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CHARTING A COURSE THROUGH CISLUNAR MASTER PLANNING

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Summary

Interest in the cislunar region is steadily growing. Given the diversity and number of U.S. and international service providers, for the first time, developing a self-sustaining space economy seems more possible than in the past. Creating a framework where all stakeholders can coordinate infrastructure investments will reduce duplication of efforts, maximize the impact, and ensure likelihood the community's interests are met. This paper discusses the need for a cislunar master planning effort and proposes establishing a domestic cislunar master planning entity to engage and coordinate with like-minded nations on cislunar planning on a broader scale.

> *"Some people argue that humanity is destined to develop space settlements and become a 'multi-planetary species.' Although this is certainly an exciting possibility, it will depend on our ability to use in-space resources and live independently from Earth's support and environment. It will also depend on finding economic reasons for living and working beyond the Earth—reasons that do not rely on support from taxpayers. At present, we do not yet know if any of these conditions are possible. What we do know is that we will not be able to determine the answers without a space exploration and development effort that reaches beyond low-Earth orbit."*
>
> *– National Space Council, July 2020*

Introduction

This paper examines the growing interest in cislunar space by multiple stakeholders and is a call to action to establish a domestic cislunar master planning effort to engage and coordinate with like-minded nations on cislunar planning on broader scale. Current national policies and commercial actions create the need to initiate holistic planning to advance goals and objectives for future cislunar settlement. For purposes of this paper, master planning for a self-sustaining cislunar ecosystem is described in terms of coordinated planning and harmonized operations of 11 foundational infrastructure layers, including, for example, communications, mobility, logistics, and power. As of June 2022, over 60 companies and 10 U.S government organizations in the United States are investing, developing, and planning to deploy capabilities for one or more cislunar infrastructure layers. Neither an integrated master plan nor a domestic U.S. master planning functional role currently exists. Time and treasure likely will be wasted without proper coordination across these

multiple stakeholders. The master planning process should inform and be informed by independent designs of systems from diverse providers. An intent is to mitigate risks for all stakeholders.

U.S. government investments in commercial services are generating interest in the cislunar region. As context, we trace the National Aeronautics and Space Administration's (NASA's) increasing commercial services acquisitions over multiple decades growing from millions of dollars in the 1990s to tens of billions of dollars in the 2020s.[1] We highlight how the government plays a key role in enabling burgeoning markets. The United States can bring U.S. government and commercial interests together and coordinate internationally to advance space capabilities in the cislunar region, similar to how NASA has coordinated the Artemis Accords among international partners .[2]

If the United States does not take the lead now, someone else will. Alternative approaches would likely be less aligned with U.S. national interests, and there is evidence that the opportunity time frame is shrinking. For example, in December 2017, China stated its ambition to become the preeminent global space power by 2045.[3] China is presently the leading operator of robotic capabilities at the moon with several "firsts" in the cislunar region. In March 2021, China signed a memorandum of understanding with Russia to cooperate on an international lunar research station. Given the need and urgency for cislunar master planning, the time is now to establish U.S. leadership in this area.

Recognizing growing excitement around cislunar space, we explore the need for coordinated planning performed by a coalition of U.S. government and private sector stakeholders. By identifying key areas essential to meet exploration, scientific, and commercial interests, master planning can synchronize investments to maximize efficiency. Our primary recommendation is to establish a U.S. master planning entity to engage and coordinate with like-minded nations on cislunar development activities and maintain America's international leadership role in space.

Perspective: Looking Back to Plan Forward

Cislunar space is the new Wild West. For the purposes of this paper, *cislunar* refers to the region from Earth out, past the moon, to 500,000 km, as shown in Figure 1.[4] This greenfield in space is becoming a popular destination for U.S. companies, federal agencies, and international parties. This excitement is expected to grow significantly over this decade, necessitating a coordinated effort among all parties for integrated infrastructure and capabilities to enable a self-sustaining space ecosystem and economy.[5]

The U.S. government has a legacy of playing pivotal roles enabling exploration and settlement of new frontiers. In the 19th century, 55 years after the Lewis and Clark expedition, the U.S. government passed laws to encourage the geographic expansion to the West and promote construction of a transcontinental railroad. In the 20th century, the Postal Service promoted development of private aviation for mail delivery, charting a course for air travel. Together with the interstate highway system, the resulting air and ground transportation infrastructure provided the backbone of the U.S. economy, improving interstate commerce, traveler safety, and defense mobility.

In some cases of exploration and initial development, new U.S. military installations encouraged infrastructural expansion out of a need for proper logistics management. Government-provided logistics for forts across the western region of the U.S. transitioned to leverage "commercial" logistics over time. Many towns and cities continued after forts were closed. More recently, in Antarctica, planning for the Palmer Station was started as a joint

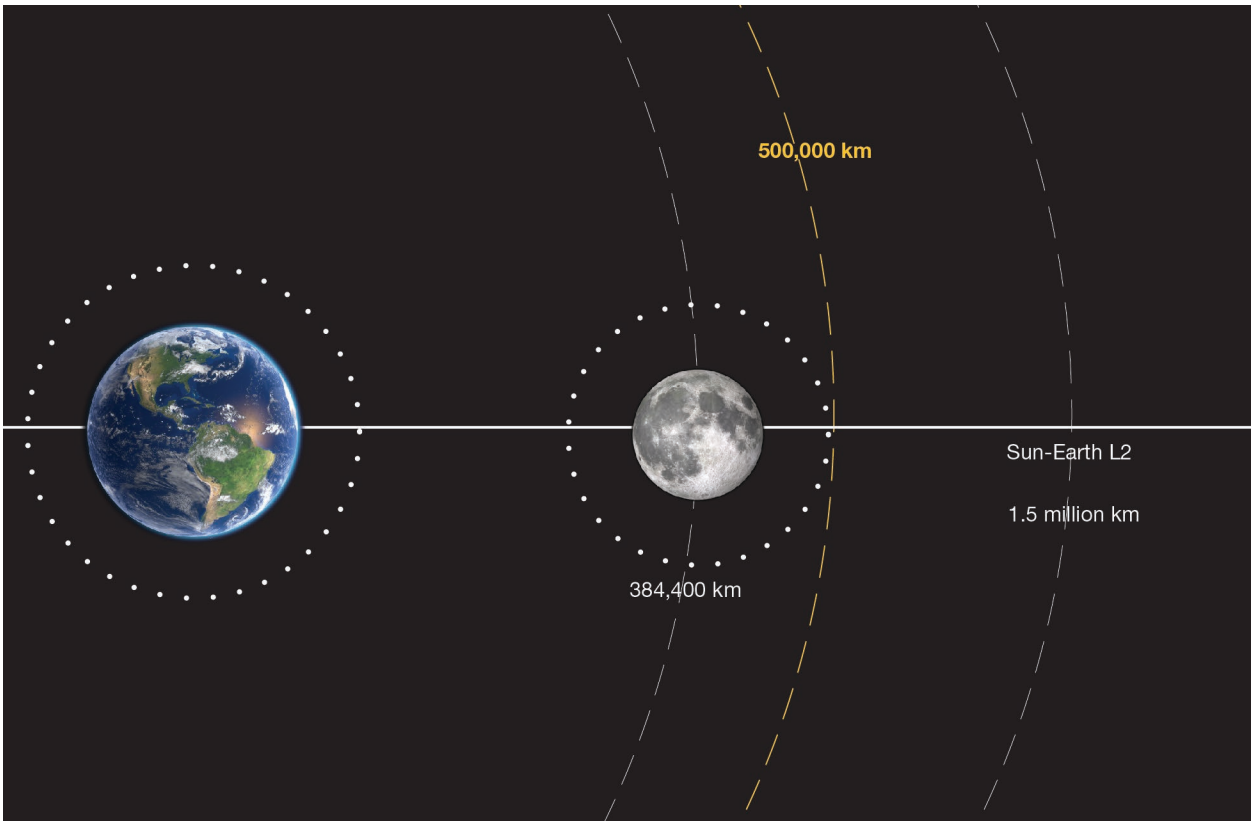

Figure 1: Cislunar space region.

effort between U.S. Navy and the National Science Foundation (NSF) and is now led primarily by the NSF.[6] Cislunar development may proceed along analogous paths enabled by U.S. government actions for exploration on a path to permanent presence on the moon.

Seeding a Future Commercial Cislunar Space Economy

In the 21st century, space is our frontier, our greenfield, our undeveloped region ripe for going beyond exploration to commercial development and on to settlement. Technical capabilities are maturing and economic barriers to sustainable space are waning.[7] Historically, only governments had the means and technical acumen to conduct risky space programs and projects through investments in developing, owning, and operating space systems. Times have changed. Since the early 2000s, the U.S. government has reinvigorated its legacy of enabling exploration and expansion through trailblazing missions. Federal agencies have been fostering entrepreneurship by procuring space commercial services where possible in place of government-owned and -operated systems. Recent government acquisitions of commercial solutions are invigorating a space economy, seeding a future cislunar ecosystem, and encouraging expansion of an increasingly diverse set of service providers. (See the appendix for a profile of NASA's commercial services evolution.)

Commercial interest in space is steadily growing. The foundation for a cislunar economy is expanding beyond NASA's shift toward commercial services.[8] Since the early 2000s, Ansari and Google challenges energized a diverse space market with companies beyond traditional "Big Space" players, and spurred

space entrepreneurs to develop long-term business models. Challenges inspired the next generation of scientists, engineers, space explorers and adventurers to enter science, technology, engineering, and math (STEM) fields. In 2021, the private sector invested on the order of $17 billion in space capabilities—an increase of 50 percent over 2020—for both low Earth orbit and in the lunar region.[9]

Recent studies, government assessments, and technical exchange meetings are confirming this trend and show signs of a bright future ahead for cislunar space. A recent PwC Lunar Market Assessment conveys growing excitement and reports "governments and their space agencies are dedicating more and more resources to developing a self-sustaining private space ecosystem."[10] Governments around the world are engaging in public-private partnerships[11] to develop and deploy cislunar infrastructure. The private sector, including both space and non-space companies, is participating in exploration and development of cislunar space.[12] The U.S. Space Force, Space Development Agency, Air Force Research Laboratory, and Defense Advanced Research Projects Agency are advancing space capabilities to protect interests and assets of U.S. civil government and commercial space endeavors. And finally, based on technical exchange meetings with government and commercial organizations, information provided by participants paints a picture of an impressive portfolio of investments in cislunar capabilities.[13]

A Framework for Coordinated Cislunar Infrastructure Investments

Given the diversity and number of U.S. and international service providers, there is potential for a long-term sustainable cislunar ecosystem. However, the current approach to establishing the cislunar frontier is decentralized. Activities in the region lack a unifying, integrated framework. While a sustainable ecosystem is aspirational at this point, there are currently U.S.-affiliated investments in 11 layers of physical cislunar infrastructure, as shown in Figure 2. As of June 2022, more than 60 companies and 10 U.S. government organizations are investing, developing, and planning to deploy one or more foundational layers.

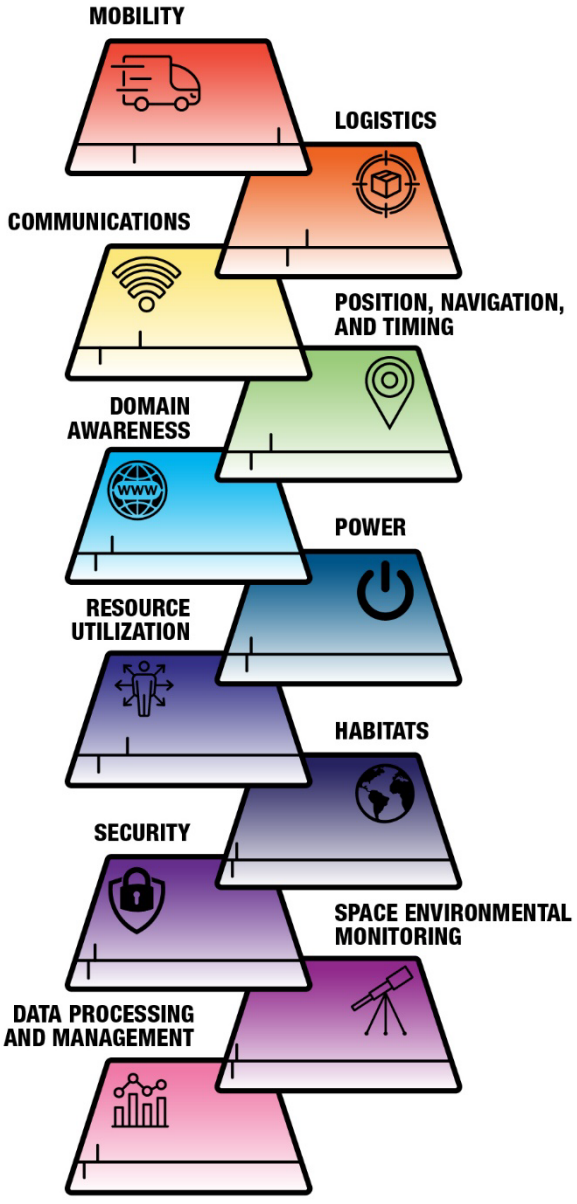

Figure 2: Foundational layers of infrastructure for a sustainable cislunar ecosystem.

Current stakeholders of federal agencies, commercial providers (space and non-space), and international partners may not know what others are developing or how their systems or services might fit within an overarching cislunar ecosystem. This lack of coordinated domestic or international planning leads to unique or isolated systems not designed to interact universally across the full ecosystem. Redundant efforts create inefficiencies that waste time and treasure. Systems of systems interoperability and harmonious coexistence will be unlikely without domestic and international coordination of infrastructure development.

The region offers an opportunity for symbiosis, a characteristic of ecosystems, through mutual relationships to benefit stakeholders. By identifying key areas essential to meet scientific, security, and commercial interests, infrastructure investments can be synchronized to maximize impact and ensure the likelihood that the community's interests are met. Establishing a unified, integrated framework for cislunar ecosystem development addresses a goal of the National Space Policy to "extend human economic activity into deep space by establishing a permanent human presence on the Moon, and, in cooperation with private industry and international partners, develop infrastructure and services that will enable science-driven exploration, space resource utilization, and human missions to Mars."[14]

Analog to Urban and Industrial Park Development Planning

Government involvement in establishing infrastructure has triggered giant leaps in the past. The cislunar region is no different. Infrastructure planning on the lunar surface and in cislunar space reminds us of visioning and planning here on Earth for urban areas and industrial parks. Industrial parks are generally a centralized collection of independent companies sharing infrastructure with no direct business connection or interaction with each other.[15] In the case of a terrestrial industrial park, each company needs access to utilities and civic services such as transportation corridors, communications, waste management, fire and emergency services, and power. Cislunar master planning, much like urban master planning for communities on Earth, would serve the general purpose of guiding the establishment and operation of foundational infrastructure elements on the lunar surface and in space proximity. A mutually dependent group of participants and projects planning together can evolve an ecosystem along the lines of a cislunar urban or industrial park.

A "space superhighway," as shown in Figure 3, is an example of U.S. government infrastructure planning for a transportation corridor to serve as an initial space infrastructure for an interplanetary supply chain. Logistics depots on multipurpose orbiting platforms or regional hubs at strategic orbits in space could provide utilities to hosted payloads, refueling, and services, and even transportation to habitats. Initial government infrastructure investments in transportation corridors can enable commerce and other activities in the cislunar region to thrive.

Based on assessments of publicly available information, U.S. government and commercial organizations have invested on the order of $7 billion to $10 billion in 2022 in cislunar infrastructure. Current projections indicate that critical thresholds of capability associated with multiple layers of infrastructure will be in place by 2028. A domestic U.S. master planning process can coordinate development of infrastructure layers, providing convenient and efficient services to all tenants. With a whole-of-nation approach, decisionmakers, investors, and developers can periodically review the master plan and identify new needs, redefine the sequence of development efforts, continuously assess roles and responsibilities, and set the pace, contributing to a sustainable cislunar ecosystem for the benefit of humanity (see Figure 4). International partners and like-minded

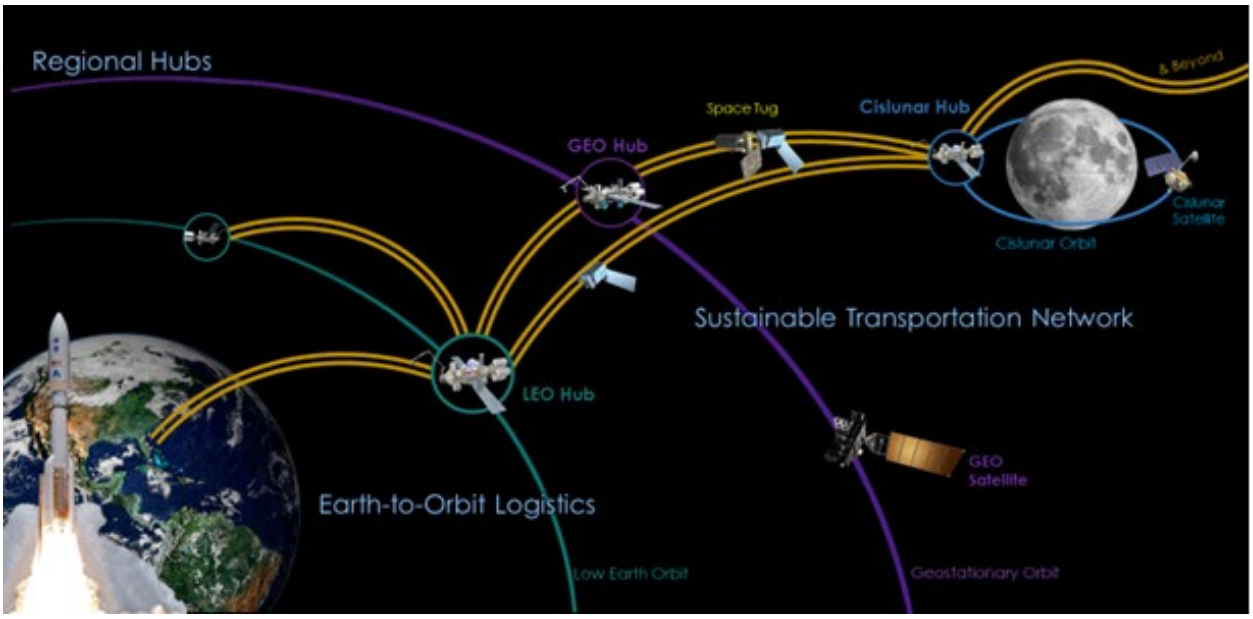

Figure 3: Cislunar superhighway. (Credit: NASA)

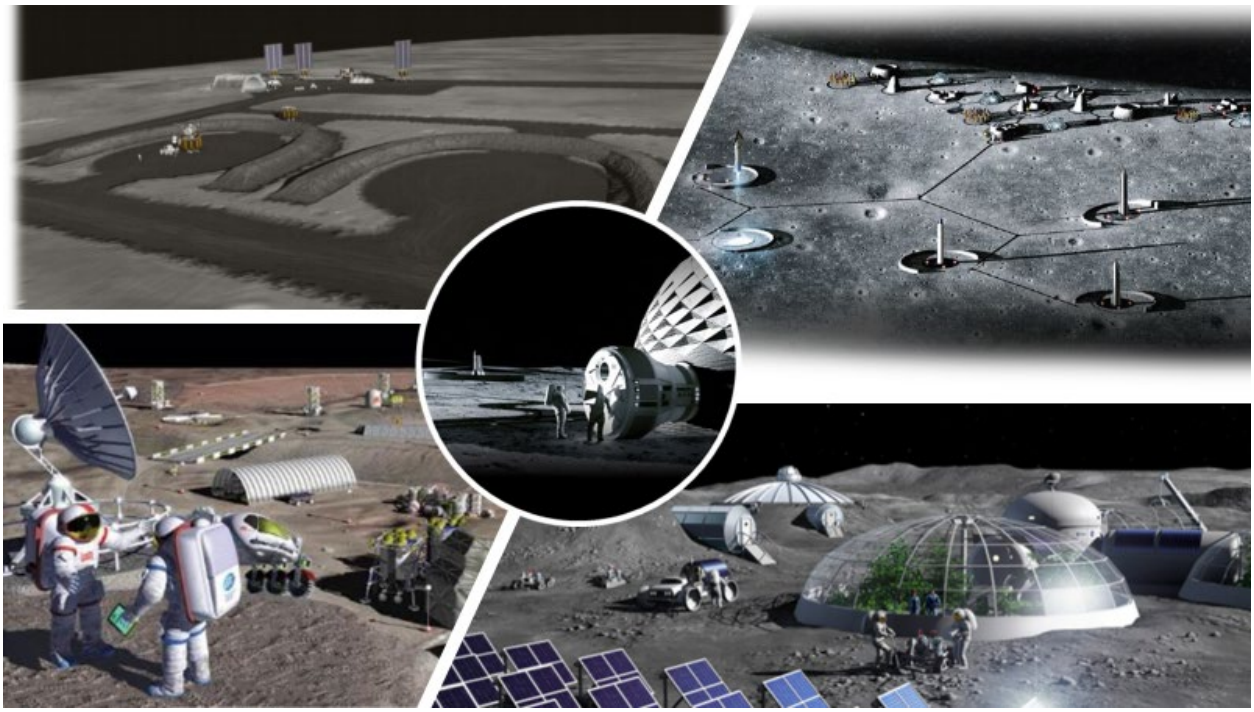

Figure 4: Future concept of cislunar ecosystem (Credit: NASA)

nations can be brought into the master planning process as appropriate. While not a perfect analogy, cislunar master planning leaders can use lessons learned from decades of urban planning and industrial park development on Earth to inform development on the moon.

Alternatives for Planning

There are five options for cislunar master planning:

- **Option 1 – No Planning:** Neither the United States nor any other entity formally conducts any disciplined, structured planning of cislunar development.
- **Option 2 – Precedence-based Planning:** First-to-market solutions drive subsequent plans.
- **Option 3 – U.S. Stakeholder Planning:** U.S. government and commercial stakeholders formally conduct disciplined, structured planning.
- **Option 4 – United States and Like-Minded Nation Stakeholder Planning:** The United States and like-minded nations stakeholder organizations formally conducting disciplined, structured planning.
- **Option 5 – Peer Competitor Nation-led Planning:** Peer competitor(s) (e.g., China and/or Russia) conduct structured planning.

The current state is between Option 1, "No Planning," and Option 2, "Precedence-based Planning." Option 3 and Option 4 are more aligned with U.S. national interests than the other alternatives. Option 3, "U.S. Stakeholder Planning," can develop approaches focused on protecting U.S. national interests conducive for the U.S. commercial space industry. A government and commercial partnership will help both industry and the U.S. government attain their goals. As stated in the recent NASA Aerospace Safety Advisory Panel (ASAP) report, "[w]hile private industry efforts are an ever more important factor in the U.S. government's future endeavors, the commercial sector alone has not, and will not, be the vehicle that drives national goals."[16] Option 4, "United States and Like-Minded Nation Stakeholder Planning," opens participation in the domestic U.S. cislunar master planning process to international partners and would be an incremental step after Option 3 has been implemented.

Consistent with direction to "plan, direct, and conduct aeronautical and space activities" outlined in the NASA Act of 1958,[17] the United States can leverage NASA's relationships with commercial and international partners to facilitate cislunar master planning. NASA, by national policy, is the "first among equals" to bring national and international interests together. NASA precedence in this role includes developing and leading the international Artemis Accords, signed initially in October 2020. As of May 2022, the Artemis Accords, signed by more than 19 countries with additional nations joining, describes "a shared vision for principles, grounded in the Outer Space Treaty of 1967, to create a safe and transparent environment which facilitates exploration, science, and commercial activities for all of humanity to enjoy."[2] NASA also facilitated the establishment of Lunar Historic Sites Protection Recommendations signed into law on December 31, 2020, to protect heritage sites on the moon, such as the Apollo landing sites.[18] The Historic Sites Protection Recommendations require both domestic and international agencies issuing licenses for conducting lunar activities to require applicants to agree to abide by recommendations in the original NASA 2011 Lunar Historic Sites Preservation report. In addition, NASA was instrumental in developing, along with its International Space Exploration Coordination Group (ISECG) partners, the Global Exploration Roadmap reflecting the cooperation needed to realize individual and

common goals and the growing global spirit of space exploration.[19] NASA's founding charter and decades of experience make it reasonable to assume that NASA would play an important role in Option 3 and Option 4 implementation.

Given the long history of international cooperation and partnerships in space exploration, science, and other space activities, with the International Space Station as an example, international collaboration for space activities is well established. However, a coordinated domestic cislunar master planning effort does not exist. A key first step for the United States and a key recommendation presented here is for the United States to form a domestic collaboration council comprised of U.S. government and commercial stakeholders to provide a forum to exchange information and plans. The role of a Domestic Cislunar Collaboration Council (DC3) would be to conduct coordinated planning for U.S.-based infrastructure layer development that could then be brought forward in the global planning arena.

A DC3 could implement master planning processes to promote synchronized efforts among all U.S. stakeholders investing in and building infrastructure for the cislunar ecosystem. For example, the "charette" process developed for city planning could inform infrastructure development for both individual stakeholder efforts and collective efforts.[20] Stakeholders could exchange views on key interest, objectives, and plans and raise concerns. As a reference, the American Planning Association, with 40,000 members from 90 counties, provides best practices and lessons learned for community planning that also may inform the broader global planning effort.

Areas for Further Investigation

Development of cislunar space is a rich topic with many facets. While a collaboration council is a key component to ensure a coordinated, interoperable, sustainable ecosystem, there are several other considerations not discussed in this paper. This paper is a call to action to establish a domestic cislunar master planning process, evolving to include international stakeholder participation, and is one of a series of planned papers on related topics. Key topics such as specific policies, interoperability specifications, technical standards, acquisition approaches, and logistics and supply chain management need to be further explored and defined to help realize a vision of a sustainable cislunar ecosystem and economy in a timely and efficient manner.[21]

Conclusion: The Clock Is Ticking

We have entered a new space race: a race against time. Many U.S. private sector companies and other spacefaring nations have their sights set on cislunar space. Organizations are making investments and developing systems that may not be interoperable or mutually beneficial. Terrestrial experience shows sustainable development for urban and industrial ecosystems and economies requires coordinated master planning.[22] The waterfall of NASA commercial service acquisitions in the 2020s time frame informs the imperative to act now. Our primary recommendation is to establish a U.S. stakeholder cislunar master planning effort that will evolve to include international partners and like-minded nation stakeholders. This initiative would strengthen America's leadership in space. The planning process would be informed by, and inform, the independent designs and solutions of systems and capabilities of diverse providers. An intent is to mitigate inefficiencies and risks of stakeholders operating in isolation.

The U.S. government has a legacy of leading exploration and settlement of new frontiers and should continue this legacy for the cislunar frontier. To facilitate master planning, a U.S.-based organization, such as a Domestic Cislunar

Coordination Council (DC3), informed by NASA's experience, could work with U.S. public and private stakeholders across the space enterprise, establishing a common vision and roadmap for ***exploration, commercial development, and settlement***. The DC3, or whatever entity emerges, would be structured to allow international partners and like-minded nation participation. Recognizing the value of cislunar master planning now will help the United States maintain leadership in the peaceful use of outer space and deliver strategic benefits not only for the United States, but for all like-minded nations who share our values of liberty, democracy, the rule of law, and free market economic principles. With the current excitement across the private sector investing in cislunar space, it is time to seize the opportunity. The opportunity time frame is shrinking. If the United States doesn't take the lead now, someone else will.

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Appendix:
NASA's Acquisition Evolution Toward Commercial Services

The U.S. government has a legacy of enabling exploration and expansion through investments in trailblazing missions, fostering entrepreneurship, and encouraging federal agencies to procure space commercial services where possible in place of government-owned and -operated systems. The NASA Space Act of 1958, Section 203, calls on the agency to "(1) plan, direct, and conduct aeronautical and space activities" and "(4) seek and encourage, to the maximum extent possible, the fullest commercial use of space." Subsequently, the Commercial Space Launch Act of 1984[23] and the Launch Services Purchase Act of 1990[24] were enacted by Congress, which further emphasized direction for NASA to purchase commercial services where practical. Commercial interest and confidence in developing a space industry has grown as result. The trend toward encouraging U.S. government organizations to procure commercial services[25] continued with the Commercial Space Act of 1998, which contained direction to "purchase space science data from a commercial provider to the extent possible."[26] Commercial sources of remote sensing data, from companies such as Digital Globe, are widely available today.

The trend toward governments procuring commercial services continued with President George W. Bush's Vision for Space Exploration in 2004,[27] directing NASA to retire the space shuttle safely and return humans to the moon. A key inflection point for expanded acquisitions of commercial services started with Public Law 109-354: NASA Authorization Act of 2005.[28] Section 108 of the act requires the administrator to "develop a commercialization plan to support the human missions to the Moon and Mars, to support low-Earth orbit activities and Earth science missions and applications, and to transfer science research and technology to society." Additionally, the act states that such plan "shall also emphasize the utilization by NASA of advancements made by the private sector in space launch and orbital hardware, and shall include opportunities for innovative collaborations between NASA and the private sector…."

Over the nearly two decades since the enactment of the 2005 NASA Authorization Act, NASA's acquisition approach for human spaceflight programs steadily evolved from the legacy approach used in the Apollo and space shuttle programs. On those inaugural space programs, NASA was the overall system designer and integrator using Federal Acquisition Regulations (FAR) Part 15 acquisitions of bespoke systems tailored for their exploration missions. NASA is steadily engaging more and more with commercial and international organizations for turnkey services. NASA acquisition approaches include using Other Transactional Authority (OTA) such as space act agreements (SAA), acquiring services using FAR Part 37 acquisitions, and international partnerships. The International Space Station (ISS) is a prime example of NASA nurturing international partnerships to provide specific transportation systems and station elements to share overall development costs and benefits. NASA engaged with the European Space Agency (ESA) in a barter deal to provide the Orion Exploration Service Module and, more recently, to provide the ESPRIT refueling and communication element for the Artemis Program's Lunar Gateway.

Multiple NASA programs encourage a commercial space market to bring down the barriers of access to

space. The Commercial Crew and Cargo Program was established in November 2005 to partner with industry and procure services to mitigate the capability gap after the space shuttle retirement. The Commercial Orbital Transportation Services (COTS) project, initiated in 2006, awarded space act agreements with three providers to develop and demonstrate a cargo transportation capability to the ISS. Toward the end of the development program, the landscape dropped to two providers: SpaceX and Orbital Sciences. NASA successfully realized the commercial off-the-shelf (COTS) mission with SpaceX's first cargo delivery flight in October 2012 and Orbital Sciences first cargo delivery in January 2014 under the Commercial Resupply Services contract, a follow-on to the COTS development. In total, NASA spent $715 million[29] for the COTS development effort for two ISS cargo transportation capabilities, sharing cost and risk of development programs with the private sector. In 2011, NASA established the Commercial Crew Program (CCP), which consisted of three phased acquisitions[30] to develop and demonstrate commercial crew transportation to ISS. NASA again achieved a goal of leveraging commercial investment to procure services with SpaceX's first crew launch as a service to ISS in December 2020.

NASA is leveraging the commercial investment and interest in a lunar economy in response to administration direction and out of the necessity to do more within budget constraints. Artemis capability acquisitions over the past few years have been predominantly for commercial services. The Commercial Lunar Payload Services (CLPS), Human Landing Systems (HLS), Exploration Suit Services, Gateway Logistics Services, Power and Propulsion Element (PPE), and the Near Space Network (NSN) Communications and Navigation Services are all examples of NASA procuring services to address its mission needs to explore cislunar space. Figure A-1 provides a historical view of the commercial acquisition trend for NASA Artemis programs for cislunar exploration.

The landscape of private companies investing in the moon evolved significantly in 2018 when NASA's Commercial Lunar Payload Services (CLPS) Program selected 14 U.S. companies to deliver science and technology to the lunar surface. The 14 providers eligible to bid on NASA delivery services to the lunar surface are:

1. Astrobotic Technology, Inc. (Pittsburgh, Pennsylvania)
2. Deep Space Systems (Littleton, Colorado)
3. Draper (Cambridge, Massachusetts)
4. Firefly Aerospace, Inc. (Cedar Park, Texas)
5. Intuitive Machines, LLC (Houston, Texas)
6. Lockheed Martin Space (Littleton, Colorado)
7. Masten Space Systems, Inc. (Mojave, California)
8. Moon Express (Cape Canaveral, Florida)
9. Orbit Beyond (Edison, New Jersey)
10. Blue Origin (Kent, Washington)
11. Ceres Robotics (Palo Alto, California)
12. Sierra Nevada Corporation (Louisville, Colorado)
13. SpaceX (Hawthorne, California)
14. Tyvak Nano-Satellite Systems Inc. (Irvine, California)

This CLPS portfolio greatly expanded the field beyond traditional "Big Space" players with new companies of varying sizes and maturity. One such company, Astrobotic, which was founded by a Carnegie Mellon professor in 2007 with the goal of winning the Google Lunar X Prize, successfully

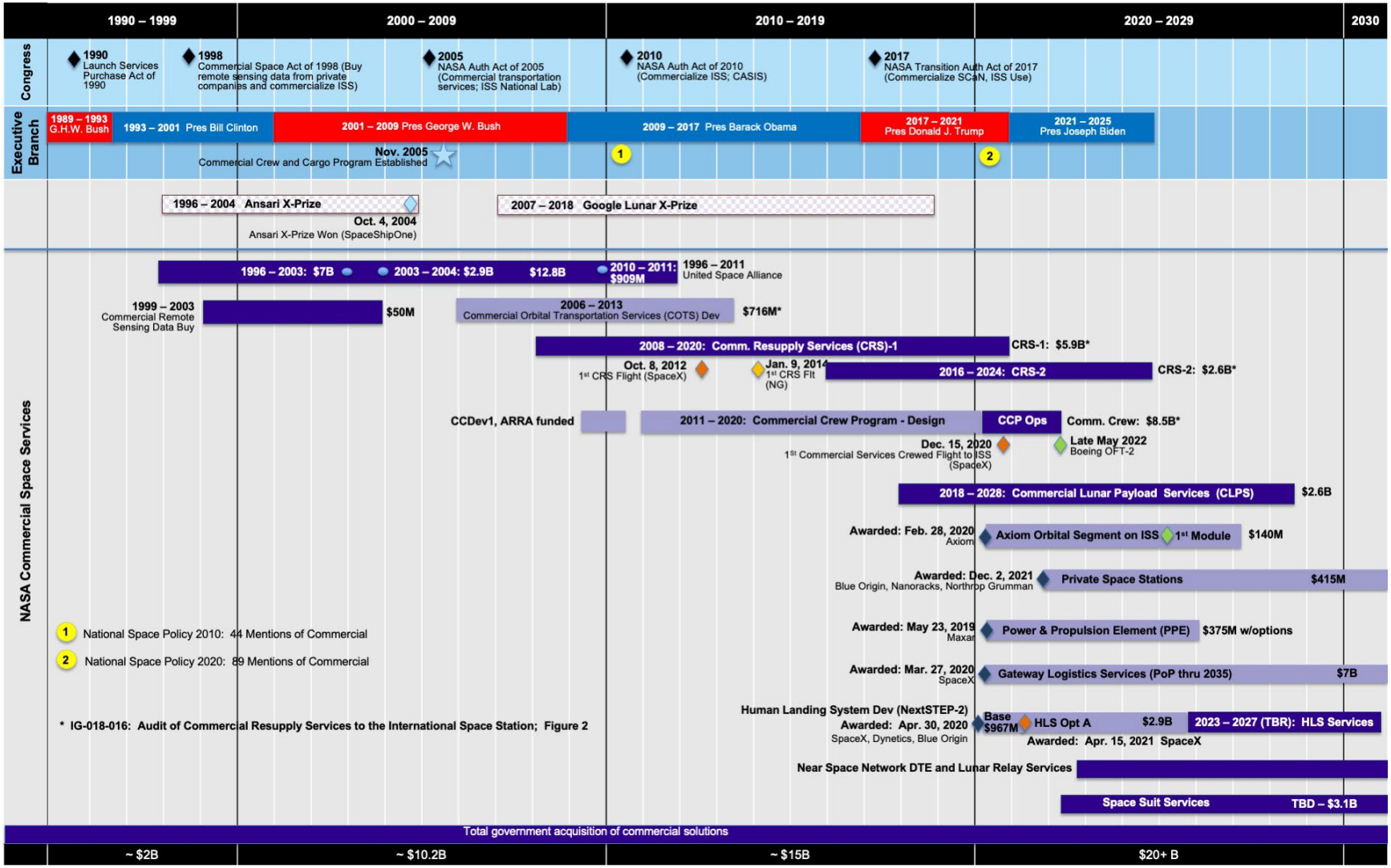

Figure A-1: Historical view of NASA commercial space acquisitions for exploration.

won a contract via the CLPS program. Another CLPS provider was founded in 2014 as a startup by a small group of entrepreneurs who self-funded the company. Firefly Space Systems (becoming Firefly Aerospace in 2017) now has a contract with NASA to deliver a suite of 10 science investigations and technology demonstrations to the moon in 2023. Using this type of services acquisition drives innovation and reduces costs to NASA and American taxpayers.

References

[1] For the purposes of this paper, the term *commercial* is described in terms of private sector enterprise bearing a reasonable portion of investment risk and responsibility for a product or service in contrast with bespoke solutions driven by government investments developed by contractors.

[2] NASA Artemis Accords, October 30, 2021, https://www.nasa.gov/specials/artemis-accords/img/Artemis-Accords-signed-13Oct2020.pdf

[3] *SpaceNews*; Op-ed | Securing cislunar space: A vision for U.S. leadership; November 9, 2020.

[4] A Primer on Cislunar Space, AFRL 2021-1271, May 2021, M.J. Holzinger, C.C. Chow, P. Garretson, https://www.afrl.af.mil/Portals/90/Documents/RV/A%20Primer%20on%20Cislunar%20Space_Dist%20A_PA2021-1271.pdf?ver=vs6e0sE4PuJ51QC-15DEfg%3d%3d

[5] G. E. Pollock IV and J. A. Vedda, *Cislunar Stewardship: Planning for Sustainability and International Cooperation*, June 2020, The Aerospace Corporation, https://csps.aerospace.org/papers/cislunar-stewardship-planning-sustainability-and-international-cooperation

[6] History of Palmer Station, https://antarcticsun.usap.gov/features/2130/# Palmer Station Master Plan 1.0, January 18, 2016, https://future.usap.gov/PalmerMasterPlan.pdf

[7] Henceforth, in this paper the term *sustainable* means self-sufficient, self-sustaining, self-supporting. This is a broader definition than used in the narrower environmental protection context.

[8] J. P. Byrne, R. Dickey, and M. P. Gleason, *The Space Policy Primer: Key Concepts, Issues and Actors*, Second Edition, The Aerospace Corporation, January 2021, https://csps.aerospace.org/sites/default/files/2021-08/Gleason-Dickey_SpacePrimer2_20210118_2.pdf

[9] "Investment in space companies hit record $14.5 billion in 2021, report says," January 18, 2022; Investing in Space; Michael Sheetz; https://www.cnbc.com/2022/01/18/space-investing-q4-report-companies-hit-record-14point5-billion-in-2021.html

[10] "Lunar market assessment: market trends and challenges in the development of a lunar economy PWC – September 2021; https://www.pwc.com.au/industry/space-industry/lunar-market-assessment-2021.pdf

[11] K. L. Jones, *Public-Private Partnerships in Space*, The Aerospace Corporation, April 2018, https://csps.aerospace.org/papers/public-private-partnerships-space

[12] State of the Space Industrial Base 2021, November 2021, J. Olson, S. Butow, E. Felt, T. Cooley, J. Mozier, edited by Peter Garretson, https://assets.ctfassets.net/3nanhbfkr0pc/43TeQTAmdYrym5DTDrhjd3/1218bd749befdde511ac2c900db3a43b/Space_Industrial_Base_Workshop_2021_Summary_Report_-_Final_15_Nov_2021.pdf

[13] "Enabling the Future Cislunar Space Enterprise" Technical Exchange Meeting, The Aerospace Corporation, May 24, 2021

[14] National Space Policy, 2020, https://www.space.commerce.gov/policy/national-space-policy/#:~:text=The%20National%20Space%20Policy%20sets%20out%20the%20nation%E2%80%99s,defending%20United%20States%20and%20allied%20interests%20in%20space.

[15] Handbook on Planning Sustainable Industrial Parks, German Development Corporation, 2015, http://seip.urban-industrial.in/live/hrdpmp/hrdpmaster/igep/content/e62771/e63552/e66395/e66503/e66637/20170330_ParticipanthandbookPlanningofSustainableIndustrialParks.pdf

[16] Aerospace Safety Advisory Panel Report, January 2022, https://oiir.hq.nasa.gov/asap/documents/2021_ASAP_Report-TAGGED.pdf

[17] NASA Space Act of 1958 – Section 3 (5) encourage and provide for Federal Government use of commercially provided space services and hardware, consistent with the requirements of the Federal Government

[18] NASA's Recommendations to Space Faring Entities, July 20, 2011, https://www.nasa.gov/pdf/617743main_NASA-USG_LUNAR_HISTORIC_SITES_RevA-508.pdf

[19] Global Exploration Roadmap, 2020, https://www.nasa.gov/sites/default/files/files/GER-2013_Small.pdf

[20] A charette is an example of a master planning approach. A charette is defined as a meeting in which all stakeholders in a project attempt to resolve conflicts and map solutions

[21] Combine the four deleted references below, into one end note here.

[22] The term *sustainable* for the purposes of this paper is defined as meeting the needs of the ecosystem from a resources and economic perspective to ensure longevity.

[23] P.L. 98-575, Commercial Space Launch Act.

[24] P.L. 101-611, Launch Services Purchase Act of 1990.

[25] The term *commercial* is defined in U.S. National Space Policy as "a private sector enterprise, bearing a reasonable portion of the investment risk and responsibility for a product or service."

[26] Section 101: P.L. 105-303, Commercial Space Act of 1998

[27] Vision for Space Exploration

[28] Section 108: P.L. 109-354: NASA Authorization Act of 2005

[29] IG-018-016: Audit of Commercial Resupply Services to the International Space Station; Figure 2.

[30] The 3 phases of acquisitions are (1) Commercial Crew Development (CCDev), (2) Commercial Crew Initial Capability (CCiCap), and (3) Commercial Crew Transportation Capability (CCtCap).