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CISLUNAR DEVELOPMENT: WHAT TO BUILD—AND WHY

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Abstract

The current administration is seeking ways to facilitate and accelerate the evolution of space commerce. At the same time, the administration plans to pursue ambitious human exploration activities beyond low Earth orbit. Both of these objectives include a key role for infrastructure in cislunar space. The administration can serve both objectives through a concerted cislunar development program. Efforts are underway in areas such as space transportation and human habitats, but a sustainable, comprehensive space infrastructure requires much more. This paper highlights some proposed development scenarios and examines the components needed to form a coherent long-term strategy that delivers permanent, sustainable, purposeful, value-generating space activity.

Springboard to the Solar System

In a 2006 speech, John Marburger, the science advisor to President George W. Bush, addressed the long-term rationale for spaceflight by saying that it boils down to "whether we want to incorporate the solar system in our economic sphere, or not… At least for now, the question has been decided in the affirmative."[1] Since that statement, slow but steady progress has been made across three presidential administrations, including the realization that multipurpose infrastructure in cislunar space[2] is a prerequisite for ambitious long-term scenarios of space exploration and development.

In December 2017, a memo from President Trump (referred to as Space Policy Directive 1) changed one paragraph in the 2010 National Space Policy, directing U.S. government agencies (particularly NASA) to

> 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.[3]

Meanwhile, the administration's revived National Space Council was devoting much of its effort to promoting and accelerating U.S. space commerce. The commercial sector has been linked for many years to the nation's exploration ambitions; its role in "incorporating the solar system into our economic sphere" has yet to be fully defined, but its highest value proposition may be development of multipurpose cislunar infrastructure in advance of the interplanetary journeys that may follow. The Trump administration and subsequent U.S. leadership may determine that the best way to achieve human expansion into space while building a space economy is by focusing on cislunar development through a combination of government programs and industry partnerships.

Space efforts spanning more than a half-century have shown that large capital outlays, long development cycles, high technical risk, and potentially unstable long-term funding commitments can be expected in such endeavors. But as with large terrestrial projects, the resources invested in space infrastructure pave the way for a multitude of missions that can use it to satisfy critical needs such as transportation, communications, energy, water, and waste management.

All space sectors—civil, commercial, and national security—share common needs for space infrastructure that will serve their missions and allow them to loosen, or even sever, the lifeline that has so far kept them dependent on Earth for all operations and support functions. The long-term reliability of that lifeline comes into question if it can offer little or no hands-on support to space systems needing attention at locations far from Earth.

Resources invested in space infrastructure pave the way for a multitude of missions…

Visions for cislunar development have been proposed by public and private stakeholders in spacefaring countries. None are comprehensive; typically, projected scenarios focus on a small subset of components needed to accomplish a particular function, such as space transportation or human habitats. There is healthy competition among solutions to some critical needs, but others receive less attention, and so far, no credible, widely accepted architecture has emerged. This indicates a need to take a step back in the planning process: before we start bending metal for an uncoordinated assortment of infrastructure elements, we need to agree on a set of common goals and objectives. Although this has been pursued internationally for many years, consensus remains elusive.

Planners understand that space infrastructure projects should be designed for broad applicability, beyond a single mission or short-term series of missions for a single agency, or even a single country (in contrast to the Apollo paradigm). However, more needs to be done to reach agreement on what the development of cislunar space should seek to achieve and what steps need to be taken, in what order, and at what pace.

A Few Examples

Cislunar activity in the next generation and beyond will be both human and robotic, government and nongovernment. For the moment, the precise mix of humans and robots, and their particular affiliation, is less important than the aggregate value derived from enterprises in cislunar space for security, the economy, scientific research, and international relations. There is no shortage of ideas, but there is insufficient agreement on steps—and funding mechanisms—leading to a comprehensive, value-generating space architecture that would allow us to "incorporate the solar system in our economic sphere." Some recent and intriguing ideas include:

- **NASA's Lunar Orbital Platform—Gateway.** Formerly Deep Space Gateway, this project envisions a crew-tended spaceport in lunar orbit for staging missions to the lunar surface and deep space. Gateway would consist of a small habitat, a power and propulsion bus, a docking system, and an airlock. Serviced by logistics modules, it could accommodate research activities as well as crews in transit.[4] Essentially, this is a smaller version of the International Space Station placed at a more distant location, and should be able to take advantage of many technical and operational lessons learned from that program.

  Gateway is one of the systems NASA hopes to build and test as it prepares for missions beyond cislunar space, particularly Mars. The deep-space environment around the moon provides a testbed for human missions headed elsewhere in the solar system. For these early building-block missions, Earth is conveniently located just days away, rather than weeks or months. The Gateway concept was associated with NASA's cislunar plans for more than a year before it was first incorporated in the president's budget request in February 2018.[5] If it is funded by Congress and brought to fruition, it will be a key element of early cislunar architecture, one piece of a much larger effort.
- **European Space Agency (ESA) Moon Village.** Johann-Dietrich Woerner, Director General of ESA and leading spokesman for the Moon Village concept, explains that the term "village" in this context does not mean "a development planned around houses, some shops, and a community center." Rather, it is "a community created when groups join forces without

first sorting out every detail, instead simply coming together with a view to sharing interests and capabilities." So far, it is "neither a project nor a program."[6]

Participation in the Moon Village may take the form of robotic or human activities in scientific research, technological development, and even tourism. Activities could include placement of a radio-telescope on the far side of the moon, where interference from Earth transmissions would be blocked; experimentation with new technologies, such as in-situ manufacturing; exploitation of lunar resources; and creation of a base for testing and deploying human spaceflight systems aimed at destinations elsewhere in the solar system.

ESA has begun discussions with China regarding collaboration on the Moon Village concept.[7] This could have implications for U.S. participation in the project if it comes to fruition.

- **Space Resources Luxembourg.**[8] This is an industrial policy rather than a strategic plan for the development of cislunar space. It sets an example for other countries that are willing to take a chance on the future of a space economy by presenting a friendly political and regulatory climate. By opening its doors to space mining and resource utilization companies, "Luxembourg provides a unique legal, regulatory, and business environment enabling private investors and companies to explore and use space resources…. Luxembourg aims to play a leading role in the exploration and utilization of these resources." The country recently enacted legislation granting property rights to extracted resources from celestial bodies.[9]
- **ULA Cislunar-1000.**[10] United Launch Alliance, the most experienced U.S. launch provider, has a long-term vision for cislunar activity, based on its own transportation technology currently in development. "Thirty years from now, 1,000 people could be living and working in the space around Earth and the moon—waking up in commercial habitats, prospecting on the moon, and even harnessing power from solar power satellites for consumption on Earth." ULA believes that "the technology for a cislunar transportation system will exist early in the next decade." ULA has recognized that "there is some economic incentive to spur the creation of the first elements of infrastructure needed for a self-sustaining cislunar economy." The company expects this incentive to show results in the near term: "Developments of commercial industries in space are quickly demanding more than the ISS can provide. This includes frequent (months or better) access, return of goods, production facilities and the ability to work with dirty and risky processes. New facilities designed to support commercial activities in space are needed."
- **Space Industrialization.**[11] Blue Origin founder Jeff Bezos believes that "over the next few hundred years, we need to move our heavy industry off-planet. Our Earth will be zoned residential and light industrial." But he is not simply dreaming about something that may happen long after he is gone. "I'm using my resources to put in place heavy-lifting infrastructure so the next generation of people can have a dynamic, entrepreneurial explosion into space. I want thousands of entrepreneurs doing amazing things in space."
- **Cislunar Space Next.**[12] For many years, lunar scientist Paul Spudis has advocated a high priority for exploration of the moon and exploitation of its resources. "The real debate is not about launch vehicles or spacecraft or even destinations; it is about the long-term purpose of our space program…. A cost-effective, sustainable human spaceflight program must be continuous, incremental, and cumulative. Our space program must continually expand our reach, creating new capabilities over time. Moreover, it should contribute to compelling national economic, scientific, and security interests."[13]
- **On-Orbit Servicing.** In early 2016, Orbital ATK signed Intelsat as the first customer for its on-orbit servicing program,[14] which will extend the life of aging satellites by attaching a module to replace their propulsion systems. On-orbit repairs are also contemplated. The president of the Space Logistics LLC subsidiary, which is responsible for this effort, says the company believes "there's a real market for space logistics." The first mission for Intelsat is scheduled for 2019, and a second is planned for 2020. (Orbital ATK is active in another area related to cislunar development: the company received an award in NASA's NextSTEP program to study the design of a cislunar habitat derived from its Cygnus spacecraft.[15]) A competitor, the Space Infrastructure

Services division of Maxar Technologies, has a contract with communications satellite operator SES to perform on-orbit refueling to extend the life of a satellite in a mission scheduled for 2021.[16]

- **Global Exploration Roadmap.** The most inclusive effort leading to a cislunar architecture is being undertaken by the International Space Exploration Coordination Group (ISECG), a coalition that includes NASA, ESA, and the civil space agencies of Australia, Canada, China, France, Germany, India, Italy, Japan, Russia, South Korea, Ukraine, and the United Kingdom. ISECG has its roots in a 2007 collaboration called "The Global Exploration Strategy: Framework for Coordination."[17] The group released its first Global Exploration Roadmap in September 2011,[18] with updates in August 2013[19] and January 2018.[20] The Global Exploration Roadmap is an evolving effort to apply collective wisdom to a reasonably comprehensive vision. As civil space agencies, the ISECG members are keen on advancing science projects and human spaceflight programs. As a result, the primary emphasis is on development of space transportation architecture and human habitation systems. But they also recognize the importance of other aspects of space architecture: capabilities and infrastructure for off-Earth operations, research on planetary defense, orbital debris management, and the role of commercial entities as they create new markets that bring benefits to all humankind. Inspiring the public is also a priority.

  The ISECG approach to the Global Exploration Roadmap appears to be a welcome recognition that exploration and development go hand-in-hand; that robust, versatile, and sustainable space infrastructure must be built; and that benefits to Earth, through new markets and solutions to global problems, must be produced to justify the investment. To realize their long-term goals, all participants will need to contribute brainpower, work, and funding. Government risk-sharing and other incentives are needed to bring in private-sector contributors along with the individual and collective efforts of nations.

  Despite some refreshing words about capabilities-driven planning, however, the Global Exploration Roadmap still has the trappings of a destination-driven strategy.[21] As it has been structured so far, all roads lead to Mars, which is referred to as the "horizon" goal. This narrowing of the parameters of space exploration and development—real or perceived—carries the risk that the endeavor could be seen as an expensive prestige activity, an elaborate series of scientific field trips, or otherwise lacking long-term societal value.

Long-Term Expectations

Between now and mid-century, some predictions are a safe bet. Geosynchronous equatorial orbit will continue to be valuable. The number of operational satellites in Earth orbit, the number of different space operators, and the quantity of orbital debris all will increase. There will be a greater variety of marketable space applications, going beyond communications, navigation, and remote sensing. The forecast through 2050 gets murkier if we try to estimate the exact amount of growth in these areas, the balance between human and robotic activity, and the relative proportions of governmental and nongovernmental activity. We are compelled to rely on the safest answer to such questions: it depends.

In addition to today's familiar applications, the cislunar work environment of tomorrow may include activities for which the moon is a hub of activity. This would naturally follow from:

- one or more scientific research outposts on the moon, especially if they are populated all or most of the time;
- the extraction, processing, and use of extraterrestrial resources, primarily from the moon at first but eventually from asteroids as well;
- the use of the moon and lunar orbit as training ground and staging points for deep-space missions;
- demand for propellant storage depots in various cislunar locations (e.g., to fuel on-orbit servicing vehicles or deep-space missions) using propellants derived from lunar ice deposits;
- employment of large multipurpose orbiting platforms that would benefit from the use of lunar materials in their construction or resupply (e.g., solar power satellites, lab/manufacturing/habitat "industrial parks").

All of these drivers are accompanied by variables that affect the amount and type of traffic in cislunar space. For example:

- How many people will be needed on orbit to support this activity, and how frequently will they rotate back to Earth? This will be dependent on the evolving state of the art in life-support systems and in robotics and human-machine interfaces. Cislunar space is small enough to permit extensive use of teleoperations.
- What solutions will be employed to mitigate the cost of access to orbit? Small numbers of large, partially reusable boosters? Larger numbers of small reusable boosters? Some of both? What will be the mix of single-mission vs. multi-mission launches?
- Will there be any geopolitical obstacles to cooperation among cislunar spacefarers? Which spacefaring entities will be friends and allies, and which will be potential adversaries? How much will the entities involved attempt to conduct in-space surveillance of each other? Will terrestrial conflict prompt decision-makers to consider disruption, destruction, or hostage-taking of cislunar operations?

It is reasonable to project that in the next 20 to 30 years, global efforts in cislunar space will aim to:

- use the unique characteristics of space—such as microgravity, vacuum, high-intensity solar exposure, and isolation from Earth—to produce useful knowledge and products;
- harvest and process extraterrestrial materials and energy resources;
- build sophisticated structures in Earth orbit and in the vicinity of the moon;
- build installations on the moon, constructed to the greatest extent possible with local materials.

Success in these endeavors could produce the following results by mid-century:

- construction and operation of advanced structures that minimize their dependence on supply lines from Earth;
- aggregation of space structures into industrial parks at locations deemed valuable for their proximity to space resources, relatively stable gravitational points ("Lagrange" or "libration" points), or other attributes;
- realization of significant contributions to the terrestrial economy (through raw materials, energy, and manufactured products for use in space and on Earth) and security (through more comprehensive and accurate space surveillance and better intelligence gathering).
- Improvements in stewardship of the Earth regarding both its environment/ecosystem and planetary defense against impact threats.

Multipurpose Space Infrastructure

The rockets and spacecraft for carrying people and cargo from Earth to cislunar space are perhaps the most visible and familiar parts of a potential cislunar infrastructure. They are, however, just part of the picture. The segments of a hypothetical system that will serve all cislunar operators—the utilities that will make the system work—include a number of diverse functions and capabilities, such as:[22]

- **Inter-orbital transportation.** In the coming decades, in-space transportation could have a renaissance comparable to the experience of automobiles, ships, and aircraft in the 20th century. This will produce a wide variety of craft that are sized and specialized for particular tasks. Just as terrestrial vehicles come in an assortment of shapes and sizes, so will future space vehicles that travel between low Earth orbit, geosynchronous orbit, lunar orbit, and Lagrange points. With the ability to change orbital planes and altitudes, they will drop off and retrieve many kinds of payloads and will carry robots and humans to locations where they are needed.
- **On-orbit servicing.** If we are serious about living and working in space for the long haul, we are not going to discard our hardware every time it breaks down or runs out of propellant. Cislunar operators are going to learn how to refill the tank, replace the gaskets, and generally take actions to extend a system's life and upgrade its capabilities. This has to become routine, unlike the elaborate and expensive Hubble Space Telescope repair missions. As much as possible, the job should be done with automated or teleoperated robots. Demonstrating the robotics should be straightforward—satellite servicing will be done in a structured environment (human-made

devices working on each other), and teleoperation is an option throughout cislunar space. Such demonstrations already have begun at NASA and DARPA,[23] multiple private-sector developers are planning demonstrations by 2020,[24] and as noted earlier, two companies already have commercial contracts for on-orbit servicing.

- **Standardization.** If retrieval, repair, and refueling of space hardware is to occur, it will be facilitated by interoperability. Establishing industry standards and common interfaces will enable broad participation by a global community of space system developers. Multinational lunar activity also would benefit from a globally accepted lunar reference coordinate system, as well as emplacement of logistics and support services on the moon, such as emergency response resources and supply warehouses.

Manufacturers may need incentives to redesign their space hardware to be serviced by robots....

Manufacturers may need incentives to redesign their space hardware to be serviced by robots using common interfaces. This should be achievable at the current stage of development, since spacecraft and component manufacturers around the world are already employing standardization to service global markets. It should be a relatively simple matter to settle on standard grappling fixtures so that satellites can be captured safely and efficiently by service vehicles. Also needed are standard ports for fuel and other fluids, electric power, and data transfer. Replacement of old or malfunctioning parts could be done with modular components. Once these standards are in place, they can be carried over to modular assembly of large platforms. Orbiting fuel depots can be among the platforms benefitting from standardization. Just like terrestrial gas stations, all manner of space travelers should be able to pull up to the pump, interface their credit information, and neatly fit the dispenser nozzle into their own tank.

- **Fuel storage.** An internal NASA study in 2011 assessed the use of a fuel depot in low Earth orbit that would fill up the final stages of missions bound for the moon or points beyond, enabling a reduction in launch mass. This would require development of cryogenic fluid management, storage, and distribution systems. The study's rough cost estimates purported to show significant cost savings compared to using a government-developed heavy-lift rocket that carried all of its fuel at launch. Further analysis is required to determine whether the depot concept makes economic sense in the broader scheme of space development.

  Ultimately, the preferred locations for orbiting fuel depots may be beyond low orbit, and may get their fuel supplies from sources other than Earth. Their best customers may come from the inter-orbital traffic throughout cislunar space (for example, satellite servicing bots and reusable orbital transfer stages), with less-frequent visits from deep-space missions needing a fill-up on their way out.

- **Energy collection and distribution.** Cislunar operations will need power generation, storage, and distribution systems to satisfy their energy demands at widely dispersed locations. We have yet to determine the appropriate balance between solar, nuclear, and fuel-cell power sources, and which particular designs are best in each of these categories. Studies at NASA and elsewhere have suggested that a large power generation system (e.g., solar power satellites) could beam energy to orbiting platforms, lunar outposts, or the surface of the Earth. NASA and its partners have not conducted, or even initiated, a pilot project to demonstrate this capability in space, which must precede efforts to scale up to a sufficient size.

  During NASA's Constellation program, it was suggested that Earth-generated power might be transmitted to satisfy the demands of lunar operations. If such long-distance transmissions are contemplated, future testing and experience may lead to placement of generation facilities at other cislunar locations (such as Lagrange points L4 or L5) to provide power to facilities in the lunar neighborhood. Collaboration across sectors and among international partners will improve the political, technical, and economic feasibility of such a grand system.

- **Other space utilities.** If operations throughout cislunar space become routine, there will be a need for dedicated communications and navigation services like the ones we are accustomed to on and around Earth. Existing services are aimed at serving Earth, so additional systems are needed to serve other parts of cislunar space, where operators of all types will need secure, reliable, and scalable communications to support mission needs. Similarly, operators will need position, navigation, and timing capabilities like GPS. Growing cislunar operations cannot depend on research facilities like NASA's Deep Space Network to provide all that is needed.

  Another essential utility is space weather forecasting. Human crews living and working in high orbits or on the moon need timely warnings and analyses of solar activities that could have dire effects on their health and their technical systems. Ideally, they should have real-time links to the warning systems to avoid any delays in alerts relayed through Earth. Future human activities spread across cislunar space will have threat-determination and risk-mitigation needs that differ from the International Space Station, and may not have the luxury of around-the-clock monitoring by teams of technicians.

- **Extraterrestrial resources.** Another essential element of sustainable, long-term cislunar operations will be on-site resource extraction and utilization. Science fiction writers and real-world space planners at NASA and elsewhere have been talking about this for decades, but we are still at an early point in the learning curve for lunar and asteroid mining. How would terrestrial mining methods need to be modified for the task? Should materials be refined on site, or in a separate orbiting facility? What kinds of final products will benefit from these materials? Will the products only be used in space, or will they be marketable on Earth? These and other questions need answers before attempting something like what was suggested in the Constellation program: "Construct facilities and manufacture hardware, materials, and other infrastructure growth products and capabilities from lunar resources, to improve the productivity of lunar operations."

  Recent evidence suggests that large deposits of water ice exist in permanently shadowed craters near the poles of the moon. Before we set up a lunar economy based on use of that ice for water, oxygen, and rocket fuel, the deposits need to be located precisely and their extent has to be estimated more accurately. (For example, is the ice in large, contiguous blocks, or thousands of tiny deposits?) Then we need to figure out how to "mine" the ice in extremely harsh conditions using an appropriate mix of humans and machines. Once extracted, the ice must be transported to a facility for processing, to turn it into potable water or to separate the hydrogen and oxygen. All of this must be demonstrated before we can count on lunar ice as a critical element in the cislunar infrastructure. The resources and expertise to accomplish this will not come from NASA alone, but from some combination of U.S. government agencies, the private sector, and international partners.

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- **Materials processing and manufacturing in space.** Although not strictly a space utility or service, an important component of "living off the land" in space is likely to be microgravity materials processing. From the space shuttle missions of the 1980s through today's experiments on the International Space Station, there has been considerable attention devoted to attempts to discover previously hidden properties of materials, take advantage of processes and conditions not available on Earth, and begin the evolution of component manufacturing in space (for example, using additive manufacturing). The research effort has always been insufficient because access to lab space on orbit is extremely limited and very expensive. As a result, the basic research phase has stretched out, and questions about which processes result in useful products, how those processes might be scaled up to industrial production levels, and whether any of this can be turned into a viable business plan remain unanswered. A key component of the economic future in space is moving away from complete reliance on Earth for materials processing and manufacturing.

Conclusion

Investment in cislunar development makes sense as a strategy for realizing stated national objectives of boosting U.S. space commerce and exploring the solar system. Priorities for the near to medium term (through mid-century) include developing the technologies, processes, expertise, and infrastructure for:

- utilizing the unique characteristics of space, such as microgravity, vacuum, high-intensity solar exposure, and isolation from Earth, to produce useful knowledge and products;
- harvesting and processing extraterrestrial materials and energy resources;
- building progressively more sophisticated structures in Earth and lunar orbits;
- building installations on the moon, constructed to the greatest extent possible with local materials;
- advancing robotic technology to minimize the need for human presence in activities that are hazardous, remote, or readily automated and to provide direct assistance to humans when required.

Broad, multi-mission application of space infrastructure is integral to cislunar development; however, much of the value of a cislunar architecture program could be lost, and its political durability jeopardized, if it is exclusively linked to limited missions that may fail to offer credible and widely accepted justification for their long-term value.

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