orbits. Since the spacecraft are on-orbit, the hardware will already be aging in the space environment. Resources must be allocated to replace the stored systems when they reach their design life or when updated technology is available/desired. Placing the spacecraft in a hibernation mode will help reduce the wear on some of the hardware while also saving on operations costs. The parking orbit selected will affect the environmental impact on the spacecraft as well as the timeline for bringing the capability online. Some orbits to consider are: Earth–Moon Lagrange points, orbits above geosynchronous equatorial orbit (GEO) but below an altitude of 100,000 km, GEO–Lunar transfer orbits, Earth–Sun Lagrange points, and possibly lunar orbit staging. Finally, getting these assets into position may require a lot of propellant, so technologies like on-orbit refueling should be considered. Staging physical assets in space nearby to the operational ones is a common practice for communication satellite companies, since they lose subscribers if they are unable to instantly replace functionality. The same principle applies to space storage in cislunar and provides two distinct advantages:

1. Time to restore capability can be much faster than methods requiring launches, especially given the long transit times if the system needs to be fuel efficient.
2. Less support is required from the ground to coordinate the handover, which could, in theory, be automated or require much less communications support.

Having assets that can be repurposed in place to provide temporary mission coverage is a much more responsive option than moving assets into position. The additional capability could be built into a proliferated architecture located in LEO, medium Earth orbit (MEO), GEO, or cislunar space, which would speed response time, support more automation, and inherently provide more coverage. An additional benefit to this approach is that the capability can be used at all times in support of whatever missions the proliferated architecture is performing.

Eventually, Moon-based support will be available to serve these missions as well. Outposts on the Moon could be equipped to provide communications relays, guidance beacons, or even surveillance/tracking sensors.

Resiliency is De-escalatory

Resiliency through both cislunar reconstitution and capability proliferation can be de-escalatory. When there are a small number of high value assets an adversary may believe there is a first-mover advantage. An adversary may be tempted to deny having affected an asset. With cislunar reconstitution capability and with capability proliferation the criticality of each individual asset drops. This means that a preliminary attack can be absorbed before responding, which negates a perceived first mover advantage. Further, as more assets are affected, attribution is clearer as the plausibility of denial approaches zero.

Use of Cislunar-Based Assets for Reconstitution

Cislunar space is almost ideally suited as a storage location for prompt reconstitution because cislunar space is large, maneuver cost from storage is relatively low, and reconstitution may not be immediately detected.

Cislunar reconstitution also has advantages over other options. In a crisis, launch from the ground may be blocked, prevented, or overwhelmed by other needs. Assets in cislunar storage are relatively quickly available. The reconstitution inventory can be built, launched, and stored over time. Prompt launch requires integration with a launch vehicle and launch that may be delayed in a crisis and at a minimum still takes time. While an adversary may be able to prevent or monitor launches, they may not immediately detect that cislunar stored assets have been brought into use.

There are additional driving considerations for reconstitution using cislunar space-based assets. First, what is the timeline that needs to be covered by these assets? The design of these systems depends heavily on when they need to be available and how long they need to last. Additionally, the broader architecture needs to be designed to facilitate this operation thread. If these capabilities need to be established in very short timelines (minutes to hours) and integrate themselves into the broader warfighting architecture with minimum reconfiguration and interruption, there may be insufficient time to relocate a spacecraft from cislunar space. Relocation from cislunar space to lower orbit regimes will require a few days at a minimum and possibly more than one week. This means that even capabilities that need to be established in a day or two will not be able to be effectively replenished by a spacecraft relocating to LEO or GEO from cislunar space. Some asset relocation can be performed, but it is unlikely that something can be efficiently brought back to Earth from the Moon in that timeframe. Regarding the duration of the replenishment period, it is not expected that the interim assets will need to operate for years. For the sake of a starting point, this section assumes that a 90-day replenishment system would be sufficient.

Second, these capabilities need to be cost effective—it will be hard to justify a reserve capability that is just as costly or potentially even more costly than the current asset performing the operation. Some consideration needs to be given to the price point at which the money spent on an on-orbit spare would be better allocated toward a more resilient primary or other assets that could be repurposed to cover the impacted mission, such as resilience through proliferation. Finally, it must be recognized that this is one of several options for meeting these needs: replenishment/relocation from other orbit regimes, replenishment via ground launch, repurposing other on-orbit systems, or reestablishing the capability via another domain. Just like all other options, there are benefits and drawbacks to staging replenishment options in cislunar space.

Mission Basis and Priority Ranking for Replenishment

This section covers the missions that could be supported by cislunar-based reconstitution and the priority in which these missions should be considered for replenishment. Some discussion is also given to the design considerations and means by which this may be accomplished.

Before replenishing any capability, we need to recognize that the organic infrastructure of cislunar operations must be maintained. It will be difficult to realize additional capabilities if the cislunar assets meant for replenishment are themselves inoperable. The supporting infrastructure for these missions, including ground interfaces, operations systems, communications relays, etc., must themselves be resilient to adversary interference. There is a trade space on the level of independence of these systems versus the cost and level of capability being deployed. For example, a single-point capability with a dedicated ground link is easier to establish and control versus a constellation capability with crosslinks and integrated operations, but it will be more limited in the scope of its operations and interoperability with other domains.

The highest priority capability for replenishment is strategic communications. Low-rate strategic communications can be supported relatively quickly without moving spacecraft away from their staging locations. Since radio frequency (RF) communications experience a distance-squared loss to their link, a capability in cislunar space will need to be able to close the link with a roughly 20 dB loss over a comparable link in GEO. Increasing the antenna size and lowering the data rate would be the first two places to look to recover this loss. If this is meant to replace a GEO asset, the ground systems will now need to be able to track the spacecraft over time. The spacecraft will move slowly, but it will not be stationary in the sky. In addition, multiple spacecraft will be needed to maintain constant coverage as the satellites' field of regard will shift over time. Since the infrastructure needs to account for moving spacecraft, it would be possible to quickly establish the capability from a cislunar parking orbit and then perform a series of maneuvers over time to relocate the spacecraft to GEO while maintaining the mission support. Maneuvers can be performed during coverage blackouts to reduce the impact to the ongoing mission.

Establishing PNT shares some of the considerations with strategic communications. The spacecraft positioned in cislunar space do not need to relocate often, but the effective isotropic radiated power of the PNT payload needs to be able to overcome the additional path loss and close the link with the existing ground hardware. The movement of the spacecraft over time is not an issue, but enough nodes need to be in the constellation to provide angular diversity for navigation. Timing can be synced more easily because the spacecraft can see more of the Earth from cislunar space. Some consideration needs to be given to the resilience of the PNT signal that comes from farther away. If the added loss is not fully overcome, the signal may be more prone to jamming.

Coverage and protection of shipping and transport lanes requires a combination of capabilities working in concert. Communications and signals support can be provided via the same techniques and capabilities as the communications and PNT examples above. Remote sensing needs must be evaluated against the sensor size and range of capability. A rough analysis of diffraction-limited optics shows that large ships and their wakes can probably be detected from cislunar ranges, but shorter observation ranges are needed to enable more than simple detection and coarse tracking (in ideal lighting). Optical remote sensing capabilities will probably need to be placed into elliptical orbits with a revolving window of coverage or relocated from a storage orbit into an operational orbit. Just like with the prior two cases, a rudimentary capability can be quickly established while improved performance and functionality is realized over time as the spacecraft are lowered into a more appropriate operations orbit. Remote sensing presents a few challenges if the capability needs to be enabled quickly. The sensitivity required for ISR or missile warning would necessitate either (prohibitively) large apertures or highly elliptical orbits that provide revolving windows of coverage. The most cost-effective approach for cislunar replenishment would be to stage the units in cislunar space and relocate them as needed to enable effective support. It is possible that coarse coverage can be enabled from a cislunar parking orbit, but the provided capability would be limited.

Terrestrial mission support follows the same trends discussed in the prior paragraphs. Communications and PNT can be supported from parking orbits, provided the supporting infrastructure is in place and ground units are able to link to these new assets as they come online. The communications capabilities can be grown in waves as more messaging is supported and greater bandwidth can be brought to bear. For units expecting GEO-like communications, the timeline to establish support will depend on how quickly assets can be inserted into GEO slots. Similarly, ISR capabilities will have to phase in as the orbits bring the spacecraft into range or orbit adjustments enable mission support.

Up to this point, all communications considered were point-to-point relays, not meshed networks. Distances get much larger in cislunar space so mesh networks become long-range communications links with mesh protocols. For example, a six-spacecraft ring at lunar orbit has ~400,000 km between spacecraft. The constellation would need to be able to locate each spacecraft and establish the links. Optical relays are not technically mature for the long ranges typical in cislunar space, and RF relays would need a significant amount of gain and power to close or would be required to function at less than useful data rates. Depending on the size of the spacecraft and the cost of the communications hardware, it may be better to rely on point-to-point capabilities while a set of spacecraft are lowered into MEO or LEO to reform a meshed transport layer.

Space and terrestrial weather monitoring can likely be supported from a parking orbit in cislunar space. Space weather monitoring currently benefits from a set of observatories at the Earth–Sun L1 point, and the resolution of Earth-observing spacecraft should be sufficient for interim weather monitoring.

After enabling the prior missions, other mission applications could be considered. The above list of capabilities is not an exhaustive list, merely a construct for organizing and ranking the capabilities that should be evaluated for cislunar-based replenishment.

System Needs

As mentioned at the beginning of the section on prioritized missions for reconstitution, there are a number of needs that must be met to facilitate these capabilities. Some of these needs are external to the specific missions and align with the needs of any large space architecture. Other needs are intrinsic to the system and have a few wrinkles that must be considered for the replenishment mission.

The major external needs that must be considered are communications, tracking, and mission interfaces. Communications for spacecraft operations need to be relayed between the spacecraft and the operations center. A shared/dedicated ground station or ground network is needed. If available, space relays or even a Moon-based communications node can be used to provide alternate communications paths. A minimum level of navigation is needed to establish communications, facilitate maneuvers, and geolocate payload data. A cislunar PNT capability can be used if it is available, but the missions should be prepared to fall back on ground-based navigation through SSA sensors or Doppler/ranging of the communications signal. Finally, mission interfaces need to be identified and configured to enable end users to interface with the replenishment systems. Common interfaces should be maintained where possible, but there may need to be tweaks to account for cases like a cislunar asset replenishing a GEO asset.

Intrinsic to the replenishment mission are impacts to the operations of the mission and spacecraft propulsion. For spacecraft operations, there would be two major phases of operations: storage and maintenance, and replenishment. During storage and maintenance, the operations team would need to be able to perform regular checkouts of the spacecraft and payload, including sensor testing and calibration, within the operational context of the mission. The team would also need to exercise deployment and employment along with planning and scheduling in preparation of the replenishment mission. It is uncertain how many of these exercises could be done with the flight hardware so a robust simulation environment would be required. During the replenishment phase, the hand-over process for inserting the spacecraft into the mission architecture and transitioning to replenishment operations would need to be facilitated by the operations center and the broader mission architecture. A large amount of delta-v may be needed for these missions, raising propulsion system considerations. Adjusting a cislunar orbit at apogee is pretty efficient, but insertion into a near-Earth orbit will be fairly costly (~2 km/s). Aerobreaking is an option for bleeding off some of the orbit energy, but it may require an aeroshell or delayed deployment of payload hardware. Electric propulsion is also an option for efficient orbit transfer, but it is likely too slow to be effective given the expected timelines required for reconstituting critical capabilities.

“Conversion Van” Approach

To manage costs, the spacecraft and payloads can be built for standardization, select specialization, and scalability. The satellite bus designs would be standardized so they could be built at scale for lower cost. This approach is starting to become a reality for LEO and GEO missions, but design considerations for cislunar space have not been fully explored. In addition, the same “assembly line” approach should be applied to payloads. A core suite of communications and remote sensing payloads could be mass-produced to manage per-unit costs. The development and integration process for both the buses and payloads should facilitate incremental updates as new technologies and capabilities are identified.

Considerations for specializing or outfitting spacecraft for different roles would drive designs for buses and payloads. Which specialized build-outs are needed for specific missions? Which build-outs are common across several missions? Which missions can be supported from what orbits and which ones require relocation? How will we operate these systems and get them to where they need to go? What bus size is needed for these missions? Spacecraft cost scales approximately with mass, so it is important to recognize which missions can be performed, for example, via an EELV Secondary Payload Adapter (ESPA)-class 100–200 kg spacecraft versus a ~500–1000 kg bus versus a >1000 kg GEO bus. There are several considerations for bus design that drive cost and complexity of the mission. The cost of modularity versus the cost for a standard design even when higher performance hardware is not required should be evaluated. The standard subsystems for a spacecraft (e.g., structure/mechanisms, thermal, power, command and data handling, attitude determination and control, tracking, telemetry, command, and propulsion) will always be required, but the payloads and missions will drive some variation in the size and design complexity of each subsystem. For example, there are several propulsion modes that could drive the design depending on the mission needs: electric propulsion for efficiency versus monopropellant for faster maneuvers, bipropellant for high thrust at a higher efficiency (but at ~3× the cost of monopropellant), and solid propellant for large one-time maneuvers at the cost of the thermal care and feeding of a solid motor. In addition, there will be some additional hardware for purposes such as environmental sensing and cybersecurity that will likely be required on all buses for security and safety reasons. Considering the operational needs for these spacecraft, the design must account for the storage environment as well as eventual operating environment. There may be additional considerations if the storage or operational orbits will be in high radiation or variable charging environments.

An additional enabling factor for these missions is software. The communications and interfacing standards are important as well as enabling autonomy. Cost savings can be achieved if autonomy or health maintenance and hibernation allow for a smaller operations crew. Other benefits may be realized if the ground dependence and communications cadence can be significantly reduced via onboard autonomy. Finally, shorter mission timelines can be achieved via rapid checkout and calibration software.

Summary

Capabilities can be reconstituted utilizing cislunar orbits. The cost versus capability trade space needs to be considered. Resiliency through reconstitution via on-demand launch systems and staging assets on orbit, and capability proliferation are technically viable options. Studies need to be performed to balance cost (a fairly easily measured quantity) versus mission performance metrics (requires physics models to quantify). These studies can define the viability of reconstitution against several mission sets. However, in all cases technology development will be required to optimize communication, timing, sensor performance, guidance navigation and control, and ground support systems to enable any of these future architectures. True end-to-end system performance and functional models will need to be developed and likely captured in an extensible and collaborative model-based system engineering architecture, and from that, requirements and standards can be determined that will allow the manufacturability and scalability required for cislunar reconstitution systems to be practical and affordable. Since cislunar is well suited for reconstitution, this option should be more thoroughly investigated.

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5. CISLUNAR POSITION, NAVIGATION, AND TIMING

Ryan Mitch

Introduction

This section of the Cislunar National Technical Vision focuses on a notional architecture to provide the position, navigation, and timing (PNT) services required for cislunar operations. Ongoing missions operating in cislunar space such as THEMIS/Artemis (2007/2010)[1] and Lunar Reconnaissance Orbiter[2] provide insight to today's PNT needs. More recent cislunar programs such as the National Aeronautics and Space Administration (NASA) Artemis and Commercial Lunar Payload Services (CLPS) programs,[3] and China's Chang'e 1–5,[4] all require extensive PNT capabilities to achieve success. The notion of a sustained presence on the Moon and an associated commercial economy has also raised a number of relevant questions about what types of future activities are possible in cislunar space, and what the PNT requirements of those activities will be. These actions include science, policing, search and rescue, space situational awareness, and robotic servicing. Additionally, NASA has created the Lunar Surface Innovation Initiative (LSII)[5] to develop a number of technologies for future human and robotic exploration on the Moon and Mars. The LSII portfolio includes the Lunar Surface Innovation Consortium (LSIC)[6] to facilitate community engagement with engineers and scientists involved in lunar and cislunar developments. The combination of historical missions, current programs, and possible future scenarios guide our development of the envisioned architecture to provide PNT information in an extensible network that can service an arbitrary number of nodes.

Cislunar PNT Needs and Challenges

Clock performances will drive our navigation architectures in cislunar space in an analogous way to the Harrison chronometer of the 1700s.[7] The British Scilly naval disaster of 1707[8] brought oscillator performance to the forefront of society, as it enabled reliable and safe navigation through accurate longitude calculation at sea. Cislunar space has a different set of navigation challenges, but precise time keeping will be critical to our ultimate capabilities. Time knowledge and transfer between nodes is complicated in the cislunar environment because of relativistic effects arising from spacecraft motion through the Moon's gravitational potential, and because of extreme thermal swings on the Moon's surface due to the long day/night cycle. The ability to disambiguate these complicating effects from typical oscillator drift in every digital system will be critical. Improvements in oscillator performance, and performance at specific size, weight, power, and cost (SWaP-C) levels such as the chip-scale atomic clock (CSAC), are a critical element to the

[1] Woodard, M., et al. (2011). Orbit determination of spacecraft in Earth-Moon L1 and L2 libration point orbits. *AAS/A1AA Astrodynamics Specialist Conference*. No. GSFC. CP. 4811.2011.
[2] Mazarico, E., et al. (2012). Orbit determination of the Lunar Reconnaissance Orbiter. *Journal of Geodesy*, 86, 193–207.
[3] NASA Commercial Lunar Payload Services. https://www.nasa.gov/content/commercial-lunar-payload-services.
[4] Future Chinese Lunar Missions. https://nssdc.gsfc.nasa.gov/planetary/lunar/cnsa_moon_future.html.
[5] LSII Status. https://www.nasa.gov/sites/default/files/atoms/files/nwerkheiser_lsii_status_0.pdf.
[6] LSIC. https://lsic.jhuapl.edu/.
[7] Britannica. https://www.britannica.com/biography/John-Harrison-British-horologist.
[8] Royal Museums Greenwich. https://www.rmg.co.uk/stories/blog/1707-isles-scilly-disaster-part-1.

architecture. High quality oscillators not only provide a good source of time for PNT systems, but they enable high data rate communications and reduce the necessary update rate to each node because of their higher time holdover capacity.

The near-term PNT challenges to autonomous operation in cislunar space are daunting because of the nascent nature of the problem. The first hurdle is the most basic: "What reference coordinate frame should be used for navigation?" Modern Earth-based navigation systems use a common datum reference frame, typically the World Geodetic System 1984 (WGS84) frame. GPS quantities are defined in WGS84, and due to GPS's near ubiquity, it has become the de facto navigation frame for terrestrial applications. Other systems and frames exist, such as the International Terrestrial Reference Frame (ITRF). In this context, a frame is one element of a reference system. Other elements are parts of the system and may include components such as gravitational and magnetic field models. A lunar analog to the ITRS is required to provide a common mathematical map for disparate sources of information such as ranges and elevations from different types of sensors such as lidars, radars, radios, and cameras. This is true for civilian, commercial, and government operators such as NASA and the newest Combatant Command—the United States Space Command.

Navigation frames are an active area of development for the U.S. government. Two Working Groups pursue these definitions. The first is the Lunar Reference System (LRS) Working Group, and the second is the xGEO Foundational PNT (XPNT) Working Group. The LRS is composed of members from numerous U.S. government agencies: the National Geospatial-Intelligence Agency (NGA), NASA, U.S. Naval Observatory (USNO), United States Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA) National Geodetic Survey (NGS), etc. It seeks to develop a new lunar-fixed, lunar-centered reference frame to support safe lunar navigation. In contrast, the XPNT working group is composed of the USNO and NGA, and it seeks to meet the Department of Defense's (DoD) foundational PNT needs for deep space, including a lunar inertial reference frame and system. There is significant overlap in the composition and goals of the two groups. While these groups are still working, there appear to be two primary frames for the lunar surface that are under consideration. The first is the Mean-Earth (ME) frame, and the second is the Principal Axis (PA) frame.[9] The PA frame is a body-fixed frame with an origin at the center of mass of the Moon and the z-axis through the axis of rotation. The Prime Meridian (0° longitude) and equator complete the other axes. In contrast, the ME frame defines z-axis as the mean rotational pole and the Prime Meridian as the ME direction. The ability to transform between the frames is a straightforward mathematical computation. This transformation is possible today using the Planetary Data System (PDS) Navigation and Ancillary Information Facility (NAIF) Spacecraft, Planet, Instruments, C-matrix, and Events (SPICE) software. Regular updates to the orientation parameters will likely be an output data product from an organization such as the LRS, XPNT, or a possible new Lunar Celestial Reference Frame Working Group.

In addition to frame conventions, these Working Groups seek to determine which frame to use in which circumstance. Historical data products from previous U.S. missions such as Apollo and

[9] NASA. (2008). *A Standardized Lunar Coordinate System for the Lunar Reconnaissance Orbiter and Lunar Datasets*, LRO Project and LGCWG White Paper, ver. 5. Goddard Space Flight Center, MD.

Clementine have recorded information in the ME frame. However, precise gravity models are body-fixed definitions in the PA frame, as are landmark features used in optical navigation around the surface of the Moon. For example, Digital Elevation Maps (DEMs) are created by using information such as the LRO's Lunar Orbiter Laser Altimeter (LOLA), and they are fundamentally a body-fixed model. Each frame is accurate to within about 10 m, but the two frames differ from each other by about 1 km[9] at the surface of the Moon. In some applications, this level of frame disagreement is irrelevant, but in many higher performance applications, a clearly selected and realized frame is required. The outputs of these working groups could augment our future navigation system implementations.

A typical body-centered reference frame and possible lunar reference frame realization are shown in Figure 2. The DoD will rely on the NGA for its definitive systems and frames. NGA's mission comes from Title 10 of the U.S. Code.[10]

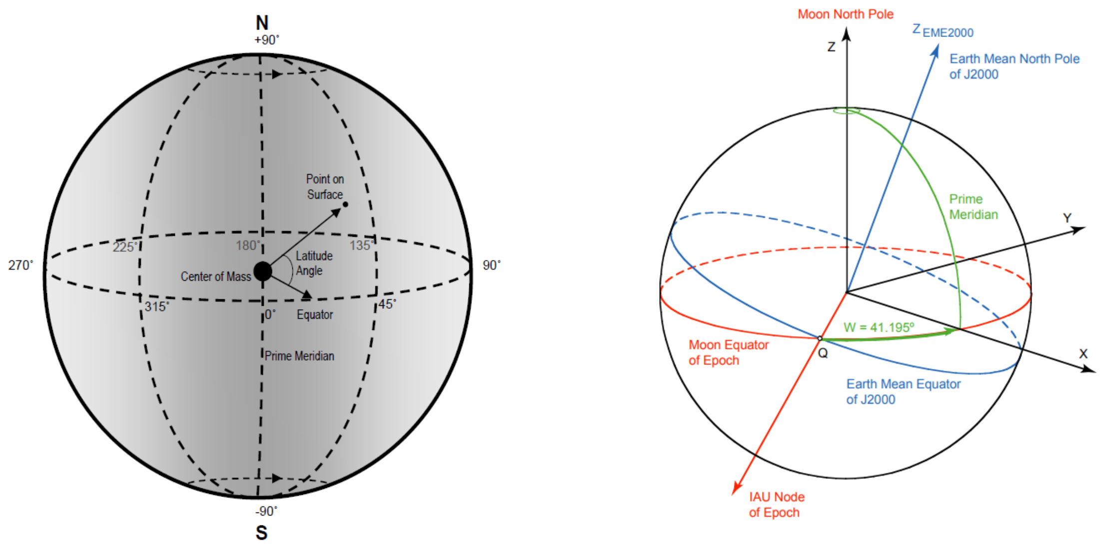

Figure 2. Planetocentric coordinates expressed as right-handed coordinates with the origin at the center of mass of the Moon,[9] and hypothetical lunar reference frame (Moon-Centered, Moon Mean Equator, and Prime Meridian, all in J2000 Epoch).[11]

Once the frames are defined, a PNT service architecture will be developed to support all of the different activities in cislunar space. Agreement on the standards this architecture uses is critical to ensure interoperability and reduce cost through design and intellectual property reuse. NASA missions have historically used technology customized to a particular application without adherence to common commercial standards (e.g., 4G, LTE, 5G, DVB-S2, etc.). This approach has been successful, but has also contributed to higher recurring cost for space systems. NASA's current efforts in this domain are from the Space Communications and Navigation (SCaN) program, which has developed the LunaNet architecture.[12] There are several key enabling features of LunaNet. The first is its reuse of communications links for PNT services. The second is its use of optical communication terminals (lasers) for the high data trunk links from Earth to the Moon,

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[10] 10 U.S.C. § 442 – Missions (2020).
[11] Roncoli, R. B. (2005). *Lunar Constants and Models Document*, JPL D-32296. Jet Propulsion Laboratory. September.
[12] NASA LunaNet Press Release. https://www.nasa.gov/feature/goddard/2021/lunanet-empowering-artemis-with-communications-and-navigation-interoperability.

and a third is the use of Delay-Tolerant Networks (DTNs) to improve data routing in an inherently intermittent network. LunaNet also has provisions for a version of GPS at the Moon, space weather alert messaging, and an Automated Identification System (AIS) message such as that used by ships or Automatic Dependent Surveillance-Broadcast (ADS-B) system used by aircraft that tells LunaNet users of the locations and velocities of other LunaNet nodes (Figure 3).

The LunaNet architecture is trending toward a NASA-first design, but with some security concessions. This is rational since NASA intends it as a system to provide services to human exploration, lunar science, and space technology missions. LunaNet has considerations for encryption (both FIPS 140 and higher levels), but the DoD may still have significant issues adopting such a system. Additional adversarial challenges such as jamming, spoofing, and meaconing (the interception and rebroadcast of navigation signals)[13] are not the primary motivators of this design. These security concerns are of higher priority to the DoD than NASA and as such the design choices may not be palatable to the defense sector. We advocate for a stronger commitment from the DoD to the PNT architecture, whether it be LunaNet or another design. This commitment requires resources in the form of staff, funding, and priorities. However, today's DoD does not have a major requirement to adhere to any architecture, LunaNet or otherwise, or even solve this type of military-hardened cislunar PNT system. This lack of requirement must change.

Figure 3. LunaNet.[12]

A recent trend in both civilian space programs and DoD space programs has been a move toward greater autonomy. For the DoD, the desire to pull humans out of the loop in time-sensitive decision-making processes is natural as those delays are sources of disadvantage in an adversarial engagement. NASA desires a maximum science return on its bandwidth-limited missions, and it may need to operate missions at certain situations that simply cannot tolerate the delay—such as the terminal phase of the recently successful DART asteroid impactor.[14] The recent trend in technology development has been enabling. DARPA Blackjack and the PitBoss computing architecture[15] are a perfect example, as are the multi-core spacecraft processors from CAES and Gaisler.[16] These higher performance computing capabilities enable embedded systems to run algorithms that would traditionally be impossible, such as image processing, machine learning, and

[13] https://informationtechniciantraining.tpub.com/14222/css/Meaconing-Intrusion-Jamming-And-Interference-Miji-88.htm.
[14] DART Mission. https://dart.jhuapl.edu/Mission/Impactor-Spacecraft.php.
[15] Military Embedded Systems Story. https://militaryembedded.com/comms/satellites/pit-boss-supercomputing-processing-hardware-developed-for-darpa.
[16] CAES. https://caes.com/products/radiation-hardened-solutions-high-reliability-components/computing/microprocessors.

artificial intelligence (AI). In the cislunar domain, these computing capabilities lead to an additional key enabler—autonomous trajectory redesign and fly-out. The lunar trajectories are much more complicated than simple Earth orbiters. Regular transmissions to and from a spacecraft reduce the autonomous nature of the missions and lead to increased labor costs. This push toward autonomy motivates the desire for a one-way, user passive system for navigation—just like GPS.

The Unites States must lead the process for developing the frames, standards, and cislunar PNT service. Leadership here is motivated by practicality, not national pride. We wish to establish cislunar PNT norms of behavior, identify violations of those norms via space situational awareness, and address those violations. One of these norms will be open access and international collaboration. Without leadership here, the United States will be reliant on whomever arrives first. The first mover will establish both the PNT systems and norms of behavior for the cislunar domain.

Heritage PNT Systems Used in the Cislunar Environment

GPS will also have a role in the cislunar environment, and deserves special attention to address its utility and shortcomings in that domain. Use of the GPS signals to navigate is a daily occurrence for most Americans, but the signals are much weaker at cislunar distances. Furthermore, the GPS user near the Moon often must make use of the side lobe instead of the main lobe, because the Earth blocks most of main GPS illumination beam. Figure 4 shows a typical geometry showing the GPS blockages.

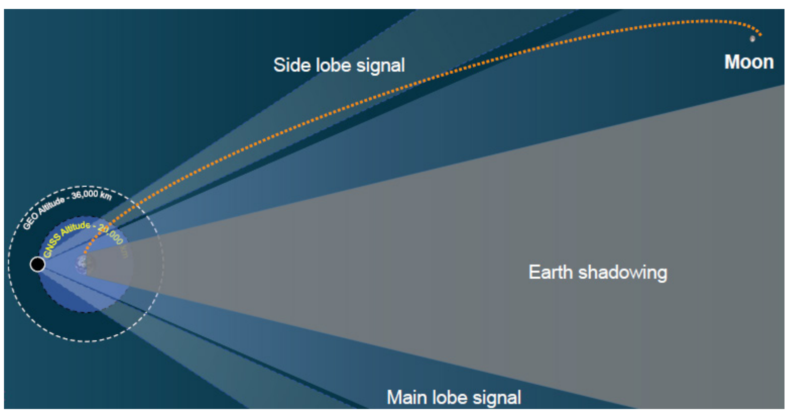

Figure 4. GPS beams and coverage at cislunar locations.

GPS use at the Moon is possible in spite of the illumination challenges. However, the receivers must be designed for weak signal acquisition and tracking. A traditional GPS receiver can detect and track at about 28–30 dBHz C/N0, but a lunar GPS receiver like the NASA and European Space Agency (ESA) partnership on LuGRE will need to have a sensitivity of about 23 dBHz.[17] This improvement in sensitivity enables detection and tracking of signals from farther away. This dramatic improvement comes at the cost of an expensive bespoke design. Additionally, the system performance will never approach that of a terrestrial user. As the distance grows between the satellite and receiver, the reliability decreases, Figure 5 (left). A terrestrial user will always see

[17] Parker, J. K., et al. (2022). The Lunar GNSS Receiver Experiment (LuGRE). *Proceedings of the 2022 International Technical Meeting of the Institute of Navigation*.

enough satellites to determine their location with high accuracy at every epoch—at least four GPS satellites, typically over eight. Cislunar users will only see two on average Figure 5 (right).

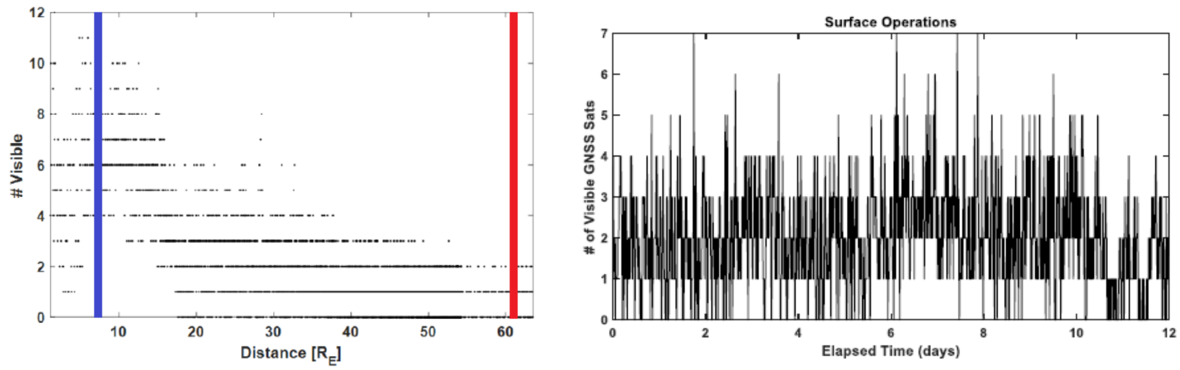

Figure 5. Number of visible satellites vs. distance from Earth for a time span (left) and a typical time series trace of the number of visible GPS satellites at the Moon's surface. On the left figure, the vertical blue line is the geostationary satellite distance, and the red line is at the Earth–Moon distance. The right figure shows a time series at the red line on the left figure.

Even with this advanced receiver, the inability to see four satellites continuously is challenging. The position determination algorithms, even those that use a long time series of data, can suffer kilometer-level errors due to the poor geometry. This insufficiency motivates further developments in the realm of cislunar PNT for autonomous operations. Augmenting the GPS constellation with new satellites to widen their illumination beams, or adding beams, is impractical due to power constraints, increased complexity, and cislunar GPS service being a low priority for the Air Force. Instead, a separate PNT system with cislunar considerations is likely to emerge.

Emergent PNT Architectures

The cislunar PNT architectures will likely fit into one of two categories: 1) bottom-up (organic and uncoordinated), or 2) top-down (centrally planned). A bottom-up example is the opportunistic reuse of the LRO radio to create ranging signals from users-to-LRO. A top-down approach is the LunaNet concept mentioned previously, but with additional supporting studies and funding. The bottom-up approach lowers the cost of each individual mission because it minimizes the number of requirements that the radio or PNT subsystem will need to meet. The top-down approach is the lowest overall cost for the PNT capability, since resources are allocated in an optimal coverage or service scheme. The bottom-up approach seems like the more natural way that a PNT architecture will emerge because it lowers the financial pain in the near term and because the future is often uncertain. However, with sufficient planning and levied requirements that are informed by a combination of NASA and DoD funding, the top-down approach is possible. Regardless of the development path, the cislunar PNT architecture will be comprised of three segments: 1) Earth, 2) Space, and 3) Moon.

The Earth-based category is the cheapest since humans are already there. The United States can create ground-based transmitters that point at the Moon and have similar characteristics as GPS (pseudolites), but with their power focused on the cislunar environment as a primary service mission. The bottom-up approach would augment the current Deep Space Network (DSN) and other (similar) stations to provide a stable one-way navigation system. The top-down approach would provide many more transmitters and measurements for improved navigation performance and robustness. Once the non-recurring expense (NRE) of a design is retired, such as the DSN, the recurring costs are only for power and maintenance. The required transmit power can be achieved with typical wall outlet sockets if the sky is decomposed into segments that are serviced by a single ground station in a sequence. This sequence may look similar to a lighthouse. The required time synchronization accuracy is readily achievable on the Earth with survey-grade GPS receivers or commercial time transfer modems. For DoD needs, U.S. military bases are a good set of placement sites since the bases are geometrically spread throughout the world, they are already in secure locations, and they have precise knowledge of time.

Figure 6. Ground transmitter directed toward the cislunar domain and Lagrange points 1, 2, 4, and 5.

Space-based augmentation is the next logical step to create a cislunar PNT capability. Spacecraft are expensive, but the United States and its corporations have plenty of experience creating spacecraft and placing them in different orbits. Any spacecraft that can get to GEO needs only marginally more thrust expenditure to be placed anywhere in the cislunar environment. Additionally, there are numerous missions planned by the United States and partner countries to go to the Moon. The NASA CLPS missions serve as one model for future cislunar missions—numerous small missions where a service is purchased instead of a mission funded. The CLPS model could dramatically lower the cost to deliver a payload to the Moon since profit-motivated companies will compete to find the lowest cost business model. If several of these spacecraft can be augmented with hosted payloads, then a PNT service could be deployed in cislunar space in a crawl/walk/run approach. The level of service provided with each launch could scale with the SWaP-C of the mission, but it is more likely that a homogenous capability from a single design on multiple spacecraft will provide the optimal solution.

A good candidate payload is the one-way time of arrival transmitter, such as GPS satellites. An architecture built from these transmitters hosted on opportunistic missions provides a user-friendly solution: low-power receivers that do not need to transmit. There are modifications that will be required to the standard GPS design to make it work in cislunar space. GPS was designed with the notion that the ground control segment would determine the satellite orbits to extremely high precision (sub-meter). Similar accuracy is not currently achievable at the Moon; even LRO was able to realize only approximately 20 meters of navigation accuracy.[2] LRO is exceptional in that it used a high cadence of radiometric measurements between the spacecraft and the Earth control segment, the U.S. Navy and a special dedicated LRO tracking station. It is unlikely that other missions will be able to afford the same level of resources simply for orbit determination. The Artemis mission serves as another reference point, with an accuracy requirement of 1 kilometer (1 sigma) and realized improved performance of about an order of magnitude. Therefore, the cislunar augmentation to GPS must also furnish the transmit satellite orbit accuracy information as a new part of the transmit message. The new receivers will also have to augment their navigation algorithms to incorporate this uncertainty knowledge into their navigation solution. The CAPSTONE mission will demonstrate a method to do this as part of its liaison navigation with the LRO.[18] LRO will provide relative range measurements to the CAPSTONE spacecraft, which will need to incorporate the uncertainty in LRO's orbit into its estimation routine. Additionally, CAPSTONE anticipates demonstrating one-way time-of-arrival ranging from its spacecraft. CAPSTONE's demonstration of both one-way and two-way ranging systems based on traditional communications links in the cislunar environment should lay the foundation for future PNT infrastructure capabilities.

The third category is the most difficult and expensive—landed PNT capabilities on the Moon's surface. NASA is working with multiple commercial companies to deliver payloads to the lunar surface under its CLPS program and will eventually succeed in developing and commoditizing a corporate lunar landing service. Lunar landing is a very complicated process, and developing the landing system is costly: $1.8 million[19] per kilogram for even newer low-cost CLPS-funded corporations. A landed PNT service node enjoys a significant advantage over an orbital asset—the location is fixed. Once the node's location is determined, it can broadcast one-way time-of-arrival measurements without worrying about inaccuracies in determining its orbit. However, there are two additional challenges for these landed nodes that result from lunar night: power storage to survive the lunar night, and oscillator stability over thermal environment changes. Outside the poles, the lunar night is about 14 Earth days long. Therefore, landers will require significant energy storage to survive, and even more power storage is required to transmit during the night when no solar power is available to collect. Even if the batteries are sufficient, the change in temperature at the transmitter's oscillator presents a challenge. Temperature fluctuations cause significant clock drift, which is a large problem for a precision timing system. The best option may be to turn on heating elements in the electronics box, which will drain the batteries even faster, or rely on radioisotopes for heating.

Common Technology

Advances in dual or multi-use technology can enable the desired extensible PNT distribution architecture. The foremost common use technology is the combination of PNT services with traditional telemetry, tracking, and control (TT&C) services. This combination of infrastructure makes efficient use of hardware SWaP-C and available spectrum. The same hardware can perform the ranging and time transfer service as well as transfer data between nodes. The combina-

[18] Thompson, M. R., et al. (2022). Cislunar navigation technology demonstrations on the CAPSTONE Mission. *Proceedings of the 2022 International Technical Meeting of the Institute of Navigation*.
[19] Astrobiotic Press Release. https://www.astrobotic.com/astrobotic-to-develop-new-commercial-payload-service-for-nasa-s-human-landing-system/.

tion of services gains efficiency since a task that once required two boxes and spectrum allocations will require a single box and spectrum allocation. The trend of combining PNT and TT&C capabilities is present in both the radio frequency and optical domains.

Another key enabling concept for the future of PNT in cislunar space is the use of incremental improvement of the service environment via a leave-behind capability from each mission. Once the primary mission of each satellite is complete, it is beneficial to the community to have that asset persist as a PNT service node. This is currently demonstrated by the NASA LRO satellite, which CAPSTONE will use as a ranging beacon to determine the CAPSTONE orbit. This approach lowers the total architecture cost when compared to architectures that use dedicated PNT nodes, such as PNT satellites placed at L4. The inherent limitation of a community leave-behind approach is that the system will have lower PNT performance than a dedicated architecture with optimized service provider locations. The blended solution will likely be the realized one: leave-behinds as opportunities arise and dedicated assets to fill any naturally occurring gaps in the coverage.

Telescopes and cameras of various styles can be dual-purposed to provide navigation information by observing the cislunar terrain. Optical (non-laser) navigation will be a critical element of the cislunar PNT architecture, but its utility is likely to be limited to applications where the user is close to the Moon. For surface navigation and entry, descent, and landing (EDL) activities, the illuminated terrain features are an excellent source of navigation information. For orbiters close to the Moon, those same features can be observed with a telescope. As the user moves away from the surface it will eventually be far enough away from the Moon that all features become indistinguishable and a simple line of bearing and apparent diameter is the extent of observable information. In these cases, the utility of the optical navigation measurements is not great, as there is not enough information to accurately determine the user position from a single measurement and it takes a significant fraction of the orbit to refine the estimate.

Each of these multi-use technologies comes with the same downside: there is a non-trivial cost for developing the combined capability and incorporating multiple sources of information into a navigation system. The combination of capabilities can be complicated, and ensuring that disagreements between multiple types of measurements do not lead to software trouble in the navigation filter is an added complication.

Considerations for Emergent PNT Architectures

The most significant problem with an emergent PNT architecture is that it is likely to be a NASA-first design, without enough consideration given to DoD needs such as security. The common DoD communication protocol Link16 serves as a good example of a combined ranging and TT&C link that uses encryption for security. This encryption is very expensive, as exemplified by the GPS M-code modernization efforts. Encryption systems are important for DoD personnel to trust the information and act on it in a contested environment, but they are only one part of the information security problem. Other issues include security of the ground segment's cyber and physical apparatus, backup systems in case of issues, and government certifications for cryptologic devices. Guarantees on information security will only be realized with significant requirements and funding from the DoD. A second potential weakness of an emergent architecture is the high likelihood of services gaps. A system constructed using nodes only placed at locations with compelling science or economic reasons to go there will likely have multiple holes. This concern is not limited to the lunar surface, but extends to cislunar space and beyond, including Earth-centered space such as GEO and highly elliptical orbits. NASA is unlikely to create the full extent of this needed parallel architecture unless it is required from the outset.

Recommendations for the Cislunar National Technical Vision

The previously discussed three navigation augmentations to GPS are candidates for providing the updated PNT service that the cislunar environment needs. The design space for the cislunar PNT service is already quite large, and the discussion here has not even touched on the different nuances of each measurement types (radiometric, optical, etc.). Creating the desired cislunar PNT service is an open problem, and one that can be solved in many sub-optimal ways. A PNT architecture should be bounded with realism by answering the following question: "What cost is the United States willing to pay for this capability?" Different academics have provided very different answers, some with four or more spacecraft at the Lagrange points, with total system costs approaching a billion dollars for cislunar GPS.[20] If a low-cost approach is most important, then the bottom-up approach is appropriate. If significant funds are to be dedicated to this pursuit, then a large trade study including both the DoD and NASA should be conducted and a system analogous in utility to a cislunar GPS should be fielded.

A likely outcome of the collective government organizations is one of ambiguity—cislunar PNT is a need for both NASA and the DoD, but there is no clear requirement with funding for the DoD to address this challenge. There is likely to be intermittent and inconsistent funding from the DoD, if at all. To realize the cislunar PNT service needed, four recommended actions should be taken.

First, DoD should allocate at least the minimum funds to participate in and jointly fund trade studies with NASA to determine an architecture that serves the needs of both organizations. A clear understanding of the architectural changes required to serve both parties (e.g., such as changes to LunaNet), and the funds it would cost to make those changes, is critical.

Second, DoD should innovate current existing technologies where possible (e.g., those developed on the Navigation Technology Satellite – III[21]), and develop new ones where needed, to create hosted payloads on the NASA CLPS missions. The CLPS missions are intended as low-cost and rapid delivery to the cislunar domain, exactly what the DoD needs and can afford in this scenario. If the U.S. government decides to separate the NASA and DoD missions, then the DoD can take a similar approach with a mixed architecture, e.g., host PNT services on an SSA mission in cislunar space.

Third, the DoD should leverage the Space Development Agency (SDA) for rapid capability development. Without coordination, this will be a missed opportunity between the SDA and NASA. The SDA plans to test DoD-relevant technologies in a new tranche of satellites every 2

[20] Duffy, L., & Adams, J. (2022). Cislunar systems architectures survey paper. 2022 IEEE International Systems Conference (SysCon).
[21] AFRL. https://afresearchlab.com/technology/space-vehicles/successstories/nts-3.

years. Similarly, NASA plans to send CLPS missions to the Moon at a rapid cadence. Systems that the DoD wishes to develop and see deployed in the cislunar domain could be fielded and tested on the current SDA tranche increment and then recreated, or upgraded, and provided to NASA for the next CLPS mission.

Fourth, low-cost cislunar augmentations to existent ground systems (e.g., GPS pseudolites for cislunar use) should be built out to enable autonomous operations in cislunar space. These four recommendations lead to a crawl/walk/run architecture and mixed capabilities that are a good value—high performance for low cost. The alternative is a PNT service grown in an ad-hoc, organic manner, one which will not be suitable to achieve cislunar security as envisioned in the Cislunar Security National Technical Vision.

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6. CISLUNAR COMMUNICATIONS

Ed Birrane and Sarah Heiner

Defining Cislunar Networking

The terrestrial internet is the largest, most effective communications mechanism in the history of our species. Its technical capabilities, user experiences, and societal impacts continue to shape our understanding of, and existence in, the world. It is, therefore, a relatively straightforward assertion that extending the internet to increasingly remote areas will similarly enable the study of our planet and our solar system; the concept of "networking" has become inseparable from the user experience of the terrestrial internet. Therefore, defining cislunar networking requires defining what "internet-like" services must be available and explaining the missions these services enable.

Evolving Internet-Like Services

There is no global catalog of "services" provided over the terrestrial internet. The same decentralized principles that make our internet scalable and resilient imply that available services differ by provider, by region, and by available technology. For example, the internet services we rely on today did not exist on the internet that existed at the turn of the century. Similarly, our missions that will exist 30 years into the future will rely on internet services that are not currently present today.

An important consideration in the evolution of "internet-like" services are the capabilities of the underlying support infrastructure. Many of the algorithms, protocols, and implementations that compose the terrestrial internet make simplifying assumptions about the capabilities of available infrastructure and the nature of the operating environment.

The cislunar environment has neither the engineering infrastructure nor the operating environment of terrestrial networks. The impact of this on networking can be seen by examining why emerging networked constellations are being built in low Earth orbit (LEO) and not geosynchronous orbit (GEO).

The emergence of LEO networked constellations provides early proof of the value of space-based networks—both to extend network access across the globe and to provide service to other space-based platforms. Building these constellations in LEO requires thousands of moving spacecraft to achieve time-varying regional coverage. The management and use of these networks imposes a complexity that could be avoided were networking spacecraft placed at GEO instead.

However, a GEO network constellation would increase per-spacecraft networking demand and signal propagation delays would prevent achieving required data rates. The same network service catalog cannot be provided at GEO that can be provided at LEO. Given the Moon is approximately nine times farther from Earth as GEO, we can intuit that cislunar network services would be even more difficult to implement and require different networking technologies.

Networked Sensing

Networks exist to transport data to and from human and machine sources and destinations. A cislunar network is no exception—cislunar networks exist to transport data to, from, and within the lunar environment. When considering how missions might use such a network it is reasonable to see how missions in other networking domains operate.

Since the cislunar operating environment differs significantly from terrestrial environments, finding a preexisting exemplar network is a little more challenging. Rather than envisioning lunar communications as extensions to the terrestrial internet or a 5G cellular network, there is simplifying utility in examining the evolution of wireless sensor networks (WSNs).

The pragmatic description of a WSN has remained largely unchanged for the past 20 years:

> Wireless sensor networks combine processing, sensing, and communications into tiny embedded devices. Peer-to-peer communication protocols then combine the individual devices into an interconnected mesh network where data is seamlessly routed among all the nodes. These networks require no external infrastructure and can scale to hundreds or even thousands of nodes.[1]

This paradigm codifies a unique and intertwined relationship between sensors and the network that combines them. Without sensors, the WSN would have no data to communicate. Without the network, sensors would have no useful way to coordinate. While cislunar networks will also support human lunar exploration, the vast majority of lunar communications will be machine-to-machine, exchanging science and engineering data.

A WSN-inspired lunar network would federate different spacecraft sensors from different space agencies (and industry) to leverage diversity and mobility for enhanced science. Combining (and recombining) sets of sensors based on changing position, pointing, and capabilities allow fewer spacecraft to provide more and more diverse sensor coverage. In a way, individual sensors form a virtual "macro-instrument" whose observations can be distributed across multiple platforms.[2]

The concept of "macro-instrumentation" across coordinated cislunar spacecraft has multiple benefits, to include the following.

- **Sensor diversity**. The value of a macro-instrument is its ability to support a diversity of individual sensors. Simply duplicating the same sensor does not always provide new or motivating insights.
- **Spatial distribution**. Isolated sensors may produce biased results by under sampling the environment. Multiple sensor inputs distributed across a spatial area reduces the likelihood of regional biases.
- **Data fusion**. An important concept behind the "macro-instrument" view of a sensor network is the creation of data products beyond those directly recorded by an individual sensor.

[1] Hill, J., et al. (2004). The platforms enabling wireless sensor networks. *Communications of the ACM*, 47(6), 41–46.
[2] NASA. https://www.nasa.gov/feature/goddard/2021/lunanet-empowering-artemis-with-communications-and-navigation-interoperability.

Building a Cislunar Network Architecture

Exchanging data to and from the lunar environment happens today without the presence of a functioning cislunar network. When considering lunar data flows—as inspired by WSN examples—there are two common architectural options for collecting and sharing data. One architectural option is an application-first approach and the other is a network-first approach. Understanding these differing approaches is important to the development of a functioning cislunar network.

Application-Centric Architectures

At the turn of the century, spacecraft communication occurred predominantly as point-to-point links between a selected spacecraft and a selected ground station. In certain near-Earth cases, this single link architecture included the use of one or more data relay spacecraft acting as "bent pipes" for communication. Link establishment occurred in a tightly scheduled and pre-planned manner and deconflicted when there existed multiple spacecraft requesting time for fewer ground stations.

This approach is termed *application-centric* because spacecraft, ground stations, and all assets in-between were custom built for the sensor(s) and the mission applications driving them. Missing a downlink opportunity (due to spacecraft issues, terrestrial or space weather, losing priority due to another spacecraft emergency, or other means) requires that applications manage local storage, defer new data observations, or delete older data. These approaches, often codified in the implementation of spacecraft command and data handling (C&DH) systems, are unique to a specific manufacturer or application framework.

As the number of spacecraft increase, and the amount of data produced by each spacecraft also increases, the only way to maintain the *application-centric* architecture is to build more application-specific infrastructure. More ground stations. More spacecraft storage. More bent-pipe relays. In doing so, planning and scheduling complexity grows exponentially with the number of new spacecraft and ground stations, requiring more operators, more compute resources, and new tooling.

This application-centric approach is not pragmatically scalable for near-Earth spacecraft and likely a poor choice for scaling in the lunar environment.

Network-Centric Architectures

To keep scalability economically feasible, spacecraft communications need to move away from an *application-centric* architecture towards a *network-centric* architecture. In such an architecture, applications generate and annotate data that is passed to an onboard networking function for storage, prioritization, and distribution.

A *network-centric* architecture builds on the concept of shared resources and common interfaces (and the establishment of shared internetworking and data transport services). Spacecraft and ground entry points are responsible for acting as routers and switches more than they act as hosts for a specific application or sensor. The primary goal of assets in this architecture is the sustainment of the network and its data.

Until recently, the construction of a *network-centric* space architecture seemed impractical. Programs such as the Transformational Satellite Communications System (TSAT)[3]—a relatively modest five-satellite constellation—was cancelled in 2009 for high cost, technological risk, and development delays.

Now, almost 20 years after the inception of the TSAT program, advances in spacecraft avionics, user needs, and computer networking have generated renewed interest in building such an architecture near-Earth, cislunar, and even in deep space.[4]

Cislunar Networking Recommendations

Emerging near-Earth *network-centric* architectures focus on the establishment of densely populated LEO constellations providing internet-like services for ground- and space-based users. Such constellations are being pursued by private industry (Starlink, OneWeb, Kuiper, Telesat) and government agencies (National Aeronautics and Space Administration (NASA), Space Development Agency).

Similarly, the cislunar architecture should be network-centric. In particular, centralizing lunar data communications in a common networking layer provides several pragmatic advantages.

- **Reduced application complexity.** Centralizing networked data distribution simplifies individual application development, which reduces development cost and risk. By not coupling application design to data transport, application reuse across missions may also increase.
- **Reduced resource utilization.** Centralizing the algorithms used for networked data distribution into a networking layer prevents duplication of code, memory, data pipelines, and compute resources. If onboard networking functions are located on a separate processor, then applications can spend their compute resources instead on generating more data and annotating it data.
- **Standard behavior.** A centralized network function ensures standardized network behavior. Application-centric approaches might have different behavior when applications control data distribution.
- **Diversity.** When applications are insulated from the specific structures of the network, end-to-end data delivery happens even when the underlying network changes. This accepted feature of terrestrial networks is just emerging in space-based networks.

Led by NASA, a consortium of national space agencies has converged on a network-centric lunar architecture that has been termed LunaNet. As illustrated in Figure 7, LunaNet serves as an exemplar for the types of varied and mobile sensor and relay nodes that will operate in the cislunar environment.

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[3] Pulliam, J., et al. (2008). TSAT network architecture. MILCOM 2008-2008 IEEE Military Communications Conference.
[4] Interagency Operations Advisory Group (IOAG). (February 2022). *The Future Mars Communications Architecture*, Volume 1. https://www.ioag.org/Public%20Documents/MBC%20architecture%20report%20final%20version%20PDF.pdf.

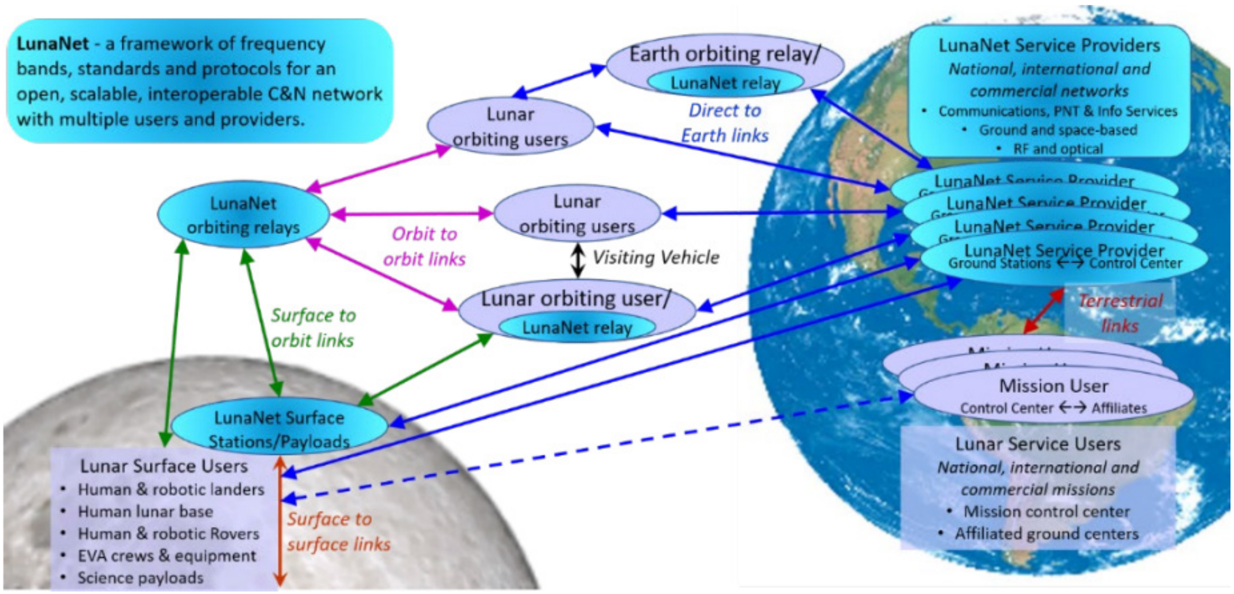

Figure 7. LunaNet: A Civil Space Agency Cislunar Network.[5]

While the LunaNet concept is still in development, common themes are emerging.

- **Regional Hierarchy**. Networked constellations incorporate different devices with different physical capabilities and visibilities. This lack of homogeneity creates partitions of *local* devices talking to *regional* connectivity providers, and ultimately through *backhaul* services.
- **Multiple providers**. Regional and backhaul services will be provided by multiple organizations each with their unique security stance and concepts of administrative control.
- **Dedicated network devices**. Particularly in near-Earth space, networking constellations will be singularly purposed to the servicing of the network.

Enabling a Cislunar Network-Centric Architecture

Establishing cislunar networks stands at an architectural crossroads in the evolution of spacecraft communications. Similar to near-Earth space networks, cislunar networks benefit from proximity to Earth for low-latency communications and access to significant compute capabilities. Similar to deep-space networks, cislunar networks must adjust to changing network topologies, lower data rates, fewer onboard compute resources, and a higher reliance on autonomy.

Figure 8 illustrates the unique nature of the cislunar environment. The top portion of this figure visualizes the distance between LEO and GEO with a green line. Terrestrial internet techniques struggle to operate in this GEO range, which is why commercial and government networking constellations exist in LEO. The bottom portion of the figure then places this green range in the context of cislunar space, which is approximately nine times farther away.

[5] Israel, D. J., et al. (2021). LunaNet architecture and concept of operations. 16th International Conference on Space Operations, International Astronautical Federation (IAF).

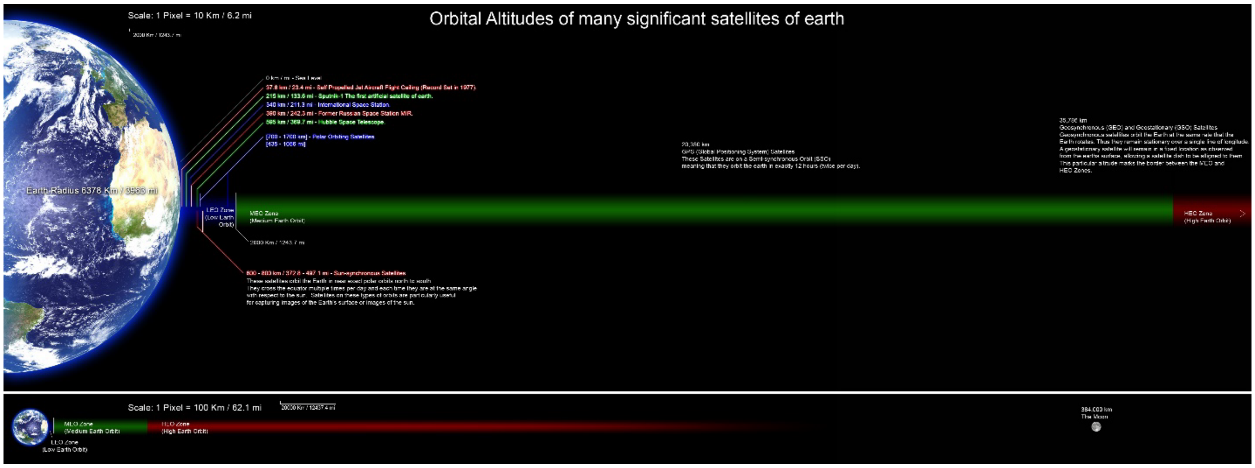

Figure 8. The cislunar environment is approximately nine times farther from Earth than GEO.[6]

It is intuitive to consider cislunar as "Near-Earth" relative to other planets. But cislunar needs to be treated like deep space in that it exists well past the boundary where certain traditional networking protocols and algorithms fail to converge.

With other national space agencies and internet vendors, NASA has developed a networking architecture termed Delay-Tolerant Networking (DTN)[7] to augment the native capabilities of the Internet Protocol (IP) suite for use in deep space. While this network architecture was developed for deep space missions, many DTN protocols and algorithms are useful in the cislunar environment. As shown in Figure 9, NASA believes that DTN protocols and associated algorithms are fundamental to the proper implementation and operation of the LunaNet concept.

The primary DTN features needed in the cislunar environment include time-variant routing, secure store-and-forward data transport, and autonomous network management. While not all of these exist in a terrestrial internet services catalog, they must be added to a cislunar networking service catalog.

Time-Variant Routing

Network routing algorithms determine paths through a computer network between message sources and destinations. These algorithms typically construct a graph-based topological representation of a useful part of the network and run some traversal algorithm over that graph. The graph represents the best known snapshot of the network at a given moment in time. Changes to that graph over time are often not considered in the route computation—most routing algorithms do not adapt to a time-variant network topology.

[6] The image "OrbitalAltitudes.jpg" by "Rrakanishu" is licensed under CC-SA 4.0. https://commons.wikimedia.org/wiki/File:Orbitalaltitudes.jpg.
[7] Cerf, V., et al. (2007). *Delay-Tolerant Networking Architecture*. No. rfc4838.

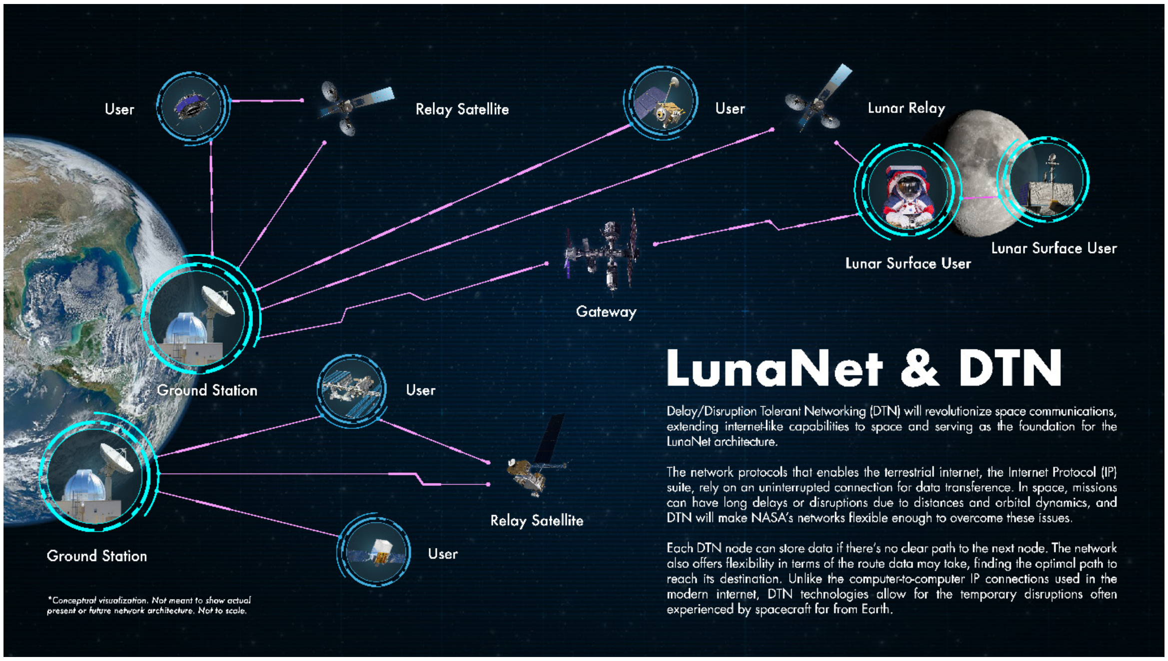

Figure 9. DTN networking technologies augment basic IP features to enable cislunar networking.[8]

In a cislunar environment, pointing of spacecraft, power-cycling radios, and loss of line-of-sight all result in a constantly changing network topology. Therefore, new network routing algorithms must be devised that can reason about both the current topology graph and how that topology graph might predictably change over time.

DTN routing algorithms focus on how planned, predicted, or discovered changes to the network can be accommodated for network routing. Figure 10 illustrates one approach to time-variant routing. Figure 10a shows how connectivity plans are calculated and uploaded spacecraft. Figure 10b then shows how those plans can be used to determine paths through the network. Finally, in Figure 10c a spacecraft determines when to forward data to its next hop along the path. That forwarding could happen immediately, or at some point in the future if waiting upon a future contact.

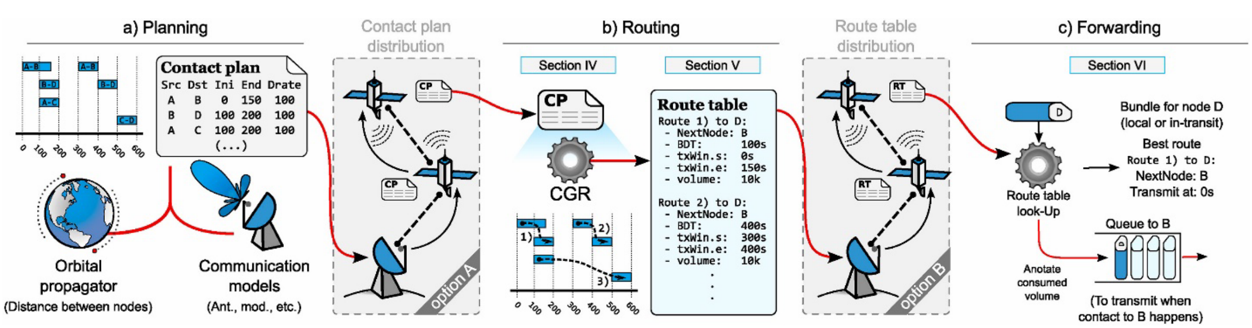

Figure 10. Routing decisions can be made around planned changes to the network topology.[9]

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[8] NASA. https://www.nasa.gov/feature/goddard/2021/lunanet-empowering-artemis-with-communications-and-navigation-interoperability.

[9] Fraire, J. A., De Jonckere, O., & Burleigh, S. C. (2021). Routing in the space internet: A contact graph routing tutorial. *Journal of Network and Computer Applications*, 174, 102884.

Time-variant routing algorithms can be used to make more intelligent use of nodes across a cislunar network. In a terrestrial internet routing algorithm, a node must decide whether to forward or delete a message in a very short amount of time (typically milliseconds). A time-variant routing algorithm would sometimes choose a third option, to store messages until a later time—particularly if an appropriate link is expected in the near future.

Secure Store-and-Forward Transport

In order to implement time-variant routing, network transport protocols that standardize the structure and behavior of message storage must exist. Such protocols are termed "store-and-forward" protocols because they support the temporary storage of networked messages until a routing algorithm can forward them to the next node along their network path.

The store-and-forward transport protocol proposed for in space operation is the Bundle Protocol Version 7 (BPv7), standardized by the Internet Engineering Task Force (IETF) as RFC 9171.[10] The protocol data unit of BPv7 is termed the "bundle" and it consists of a series of "blocks" representing discernable types of information such as a primary header, multiple secondary headers, and a payload as shown in Figure 11.

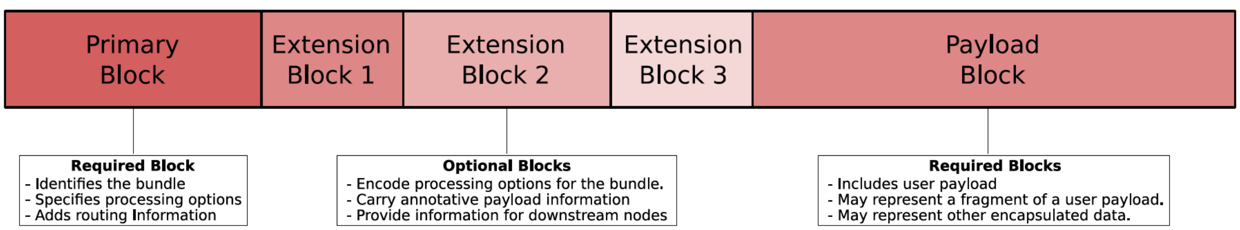

Figure 11. BPv7 bundles carry more information than IP packets.

Different extension blocks can carry different types of information such as network information relating to the bundle, annotative information about the payload, and even control channel information not related to a specific payload. Unlike IP packets, BPv7 bundles support multiple, variable length secondary headers that can be added, removed, or updated by intermediate nodes in the network.

The Bundle Protocol Security (BPSec) extensions, standardized by the IETF as RFC9172,[11] implement end-to-end security for BPv7 bundles. Just as IPSec secures IP packets, BPSec secures BPv7 bundles. However, BPv7 bundles have a different structure, behavior, and feature set from IP packets and, thus, BPSec provides additional features that are useful in a cislunar environment. These security features include the following.

- **Block-level granularity.** BPSec enables securing individual headers and payloads of a bundle separately. Networks might, for example, encrypt a payload and one extension block while signing other extension blocks. Unlike other security protocols, BPSec does not mandate a "one-size-fits-all" security approach for bundles.

[10] Burleigh, S., Fall, K., & Birrane, E. (2022). *Bundle Protocol Version 7*. IETF RFC9171.
[11] Birrane, E. J., & McKeever, K. (2022). *Bundle Protocol Security (BPSec)*. doi:10.17487/RFC9172.

- **Security contexts.** BPSec allows for the standardization of different contexts in which security is applied and configured in a network. This allows near-Earth BPSec deployments to use familiar key management and cipher suite techniques separate from cislunar and deep space deployments. This added layer of security configuration allows one standard security protocol to function in multiple different security environments.

The combination of BPv7 and BPSec allows networks to use less data encapsulation and maintain a flatter information structure that enables flexibility in more networking scenarios.[12] For example, as shown in Figure 12, a single bundle can carry multiple sets of differently secured information. This reduces the number of route computations, calls to security libraries, and per-packet storage requests in the network.

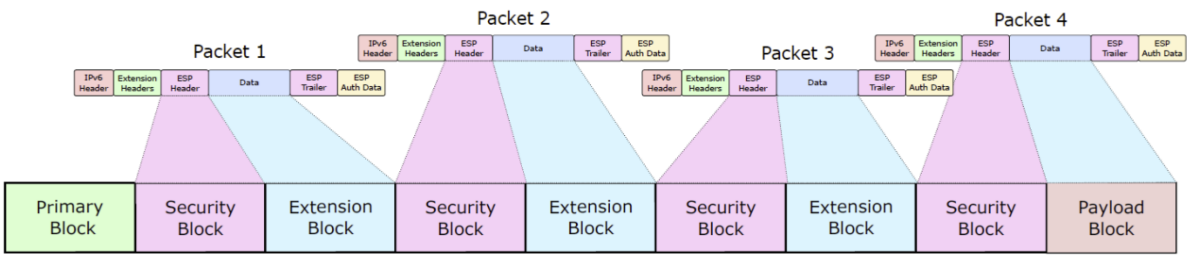

Figure 12. BPSec allows different data in a bundle to be secured differently.[13]

Autonomous Network Management

Deep space flight software systems implement stimulus-response autonomy systems for onboard system maintenance and fault management. This design stems from the recognition that some spacecraft failures might happen when a spacecraft is not in contact with Earth and, thus, unable to receive a human-in-the-loop response to onboard problems. This popular approach has advantages in processing, but is frequently coupled to a specific spacecraft design and rarely tied to any kind of networking concept of operations (CONOPs).

Alternatively, terrestrial network management, such as that deployed in datacenters, focus on standards and open-source tools for which there has been large community investments. These standards focus on providing actionable information to network operators in near real-time. Since datacenters often have significant compute capabilities, the efficiency of algorithms and protocols are less of a concern than is typically seen in spacecraft flight software systems.

As shown in Figure 13, a cislunar network management ability must find a useful way to combine the deterministic autonomy of spacecraft systems with the standards and networking CONOPs from terrestrial deployments.

[12] Birrane, E. & Heiner, S. (2020). A novel approach to transport-layer security for spacecraft constellations. Small Satellite Conference 2020.
[13] Birrane, E., Heiner, S., & McKeever, K. (2022). *Securing Delay-Tolerant Networks with BPSec*. Wiley and Sons.

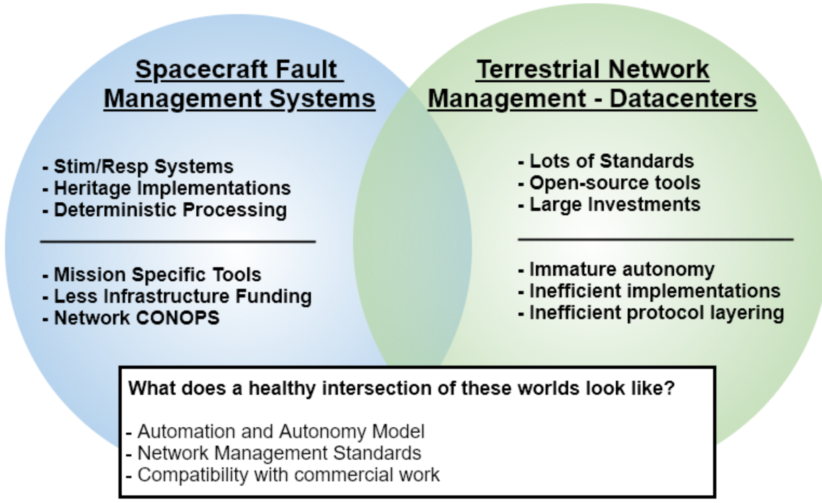

Figure 13. Cislunar networks must combine autonomy and management best practices.

Just as fault protection autonomy protects the spacecraft from hardware and software errors, some level of network protection autonomy can protect the spacecraft from communications and networking failures. Over the terrestrial internet, this level of network fault protection is accomplished through the use of network management and configuration protocols. However, many of these protocols require timely, available connectivity to centralized network operations centers.

Just as spacecraft in a cislunar environment must contend with time-variant routing topologies and store-and-forward data transport, some level of in-situ autonomy must be built into the network management of any spacecraft operating as a network node.

The Future of Cislunar Networks

The motivation for cislunar networking is to achieve (in the lunar environment) the benefits of a diverse, shared communications infrastructure as has come to be expected with the terrestrial internet. This happens by building “internet-like” services in an environment that is, otherwise, absent “internet-like” infrastructure.

Many of the “internet-like” services used for Near-Space and terrestrial networks will have immediate applicability to a cislunar network-centric architecture. However, the relatively sparse number of cislunar assets and significant signal propagation delays mean that the cislunar network requires some capabilities more common in deep space missions. Specifically, a functioning cislunar network requires new services such as time-variant routing, store-and-forward data, and autonomous network management.

Currently, multiple space agencies are converging on the construction of an international cislunar network—LunaNet—that will define an initial set of services and new technologies needed to bring this vision to reality. The technical challenges are significant, but the promise of a richly connected celestial environment promises significant leaps for the coming generation of advanced lunar engineering and scientific advancements.

APPENDIX A. ACRONYMS AND ABBREVIATIONS

ADS-B	Automatic Dependent Surveillance-Broadcast
AFRL	Air Force Research Laboratory
AGI	Ansys Government Initiatives
AI	Artificial Intelligence
AIS	Automatic Identification System
APL	Johns Hopkins University Applied Physics Laboratory
BP	Bundle Protocol
BPSec	Bundle Protocol Security Extensions
C&DH	Command and Data Handling
CLPS	Commercial Lunar Payload Services
CLSC	Cislunar Security Conference
COMSPOC	Commercial Space Operations Center
CONOPs	Concept of Operations
CSAC	Chip-Scale Atomic Clock
CSpOC	Combined Space Operations Center
DARPA	Defense Advanced Research Projects Agency
DEM	Digital Elevation Map
DIA	Defense Intelligence Agency
DoD	Department of Defense
DSN	Deep Space Network
DTN	Delay Tolerant Network
EDL	Entry, Descent, and Landing
EOIR	Electro-Optical and Infrared
ESA	European Space Agency
ESPA	EELV Secondary Payload Adapter
FY	Fiscal Year
GEO	Geosynchronous Equatorial Orbit
GPS	Global Positioning System
GTO	Geosynchronous Transfer Orbit
IDA	Institute for Defense Analyses

IETF	Internet Engineering Task Force
IMO	International Maritime Organization
IOD	Initial Orbit Determination
ISR	Intelligence, Surveillance, and Reconnaissance
ISRU	In-Situ Resource Utilization
ITRF	International Terrestrial Reference Frame
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LOLA	Lunar Orbiter Laser Altimeter
LRO	Lunar Reconnaissance Orbiter
LRS	Lunar Reference System
LSIC	Lunar Surface Innovation Consortium
LSII	Lunar Surface Innovation Initiative
LWIR	Long-Wave Infrared
ME	Mean-Earth
MEO	Medium Earth Orbit
MOU	Memorandum of Understanding
MWIR	Mid-Wave Infrared
NAIF	Navigation and Ancillary Information Facility
NASA	National Aeronautics and Space Administration
NGA	National Geospatial-Intelligence Agency
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NOTAMs	Notice to Air Missions
NRE	Non-recurring Expense
OST	Outer Space Treaty
PA	Principal Axis
PDS	Planetary Data System
PNT	Position, Navigation, and Timing
PRC	People's Republic of China
RF	Radio Frequency
RSO	Resident Space Object

SCaN	Space Communications and Navigation
SDA	Space Domain Awareness; *also* Space Development Agency
SDS	Space Defense Squadron
SGP	Simplified General Perturbations
SNR	Signal-to-Noise-Ratio
SP	Special Perturbations
SPD-1	Space Policy Directive 1
SPICE	Spacecraft, Planet, Instruments, C-matrix, and Events
SSA	Space Situational Awareness
STEM	Science, Technology, Engineering, and Mathematics
STM	Space Traffic Management
SWaP-C	Size, Weight, Power, and Cost
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TLE	Two-Line Element
TSAT	Transformational Satellite Communications System
TT&C	Telemetry Tracking & Control
UAE	United Arab Emirates
UAV	Unmanned Aerial Vehicle
UCT	Uncorrelated Track
U.K.	United Kingdom
U.N.	United Nations
USGS	United States Geological Survey
USNO	U.S. Naval Observatory
USSF	United States Space Force
USSPACECOM	United States Space Command
VCM	Vector Covariance Messages
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
WGS84	World Geodetic System 1984
WSN	Wireless Sensor Network
xGEO	Extra-Geosynchronous Equatorial Orbit
XPNT	xGEO Foundational PNT

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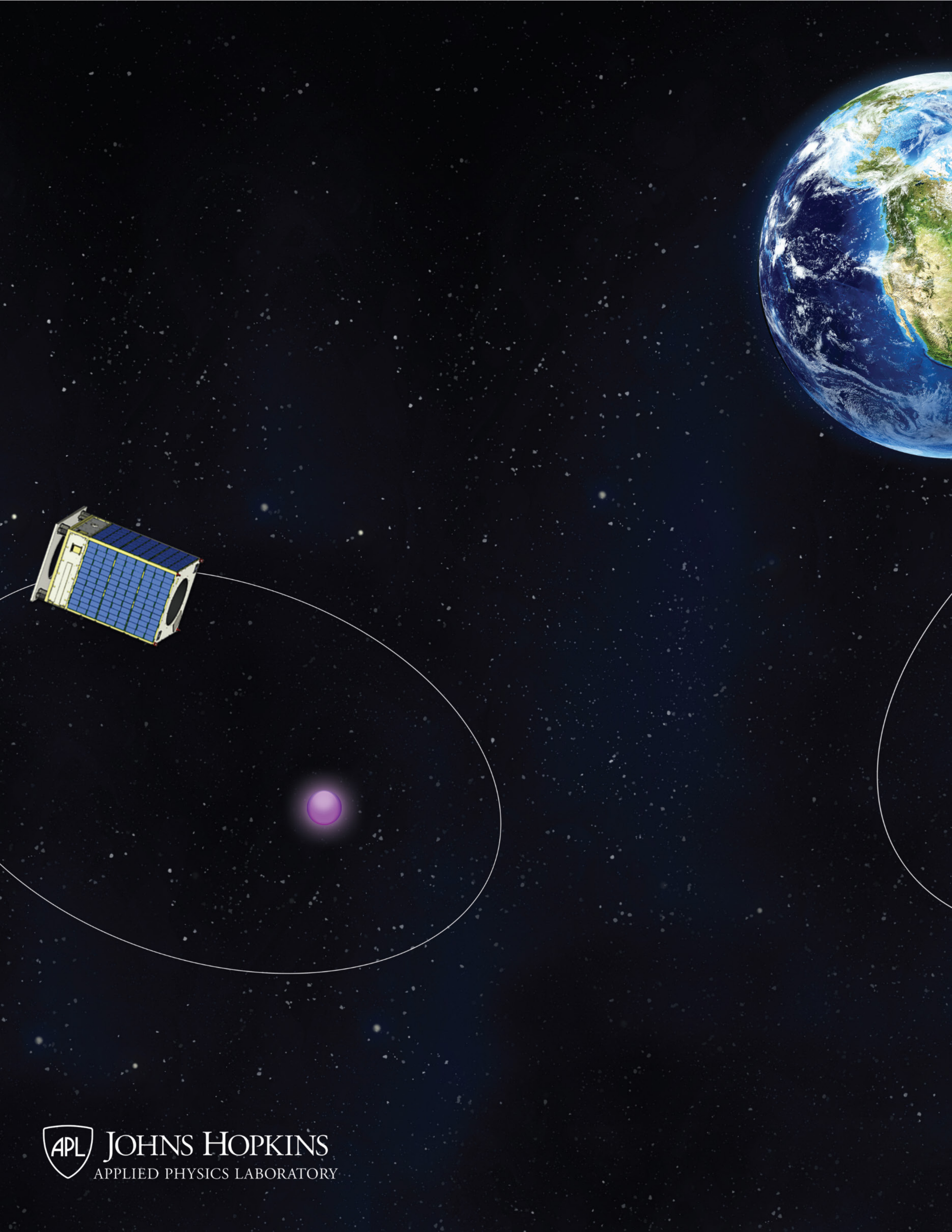
APL
Johns Hopkins
Applied Physics Laboratory