CENTER FOR SPACE
POLICY AND STRATEGY

SPACE AGENDA 2025

MIND THE GAP: COMMERCIAL SPACE STATIONS AND THE ISS

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Executive Summary

Low Earth orbit (LEO) is an important testbed and proving ground for advancing space activities and human exploration, as well as a close-to-Earth location for new entrants and potential in-space manufacturing for return to Earth. LEO space science and research has been rooted in decades of international cooperation and diplomacy, specifically the International Space Station (ISS), which is an enduring source of national pride and prestige. With the planned retirement of the ISS around 2030 and the development of several private space stations to replace it, there is now a need to consider how the U.S. government can help minimize disruption of current space science initiatives and supply chains, while maintaining a cooperative leadership position in exploration and science.

If the national goals for deep space exploration, a future LEO in-space economy, and U.S. leadership in space diplomacy are to be maintained, then the U.S. government must create opportunities and an environment to thrive that buys down risk and encourages more partnerships and private investment. A stable commercial station customer base is highly speculative without continued government interest for such things as funding relevant government projects, maintaining oversight of safety and liability, transitioning LEO activities from the ISS to newly launched commercial stations, and helping private companies to diversify partnership models.

Other nations are now competing for space science leadership by demonstrating technological developments supporting cislunar and deep space exploration and by funding commercial LEO activities. The U.S. government should continue developing opportunities to fulfill its mandate to advance knowledge and space exploration that overlap with prospective partnerships and the development of a future in-space economy.

Introduction

The International Space Station (ISS) has been on orbit for 25 years as the longest-running and continuously human-occupied space station in history.[*] However, it is not the first orbital habitat and will not likely be the last (see Table A-1). Russia's early Salyut and *Mir* space stations, as well as the U.S.' Skylab, fueled our collective imagination of living in space, but humans have considered visiting and living in space for centuries.[1]

The ISS has enabled research across five lines of business, including: education and outreach, fundamental science, technology demonstration, applied research and development, and commercial facility utilization.[2] Within the microgravity environment where matter behaves differently, the ISS has hosted more than 3,700 onboard experiments[3], including hundreds of student experiments involving 2.6 million students across the United States.[4] Observing how humans survive and thrive in space long term has led to fundamental insights into how we live on Earth, such as how to improve bone health, build water purification systems, and increase crop yield in challenging environments.[5] Positioned in LEO, the ISS also serves as a supplemental Earth and deep space observation platform.

The ISS is currently planned for decommissioning and deorbit between 2030–2031.[6] Today, several private space stations are in various phases of planning and development under NASA's Commercial LEO Destination (CLD) Development Program through partnership agreements with commercial companies. The CLD Development Program aims to provide a LEO space station presence overlapping with the end of life for the ISS. Through a series of contracts and agreements, various private companies intend to provide a private space station's integrated infrastructure and services such as transport, refueling, and robotics. (For a list of planned LEO space stations, see Table A-2.) The U.S.-planned commercial space stations take a wide variety of technical approaches, but all are intended for shared use and funding between the public and private sectors, shifting from a model of incidental commercial use of a government capability to a commercial-first approach—albeit with the government serving as a heavy source of revenue.

Planned commissioning dates for these future space stations are scheduled to occur before retirement of the ISS to ensure continuity of U.S. activity in LEO. However, there is concern in the space community that the U.S. commercial stations currently planned will not be fully operational by the time the ISS is retired. Perhaps even more concerning, the CLDs could fail to build a non-governmental customer base in the long term and become economically unviable to maintain.[7] Losing U.S. access to a space station in LEO even temporarily could have longer-term negative impacts, particularly on U.S. companies supporting LEO activities, including:

- Loss of momentum for ongoing space science and research
- Disruption or loss of ground support for services, resupply, and launches
- Disruption of the space supply chain, especially for fragile lower-tier suppliers and developers[8]
- Termination of international agreements with like-minded states
- Allies and industry turning to non-U.S. LEO stations to pursue science and technology (S&T) goals[9]

With NASA placing priority on human exploration missions to the Moon and beyond, there will be less resourcing available for LEO science and technology work. The planned transition to commercial LEO destinations has risks, but it also offers an opportunity for NASA, as the national space agency for the United States, to maintain its mandate for deep space human exploration and for private industry to establish and grow a LEO economy. While commercial space destinations will likely be less central to space-based soft power diplomacy, they are nonetheless a tool worth pursuing.

[*]For the purposes of this chapter, "space station" will refer to those stations which are pressurized and intended for more than short-term human habitation, and is limited to those in low Earth orbit, not potential future stations beyond LEO.

Rooted in cooperation. Russia initially led the development of LEO space stations (cosmonauts have lived and worked in space almost continuously since 1971[10]) but the ISS' rich history of human spaceflight and international cooperation is significant. As early as 1972, a cooperative agreement between the United States and the Union of Soviet Socialist Republics (USSR) was signed. Titled the "Agreement Concerning Cooperation in the Exploration and Use of Outer Space for Peaceful Purposes," this bilateral treaty called for a wide range of cooperative ventures, including an experimental Apollo-Soyuz rendezvous and docking mission.[11] Beyond the world's superpowers, space cooperation was also embraced by other nations. Beginning in 1988, the United States partnered with the Canadian Space Agency (CSA), European Space Agency (ESA), and National Space Development Agency of Japan (NASDA) to establish an international coalition supporting Space Station Freedom. In 1994, the United States and Russia established the Shuttle-*Mir* program that delivered 10 shared docking missions and ultimately funneled $400 million into Russian science programs and the workforce. And finally in 1998, the "Intergovernmental Agreement (IGA) on Space Station Cooperation" was renegotiated and Russia was brought into the existing international coalition; the International Space Station program was born.

To this day, the ISS continues to be a five-agency international coalition of space agency decisionmaking and ownership. ISS visitors have been astronauts and "spaceflight participants" from government, academia, the private sector, and citizen advocates. As of March 2024, the ISS has hosted 280 visitors from 23 countries (including 13 private visitors).[12] The ISS has been a hub for a globally distributed group of launchers, operators, designers, and builders. Private industry partners have tested microgravity manufacturing concepts for products intended for use on Earth, such as artificial retinas, pharmaceuticals, microchips, and optical microfiber. In some cases, these products are smoother, more uniform, and higher performing than those produced on Earth.[13] These partnerships have offered research dividends to partially offset cost and risks and have demonstrated the myriad benefits of international collaboration for science and technology research.

> ***Besides government and industry collaboration, the ISS "also brings together international flight crews and globally distributed launch, operations, training, engineering, communications networks, and scientific research communities. Although the primary Mission Control centers are in the U.S. and Russia, several ancillary control centers in Canada, Japan, and Europe also have a role in managing each nation's elements and crew members.***
>
> ***—May 2023 https://www.nasa.gov/reference/international-space-station/.***

Splintered competition. Cooperation in space today has evolved to include emerging spacefaring nations looking for opportunities, and the interests of private industry that are sometimes outside those of single governments. There is growing international competition in space, including the Russian Orbital Station (ROS) recently announced to launch in 2027,[14] though the current war in Ukraine may strain the $7 billion budget. Additionally, India's Bharatiya Antariksh Station recently completed the preliminary development phase and will initially focus on robotic activity with a longer-term eye toward human spaceflight.[15] China is proposing the most comprehensive alternatives to U.S. space programs and is seeking to fill any gaps in LEO and/or cislunar space science left open by the United States.[†]

Though much smaller than the ISS, China's Tiangong orbits Earth today as the country's first long-term LEO space station and the only on-orbit alternative to the ISS. China unveiled initial program plans for Tiangong in April 2011–the same month that the U.S. Congress passed the Wolf Amendment, which limited most direct, bilateral cooperation between NASA and the Chinese national space program.[16] Tiangong first launched in 2021, became fully operational in 2022 with three modules, and has three more modules promised for the future. As China was barred from taking advantage of U.S.

[†]Cislunar is defined as beyond Earth's geosynchronous orbit and mainly under the gravitational influence of the Earth and/or the Moon, including Earth-Moon Lagrange point regions and the lunar surface. National Cislunar Science & Technology Strategy 2022 https://csps.aerospace.org/sites/default/files/2024-07/11-2022-NSTC-National-Cislunar-ST-Strategy.pdf.

government collaboration in space science and technology, the country chose to compete through its own human habitat program, building upon previous successes of its human space program.

More recently, China has signed a number of S&T agreements with other national space agencies and institutions. As of August 2023, China had "signed [Tiangong] cooperation framework agreements with the United Nations Office of Outer Space Affairs (UNOOSA), ESA and space agencies of Russia, France, Germany, Italy and Pakistan," with 110 on-orbit experiments lined up."[17] The China-led International Lunar Research Station (ILRS) that was jointly announced with Russia has also gained attention for its space partnerships, including cooperative agreements with nations such as South Africa, Venezuela, Azerbaijan, Pakistan, Belarus, Brazil, and Egypt, and with non-governmental universities and associations.[18] See Table A-2 for more information on the various non-U.S. station plans.

Why do we need LEO anyhow? In 2017, Public Law 115-10 directed NASA to begin transitioning from human space flight activities in LEO such as that of the ISS regime "that relies heavily on NASA sponsorship, to a regime where NASA is one of many customers of a low-Earth orbit commercial human space flight enterprise," while maximizing utilization of the ISS and LEO in pursuit of deep space human exploration objectives.[19] Since then, fiscal pressures have grown, with final enacted appropriations for FY2024 that included the deepest cuts relative to the presidential administration's request in decades.[20] Meanwhile, today's ISS operations and maintenance require substantial (and ever-growing) funding and astronaut time,[21] and both U.S. and global attentions are turning toward the Moon and Mars. The U.S.-led Artemis campaign has now secured 45 countries as signatories to the Artemis Accords as of October, 13, 2024. However, there are compelling reasons to *not* leapfrog LEO and go straight to lunar and cislunar.

First, maintaining a U.S. government presence in LEO facilitates further exploration overall. The Moon is hard, and Mars even harder. If the United States intends to pursue these far-off destinations, LEO remains the optimal environment in which certain scientific and technological steppingstones exist. Many of the support systems for extended human activity in space still need to be developed. These systems need to withstand the harsh environments associated with missions to other celestial bodies, including high levels of radiation, lunar surface ejecta (dust), sustained extreme cold, limited communications, robotics, and in-situ recycling. From relatively easy-to-reach lower orbits, researchers can study human physiology and test advanced technology for living and working in space. However, while commercial space companies may have the savvy to solve these hard problems, they may not have the risk tolerance. This is because business plans are more likely to target markets such as those using robotics and tele-operation that do not have the high cost and risk of maintaining humans in space, or markets where using an orbiting platform designed for a single purpose (e.g., manufacturing) is more optimal than an all-in-one platform that includes humans. Therefore, LEO remains an important proving ground to buy down the risk of any future deep space human exploration missions.

Second, access to LEO requires less fuel and is cheaper to get to and return from. This is especially relevant to any actors wishing to do space science with limited funding, such as private start-up companies, academia, and new entrant nations. In terms of the potential for off-planet industrial manufacturing and biotechnology for return to Earth, LEO is logistically more affordable; the shipping lane from LEO is ~158,000 miles shorter than from a lunar orbit. Moreover, future commercial stations that are in a lower-inclination LEO than the current ISS could further reduce launch and return costs.[‡] Therefore, as a testbed for small business, like-minded emerging space nations, and academia, LEO still offers the most promise for continuing current research, revealing new research and business opportunities, and establishing flight heritage.

Third, the strategic imperative of maintaining a strong U.S. presence in LEO goes beyond getting to Mars or normalizing in-space manufacturing and transport, and beyond basic science and fundamental research. Studies show that investments in S&T, including that for space, improve overall economic growth, increase skilled technical jobs, and lead to new

[‡]Inclination is the angle of the orbital plane (e.g., of a satellite) relative to Earth's equator. The higher the inclination, the more energy required to reach the orbit when launching from lower latitudes. Launching from Florida, USA, for example, takes much more energy to reach the highly inclined ISS orbit than launching from Kazakhstan—the primary launch site for the Russian Soyuz rockets used to reach the ISS.

discoveries, technologies, products, and industries.[22] Supporting development of basic scientific research in LEO around commercial space stations, and the services and products they could provide, could stimulate adjacent sectors and follow-on technology.

Finally, while soft-power diplomacy of government-to-government space partnerships is often underappreciated, it has long been recognized[23]—and the so-called *diplomatic calculus of space collaboration* cannot be overlooked. Soft-power diplomacy gleaned from civil space exploration and science does not come exclusively from having technology and knowledge, it also comes from *the sharing of that knowledge* with others. The knowledge and prestige associated with space activities is often exported to new partner nations participating in U.S.-led private space missions, potentially strengthening alliances and global stability. And regardless of nationality, there is true power in the shared experience of the *overview effect* when viewing Earth from space.

The case for commercial. Along with billionaires and venture capitalists across the globe and a growing number of niche space start-ups, there are also many emerging spacefaring nations and regional space efforts looking to gain a foothold in the growing global space industry and reduce their dependency on international partners for space services. For instance, India recently loosened its foreign investment policy for building and launching satellites to stimulate its aerospace industry.[24] Additionally, regional efforts like the African Space Agency (2023) and Latin American and Caribbean Space Agency (2021) are looking to benefit members and advance indigenous space capabilities and collaboration among signatory nations. Even Space Florida[25] and the Texas Association of Business[26] have signed agreements with the Israeli Space Agency. Elements of these types of regional partnerships, driven by both geopolitical and commercial ambitions, will continue to shape the space sector. However, the 1967 Outer Space Treaty, and subsequent multilateral space treaties, define space activities and oversight of sub-national space entities to be the responsibility of nation states. Given that governments play this essential role in commercial LEO development, major governmental players should consider how they can best build national capacity and leadership.

Thus far, government has been the primary enabler for research performed by private space companies in LEO. For instance, NASA awards millions of dollars through the In Space Production Applications (InSPA) program for selected companies to demonstrate and implement key technologies on the ISS.[27] But government-provided seed capital in terms of research, prototyping, and early-stage operations can only take industry so far. Predictably, commercial space station companies expect two things: (1) government will continue to fund investments at some level in microgravity science and research, and (2) the ISS will be decommissioned in a timely fashion to make room for new LEO entrants. It will also be necessary to seek ways to reduce risk in investments in areas such as increased space safety, supply chain, and workforce (see Table 1).

Table 1: Model of Success for Private Industry

	Seed	Revenue and Growth
Prerequisite	Continued government interest in microgravity R&D ↓	Timely ISS decommissioning and few competing commercial on-orbit labs ↓
Needs	Help secure the customer base	Business model to generate and grow revenue
Throughout the project lifetime, monitor project value and de-risk across costs, markets, regulatory compliance, safety, and orbital requirements, etc.		

The primacy of NASA and other governmental entities as customers has the added benefit of government being able to continue targeting key technologies and high-priority agency needs for the Moon and deeper space exploration. In fact, absent NASA funds, research on necessary long-term spaceflight human factors is likely to atrophy. For example, while robotics material processing and pharmaceuticals manufacturing could yield the highest returns with the lowest risk for commercial space companies, they do not match the highest priority of NASA to advance human deep space exploration.

The March 2023 U.S. National Low Earth Orbit Research and Development Strategy (National LEO Strategy) presents a plan to maintain and expand the "microgravity research ecosystem" in collaboration with the commercial sector and international partners. Among the challenges:

- Maintain the necessary capabilities and human presence in LEO during the transition from the ISS to commercial successors
- Attract new, impactful research from the U.S. government, academia, and international partners
- Support the development of commercial R&D and in-space manufacturing before and after the retirement of the ISS

Seeding innovation, targeting deep space technologies and research, and maintaining priorities of the National LEO Strategy should be continued.

In terms of a prerequisite to revenue and growth for commercial space stations (see Table 1)—from research to manufacturing—minimal competition from government-owned stations will be necessary. If the ISS, for example, is still on-orbit accepting micro-gravity experiments and hosting visitors, the much-smaller commercial stations may have trouble finding customers and maintaining investors, especially if the ISS is providing services at what amounts to subsidized rates. To that end, if NASA desires a smooth transition to a commercial LEO model, it will need to maintain the scheduled retirement of the ISS to avoid cannibalizing the commercial space station market share. NASA should also continue refining its requirements for how it will use commercial space stations in the future.[28] The ability of planned commercial stations to capture NASA use-cases in their design planning will be integral to a growth-minded business model.

However, the business case on LEO commercial activities will most likely depend on a strong government commitment. The level of support needed for CLDs is up for debate—anchor tenancy on one hand or "just another customer" on the other.[§] While LEO space science has had many government and private customers, a stable commercial station customer base continues to be speculative without continued government interest.[29] U.S. Code Title 51 lays out specific requirements when considering anchor tenancy, such as meeting mission requirements, achieving cost effectiveness, and ensuring a competitive process for selection.[30] The business requirements are the most challenging, wherein commercial space stations must:

- Identify existing or potential customers for the good or service other than the U.S. government
- Prove that long-term viability of the venture is not dependent upon a continued government market or other non-reimbursable support
- Ensure private capital is at risk in the venture (e.g., CLD Program providers should have "skin in the game")

The future of commercial LEO endeavors and the stature of the United States as a global space leader could be diminished by business failures. Therefore, government should assess commercial station business plans to ensure compliance to

[§]While the term "anchor tenancy" is defined for NASA's purposes in U.S. Code Title 51 as procurement sufficient to make a commercial venture viable, the concept has its origins in the retail sector. An anchor store—which attracts customers, and in turn attracts other smaller stores hoping to piggyback on the increased activity, *usually enjoys discounted rent in exchange for signing a long-term lease*.

Title 51 including: clear milestones to avoid business failures, and a means to support the establishment of a viable commercial LEO *economy* that is not reliant on government subsidies.

Particularly noteworthy is the plan to attach the Axiom Orbital Segment to the ISS and then detach the segment before retirement. However, Axiom Space announced several schedule slips in early 2024. NASA subsequently announced renegotiations for its direct contract, and in September 2024, media stories broke of Axiom Space's financial struggles and adoption of a smaller, less-powerful module, thus affecting the business case for non-governmental customers.[31]

To be sure, government funding for continued space science in LEO and for ISS retirement is necessary to support almost any development of the nascent commercial LEO ecosystem. But a successful program will require a balanced and well-crafted partnership model to ensure a reasonable sharing of risks, costs, and benefits. In this regard, public-private-partnership arrangements will play a critical role in sustaining human presence in LEO, applying a range of potential contractual arrangements to finance, design, build, maintain, and/or operate projects whereby both parties share risk and investment.[32]

A look at NASA partnership models. NASA uses several types of funding modalities to support commercial space station and LEO technology development. To advance the CLD Program, NASA-to-private development models range from traditional direct contracts awarded via competitive Broad Agency Announcements (BAAs) to Space Act Agreements (SAAs) which are written into the Space Act of 1958 charter as "other transactions."[**]

- Through the competitive BAA, Axiom Space was awarded a $140 million firm fixed price contract to provide at least one habitable commercial module to augment the ISS. Upon ISS decommissioning, the Axiom Space station would detach and remain in orbit.
- The Orbital Reef and Starlab teams are each working under *funded* SAAs. Initial awards totaling $415 million were made in late 2021 at the beginning of the CLD Program Phase 1 Design Maturation activity.
- Through *non-reimbursable* SAAs, NASA has partnered with seven companies through the competitive Collaborations for Commercial Space Capabilities (CCSC)-2 to develop LEO infrastructures, architectures, or transportation in support of the CLD Program. [††]

NASA plans to implement a five-year CLD Program Phase 2 Certification and Purchase of Services in 2026.[33]

These innovative agreements may not be traditional public-private-partnerships, but while government is building up the U.S. commercial industrial and innovation base, private companies are simultaneously able to leverage these funding models to gain NASA's knowledge and experience.

Other types of funding strategies. Having a range of partnership strategies allows for many ways to increase innovation, build U.S. economic power, and reduce risk to government. Table 2 shows a general partnership framework across various considerations.[‡‡] It is notable that both leadership and diplomatic opportunities for the United States may depend on the sharing of data, information, and technology with other countries. While these exemplars are narrowly described here, a

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[**] SAAs are a type of contracting vehicle to enable external partnerships and include *reimbursable* agreements wherein NASA costs are reimbursed by the SAA partner and *non-reimbursable* wherein NASA and one or more partners each cover the cost of their own participation with no exchange of funds. These SAAs aim to specifically leverage private, commercial companies to design, build, launch, and operate LEO space stations.

[††] They are Blue Origin, Northrop Grumman, Sierra Space, SpaceX, Special Aerospace Services, ThinkOrbit, and Vast. https://www.nasa.gov/news-release/seven-us-companies-collaborate-with-nasa-to-advance-space-capabilities/.

[‡‡] Detailed analysis of possible international partnerships—bilateral or multilateral—are outside the scope of this chapter.

Table 2: Partnership Strategies—Optimizing Investment and Lowering Risk			
	Leadership	**Diplomacy**	**Doing Business**
U.S. Government Only	Sole U.S. government ownership may diminish global leadership opportunities	Limited opportunities	• Domestic market • Subject to budget variability
U.S. Government + International Governments/Agencies	Opportunity for United States to lead partners, allies, and emerging spacefaring countries	Builds upon existing space diplomacy	• Global market • Balances risk and investment across shared operational capabilities
U.S. Government + U.S. Commercial Companies	U.S. government maintains leadership among near peers and private space competitors	Limited opportunities	• Competitive global market will demand strong business case • Boosts U.S. space industrial base • U.S. government seed money imperative
U.S. Government + International Commercial Companies	U.S. government maintains leadership position among spacefaring governments	Builds global space business that could be more sustainable than "going it alone"	• Global market necessitates open sharing of technology (export controls) with competing entities

combination of U.S. government, other governmental space entities, and commercial space offers the greatest reach across markets and possibilities for international relations.

Still, there are other types of partnerships that may appear frivolous yet serve to raise public awareness—e.g., unique marketing stunts such as launching a sports car into space (SpaceX, 2018), or name-brand experiments like baking chocolate chip cookies on the ISS (DoubleTree by Hilton, 2020), but there are other examples of more lasting partnerships. In 2022, Hilton partnered with Starlab to design the interior facilities for visitors of their futuristic hospitality-first habitat. In January 2024 the food group Barilla sent ready-made pasta to the ISS on Axiom Space's private astronaut mission. This type of brand recognition promotes interest in space and appeals to new audiences, which may in turn attract diverse investors.

Finding synergy between U.S. government and private industry. While there is still no singular application or key technology considered indispensable to the future of LEO activities, there are developments that could lead to synergetic business models that provide value to both the U.S. government (e.g., a public good) and private industry (e.g., expanded markets, revenues, or profits). While not an exhaustive list, Table 3 explores some of these.

As stated earlier, delivering a public good and benefiting private sector partners are typically the central design goals of any public—private partnership; however, intellectual property and other information that bring competitive advantage are often the drivers for private involvement. There is a tug of war between space "for the benefit of all humanity" and private-sector goals that may decrease open data and free sharing of S&T discoveries. Understanding how to balance private ownership and public benefits will be important.

There are myriad other ways to sometimes find synergy between government mission and strategic commercial goals that may or may not be specific to pressurized space stations—e.g., the Department of Defense's in-space access, mobility, and logistics (SAML) programs that are rooted in resilience through maneuvering and resupply in space and rely on some of the technologies that feed into commercial space stations such as launch on demand, robotic maneuvers, universal docking systems, and vehicles for transport of power, data, and goods. Private companies should look for ways to tap into those

Table 3: LEO's Next Big Things—Maximizing for Government and Industry		
	What are the benefits of LEO to U.S. government goals?	What has timely and significant return on investment (ROI) for private industry?
Growth—Scaling Up	◆ **Testbed** for small-scale manufacturing, robotics ▸ Informs human habitation on Moon and Mars	◆ **Industrial manufacturing**—retinas and other body parts, microfibers, microchips, etc. ▸ If scalable in space or on Earth, return trip is cheaper from LEO
Technology Transfer	◆ **Human spaceflight science**—effects on the human body biomedical, testing new technology (robotics, materials), biology, agriculture ▸ Informs human habitation on Moon and Mars (eventually must test longer-term/higher radiation environs)	◆ **Biotech, pharmaceuticals, and materials science**—stem cell research, life sciences research, patented medicine, luxury cosmetics, etc. ▸ Highest profit margins will mean launch/return and in-space experiments pay off
U.S. Competitiveness	**Allies' alternative to China's** Tiangong or other nations controlling and owning S&T from LEO	**Intellectual property (IP)** ownership is held among like-minded players
Space Leadership	National **pride and prestige** of sending people to/from space	Novel approaches to **space marketing** and business-to-business partnerships

needs and find new market applications. Another example is NASA's focus on in-space servicing, assembly, and manufacturing (ISAM) that aims to build and diversify the U.S. industrial base[34] and present opportunities for new technology to feed into the launch and continued operations of commercial space stations—especially in terms of resupply or space rescue. Private companies that develop a technology that contributes to just one aspect of the complexities of SAML and/or ISAM could be positioned for other business opportunities related to future human-tended LEO stations.

Conclusion

A future viable commercial LEO ecosystem offers enormous potential, but strong foundations must be in place. To that end, this analysis emphasizes the role of cooperation and competition in LEO space science past and present; the continued relevance of LEO as a proving ground and manufacturing hub; and the need for continued government interest and support for development of a viable LEO ecosystem. Fortunately, there are now opportunities for success through partnerships, which allow private sector and government stakeholders to combine their expertise and strengths to advance LEO-based science, technology, research, and manufacturing.

Some observers, particularly the Chinese, will attempt to present an ISS end-of-life narrative as a diminishment of NASA capabilities and a symbol of the decline of the West. That narrative must be countered with the message that the transition to long-term, viable commercial operations—however long it takes—will define the future course of cislunar development. A post-ISS gap in services could take many forms—short (not more than a year or two) or long (several years), depending on the line of research. If the latter becomes reality, it could also create a gap in U.S. prestige and a missed opportunity for domestic and allied private industry alike.

Acknowledgments

Thank you to Jerry Miller, James Vedda, Martha Hess, and Jeff Hanley for their reviews. Thank you to Karen Jones for serving as editor.

Appendix

Table A-1: Space Stations Then—The Shift from Pilots to Scientists[35]

On-orbit	Name	Ownership	Of Special Note
1971–1991	Salyut Stations	USSR	Seven iterative missions from single- to multi-module, longest stay 237 days
1973–1974	Skylab	United States, NASA	Experimental using "spare parts" from Apollo's launch vehicle and other spare parts; designed for crew of 3; total of 3 scientific missions; longest stay ~90 days
1986–2001	*Mir*	Russia	Multi-module,1-year visits
1998–Present	ISS	Multi-national: United States, European Space Agency, Canada, Japan (then-USSR 1998)	Multi-module
2006–2007	Genesis I, II	Bigelow Aerospace	Prototypes
2011–2018	Tiangong-1	China	Single module

Table A-2: Space Stations Planned for Longer-term Human Habitation (Selected List)

Space Station	Origin	Funding	Proposed Purpose	Design Features	Of Special Note
Axiom Station	• Axiom Space • MOUs with ESA, NZ, other international organizations	• NASA-funded • Firm-fixed-price contract, indefinite-delivery/quantity • Initially $140 million	• Private citizen launches to ISS currently using SpaceX Dragon	• Late 2026 • Comparable to ISS • Capacity: 4 modules of 4 crew each	• Contract content being renegotiated January 2024 • Initial ISS rendezvous, then free-flying
Orbital Reef	• Blue Origin and Sierra Space • Boeing Transport, Redwire Labs, Amazon	• NASA-funded • 2021 Space Act Agreement (PPP)	• "Mixed-use business park" for science and tourism with sports facilities	• Baseline by 2027 • Free-flying • Capacity: baseline 6 people	• $172 million as of January 2024
Starlab Space	• Nanoracks/ Voyager Space, Airbus Defence and Space, Mitsubishi Corporation, and MDA Space Ltd.[36] • (U.S. majority-owned)	• NASA-funded • 2021 Space Act Agreement (PPP)	• Privately operated, First free-flying, habitable, includes a "science park" • Partners include Hilton, Northrop Grumman	• Could launch late 2028/2029 • Free-flying, rotating artificial gravity • Single launch inside Starship • Capacity: 4 people	• $217 million as of January 2024 • Global joint venture network • Northrop Grumman pulled out

Table A-2: Space Stations Planned for Longer-term Human Habitation (Selected List)					
Space Station	**Origin**	**Funding**	**Proposed Purpose**	**Design Features**	**Of Special Note**
Haven-1	• Vast Space[37] (Long Beach, CA)	• NASA (unfunded SAA) • Part of NASA CCSC-2 program	• Tourism; all-commercial crew	• End of 2024 • Spinning artificial gravity[38] • Capacity: 4 people	
ThinkPlatform-3	• Think Orbital	• Privately funded • Part of NASA CCSC-2 program	• Depot, ISAM, then research and tourism	• Spherical, scalable • Capacity: 40 people	• Includes additive manufacturing for large-scale, in-space fabrication
Pathfinder	• Sierra Space	• Privately funded • Part of NASA CCSC-2 program	• Standalone version end of 2026	• Large Integrated Flexible Environment (LIFE) technology is inflatable, scalable	• First missions set for biotechnology
Starship	• SpaceX	• Privately funded • Part of NASA CCSC-2 program			• Already planned for crew and cargo transport
Tiangong Space Station[39]	• China Manned Space Agency	• Government of China	• Crewed on-orbit scientific research facility	• Operational • Currently 3 modules with plans to add 3 more	• Occupied nearly 3 years • Crew of 3
Indian Orbital Space Station, Bharatiya Antariksha Station (BAS)[40]	• Indian Space Research Organisation (ISRO)	• Foreign civil government agency with potential private and public partnerships		• Design phase as of June 2024; part of India's Space Vision 2047 • First module launch 2028; completion by 2035	• Modular, in-space assembled, permanent escape module included • Capacity: robotic initially
Russian Orbital Station (ROS)[41]	• Roscosmos Agency	• Foreign government space agency with potential private and public partnerships		• Roadmap for development announced July 2024 • Phased deployment 2027 to 2033 • Crewed and uncrewed options	• Modular, in-space assembly, gyroscopic power generation, autonomous enabled

Table A-2 Notations

In the design of LEO space stations and for the purposes of this chapter, there are several considerations:

1. **Modularity.** Single-module design requires a large launch vehicle versus a multi-module design that can be launched in pieces but that requires the added complexity of assembly on orbit.
2. **Occupancy.** The number of intended occupants dictates how usage fees are planned and delivered, whether government-funded or by private customers.
3. **Intended purpose.** Tourism, science, and manufacturing yield varying infrastructure and life support needs that could raise complexity as well as liability issues.
4. **Partnerships.** Including cross-national, private investors could either grow or stymie design factors.
5. **On-orbit lifespan.** The added costs of maintenance (internal and external) and resupply could become expensive factors as is the case with ISS more recently.

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This paper was published as a chapter of *Space Agenda 2025*, with Angie Bukley, Colleen Stover, and Victoria Woodburn serving as editors in chief. *Space Agenda 2025* is an effort by the Center for Space Policy and Strategy (CSPS) at The Aerospace Corporation to highlight and provide insights into some of the major space challenges facing policymakers. You can find the complete list of individual *Space Agenda 2025* papers at http://csps.aerospace.org/SA2025, as well as download the combined set of 16 chapters in the *Space Agenda 2025 Compendium* at https://csps.aerospace.org/papers/space-agenda-2025-compendium, all available to you with our compliments.

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