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Space

The commercialization of low Earth orbit

The promise of a new era in space exploration stands to transform our economy by leveraging the untapped power of LEO and beyond.

Volume 5: Providing the foundation for growth

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Volume 5: Providing the foundation for growth

This is the fifth entry in a series of Deloitte Consulting publications on the commercialization of low Earth orbit (LEO). In this volume, we turn our attention to the infrastructure and services (I&S) segments of the LEO economy that stand to enable growth in a variety of value-generating use cases for human spaceflight. We explore the progress, current state, and challenges that lie ahead for I&S as the foundation for growth of a vibrant commercial LEO economy.

Contents

The critical role of commercial space infrastructure & services

The 2020s have witnessed major breakthroughs across the commercial human spaceflight market. Millions watched the return of human spaceflight from US soil on commercial vehicles, private astronaut missions are gaining traction, and a variety of potentially game-changing vehicles are being designed and tested. Coverage across news, streaming, and social platforms has once again thrust human space exploration to the forefront of the public eye. But while much of the fanfare has focused on 'big firsts' in low Earth orbit (LEO), each major leap is the culmination of decades of investment and innovation. Together, a robust ecosystem of public, private, academic, and non-profit players has the capabilities to make activities in the 'new space' economy possible.

However, as we noted in previous volumes of the *Commercialization of LEO* series, the high cost and infrequency of orbital launches continue to constrain many of the business cases that make up our vision for a vibrant commercial LEO economy. Additionally, until commercial LEO destinations come online, several prospective business cases face a hard upper limit for growth. And finally, supporting a diverse mix of commercial activities in LEO and beyond will require growth and maturation of enabling capabilities, services, and standards both on Earth and in orbit.

Overcoming these challenges, which span the infrastructure and services (I&S) segments of the LEO value chain for commercial human spaceflight, is vital to making LEO economically viable as a commercial marketplace. Given the complexity of the LEO ecosystem, overcoming these market barriers isn't likely within reach for any individual company or agency. Instead, the next generation of infrastructure and services will be born from countless investments and innovations across the private sector, government, and academia. As we explore how I&S might evolve in the decade to come, we will discuss key dependencies and opportunities for these segments, as well as the actions players can take across the ecosystem to build the foundation of a vibrant human spaceflight market in LEO.

Defining I&S within the commercial human spaceflight value chain

The I&S segments of the LEO value chain for commercial human spaceflight encompass an enormous range of products and services, from component manufacturing to spaceports and launch vehicles to on-orbit servicing and communications. Simply put, I&S includes everything that is needed to travel to and from space and enable all the human activities that create value on orbit. In that sense, I&S constitutes the supply-side of the value chain, while activities like on-orbit R&D, on-orbit manufacturing, space tourism, and media, entertainment and marketing constitute demand.

Our team has explored the market dynamics and potential for growth in each demand segment in previous volumes of the *Commercialization of LEO* series. In the present study, we focus our attention on the anticipated constraints, dynamics, and opportunities for I&S as the foundation for that demand. While not exhaustive of all I&S advancements needed, this paper reflects what our analysis has revealed to be the most significant and proximate enablers for future commercial human spaceflight activity. Namely, we focus on the sub-segments of I&S illustrated in Figure 1.

Making LEO economically viable means ensuring that it is safe, accessible, sustainable, and efficient. The I&S segments are instrumental in achieving these goals.

A new generation of I&S for commercial human spaceflight

The I&S segments of the LEO economy are as foundational today as they were in the space race of the 1960s and, in many cases, still support the same overarching functional objectives. Ground stations are still essential for communications, tracking, and telemetry. Rockets and capsules still carry crew and cargo to space and back. Space stations still provide the power, pressurization, thermal management, and life support needed for astronauts to complete their missions. Essentially, I&S segments remain the backbone of safe and reliable access to space. However, the landscape of users, providers, and business cases is dramatically different today – and is changing rapidly. Where human spaceflight was once only accessible to national space programs, NASA's investment in new commercial crew vehicles and increased access to the International Space Station (ISS) have opened the door for commercial uses.

As we've emphasized throughout the *Commercialization of LEO* series, demand for commercial human spaceflight appears to be at an inflection point of growth. On the heels of the first all-civilian orbital spaceflight mission (Insipiration4, September 2021) and the first commercially-operated private mission to the ISS (Ax-1, April 2022), several companies are vying to service demand they anticipate for R&D, manufacturing, tourism, and media and entertainment activities in LEO.

Making these activities economically viable will require significant transformation towards a new generation of I&S. Some sub-segments of I&S, such as new commercial destinations to replace the ISS, are central to most commercial human spaceflight use cases. Other sub-segments may present more nuanced opportunities and dependencies for individual use cases. Below, we highlight some of the standout needs and dependencies that span all commercial human spaceflight, as well as select considerations for each individual demand segment of our value chain framework.

FIGURE 1 | **Infrastructure and services sub-segments to enable commercial human spaceflight**

Cross-segment needs and dependencies:

- Net new capacity in **destinations (space stations)** with significantly lower operating costs is needed to enable sustainable growth in commercial human spaceflight in LEO.
- Increased **launch frequency** and lower cost per seat are needed to close the business cases of most commercial activities.
- **Space traffic management**, driven by enhanced space situational awareness (SSA) and shared norms and standards to guide behavior, needs to mature quickly to enable safe operations in an increasingly congested environment.
- Advancements in **space logistics** – both on the ground and in orbit – are needed to increase efficiency and predictability as the scale and complexity of launch and orbital operations increase.
- A host of **in-space servicing** capabilities, such as robotic assembly and automated rendezvous and docking, are needed to provide cost efficiencies and secondary benefits to human operations in LEO.
- Advancements in **astronaut health** are needed to better understand and mitigate the physiological and psychological effects of spaceflight on humans.

Segment-specific needs and dependencies:

On-orbit R&D:

- Advanced **robotics and automation, including the use of AI**, may dramatically reduce cost and increase R&D throughput.
- Enhanced **on-orbit computing**, including both classical and quantum computing, to process data 'at the edge' may maximize insights/results from the massive amounts of data captured in orbit.

On-orbit manufacturing:

- Advanced **robotics and automation, including the use of AI**, may dramatically reduce cost and enable manufacturing at scale.
- More **diversity in crew and cargo vehicles** may enable use cases with unique physical properties or supply chain constraints.
- Specialized **facilities to maximize microgravity properties** (i.e., vibration dampening and managed re-boosting) may enhance products made in space.

Orbital space tourism:

- Tailoring crew vehicles and habitats to **enhance comfort and accessibility** for non-professional astronauts may strengthen demand for orbital space tourism.
- Large scale growth may require **new models for hospitality** services provided by professional private astronauts, allowing tourists to focus their time on recreation and leisure.

Media, entertainment & marketing:

- Major improvements in **bandwidth, latency, and availability of space communication networks** may be needed to enable use cases for live and high-resolution productions.
- New **commercial-oriented facilities** may unlock media use cases currently limited by NASA regulations.
- Production technologies like 8K cameras and image stabilization may need to be adapted and certified for use in space.

Dependencies for I&S across human spaceflight demand segments

Below is a summary assessment of the maturity of each I&S sub-segment, as well as the extent to which growth in the four demand segments for commercial human spaceflight (e.g., tourism or manufacturing) depends on an increase in maturity for the corresponding I&S sub-segment. The rating for each I&S sub-segment's **current maturity** indicates how well-developed it is relative to what may be needed to support transformative growth outcomes. The rating for each **human spaceflight demand segment's dependence on I&S** indicates the degree to which transformative growth outcomes in the respective demand segment (shown in columns below) is reliant on an increase in maturity for the corresponding I&S sub-segment (shown in rows below).

Note that ratings of low, moderate, and high are qualitative representations of the opinions of the authors of this paper. They are offered to identify in general terms where investment and innovation are most needed to enable long-term growth. In the pages that follow, we will examine the maturity and needs within each I&S sub-segment in more detail.

I&S sub-segments & current sub-segment maturity	**Human spaceflight demand segment dependence on I&S**			
	On-orbit R&D	On-orbit manufacturing	Orbital space tourism	Media, entertainment & marketing
Launch services Current maturity: moderate	Moderate	Moderate	High	High
Space traffic management Current maturity: low	Moderate	High	High	Moderate
Destinations (space stations) Current maturity: low	High	High	Moderate	High
Communications & computing Current maturity: moderate	High	Moderate	High	High
In-space servicing, assembly & mfg. Current maturity: low	Moderate	High	Moderate	Low
Astronaut services & health Current maturity: moderate	Moderate	Moderate	High	High

Macro forces in the market

As we consider how potential action or inaction may contribute to progress in the I&S segments, we also keep in mind that broader trends and conditions may help or hinder advancement. These forces, outlined below, may steer the trajectory for I&S.

Forces Pushing Back

- The growing density of spacecraft and debris raises the **risk of collisions**; in a worst-case scenario, entire orbits become inaccessible.
- **Military conflicts** like Russia's war in Ukraine have blurred – or erased – the line between civilian and defense space infrastructure. Attacks on commercial satellites could stymie investment and growth.
- **Losing ISS international partners**, namely Russia, may present new hurdles.
- While commercial space station developers have signaled schedule confidence, history suggests that new infrastructure projects may **struggle to meet nominal timelines**.
- As the **macroeconomic environment** changes, investment in space ventures with long lead times may tighten.
- The **talent market** may be strained as Apollo and Shuttle era engineers retire and skilled manual labor positions remain hard to fill.

Forces Pushing Forward

- **Advanced technologies** often cited as components of Industry 4.0 – like additive manufacturing, digital engineering, and AI – are growing in many industries; they may also transform manufacturing and maintenance of space infrastructure.
- The rapid growth of **broadband satellite constellations** in LEO may help address key constraints for HSF, such as driving down the cost-per-Kg to orbit and providing a potential architecture to improve space-to-Earth communications.
- **International competition** in LEO, namely from China's space station, may encourage **political support** for US ambitions.
- **NASA is continuing collaboration with industry** to define its requirements and establish a concept of operations for commercial LEO destinations.

Launch Abort Engine Test
Image Credit: NASA

Getting to orbit: launch services

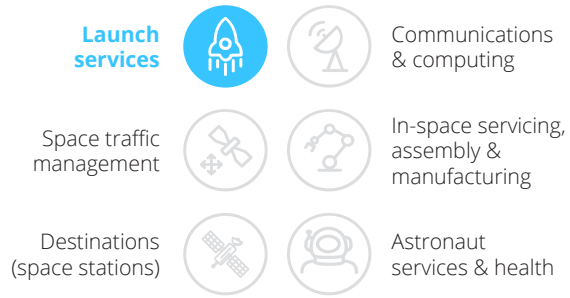
Getting crew and cargo to orbit is obviously a crucial component of the mission architecture for all commercial human spaceflight activities in LEO. As such, the introduction of commercial crew and cargo vehicles over the last decade is a major leap forward. However, supplier diversity is currently limited. Below, we highlight current state capabilities, future trends, and remaining gaps in launch services to enable the commercial human spaceflight market.

Crew and cargo space vehicles

As of March 2023, SpaceX's Crew Dragon capsule is the only US commercial crew vehicle certified by NASA for astronaut missions.[1] Boeing's Starliner vehicle is expected to fly its first crewed mission in 2023, after which it may become the second certified commercial crew vehicle.[2] These vehicles share many fundamental performance capabilities, as they were intended to provide NASA with 'dissimilar redundancy' for reliable access to LEO through the Commercial Crew Program (CCP).[3]

There are currently two vehicles in NASA's Commercial Resupply Services (CRS) program capable of ferrying cargo to the ISS, SpaceX's Dragon capsule and Northrop Grumman's Cygnus capsule. A third vehicle funded by the CRS program, Sierra Space's Dream Chaser, may make its inaugural flight in 2023.[4] In a similar paradigm to CCP, the cargo resupply capabilities of these vehicles are intentionally redundant – at least for the trip to space. The return leg is where these vehicles' capabilities vary. Of the two currently in operation, only one can return cargo to Earth, and it does so with a splashdown in the ocean. The soon-to-be-fielded Dream Chaser sports a glide-body design and horizontal landing profile that, according to Sierra Space, enable an estimated 1.5g reentry and landing on conventional runways.[5] This return profile may be advantageous for fragile cargo like biopharmaceuticals or printed tissues, the focus of several microgravity R&D efforts.[6] While these benefits have yet to be proven, our future-state scenario modeling suggests that down-mass capacity quickly becomes a bottleneck for growth in R&D and manufacturing activities in LEO. Vehicles that add down-mass capacity are critical for the future of I&S.

I&S subsegments



Reusable rockets and the rideshare paradigm

As we have previously noted, the cost of access to LEO is one of the greatest fundamental constraints on growth across the range of human spaceflight activities in LEO.[7] Several new technologies have already taken a large bite out of launch costs, and more innovations are on the horizon. For example, reusable first stage boosters have moved from proof of concept to an industry workhorse for SpaceX, contributing to Falcon 9's record-breaking launch cadence in 2022[8] and enabling a decrease in the cost-per-kilogram to LEO of over two orders of magnitude when compared with the Space Shuttle.[9] Meanwhile, other launch providers are actively developing and testing their own reusable rockets, with some even pursuing full reuse.[10] All told, rockets may soon be the most mature sub-segment of I&S for commercial human spaceflight in LEO, but continued innovation and competition are needed to continue advancing the market.

During the 2010s, a multitude of companies set out to build small launch vehicles to capture what was expected to be a growing market for small satellite (SmallSat) launch. While the SmallSat market has grown tremendously, small rockets have not been the driving force. Instead, 'rideshare' services on larger vehicles, whereby customers can hitch a ride with larger payloads or dozens of other SmallSats, have changed the game. A similar model may be emerging for human spaceflight, but where satellite rideshares carry multiple payloads, passengers on crewed flights may be asked to conduct a variety of revenue-generating activities. Indeed, the upcoming Ax-2 mission claims a "full mission manifest of science, outreach, and commercial activities" packed into a 10-day stay at the ISS.[11] This variety of 'mission-sharing' may become a common strategy for maximizing return on investment in the long-term.

The future of spaceports

As the space industry sees unprecedented demand on its infrastructure, both commercial and government entities will need to look for innovative ways to maintain and improve launch pads and supporting infrastructure at spaceports. US spaceports are primarily government owned and operated, with four sites capable of the orbital vertical rocket launches needed to reach LEO: Cape Canaveral Space Force Station (including the Kennedy Space Center), Pacific Spaceport Complex Alaska, Vandenberg Space Force Base, and Wallops Flight Facility. As demand grows, we expect the 'spaceport of the future' will need to 1) increase the supply and availability of launch pads, 2) modernize range infrastructure to support next-gen needs and higher launch cadence at lower cost, and 3) transform government-centric operating and financial models for the increasingly commercially-driven launch sector. For example, capital improvements may be needed to alleviate bottlenecks in payload processing functions like fueling, testing, integration, classified payload handling, and commodities storage.

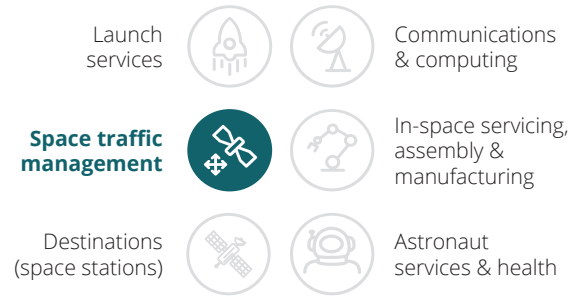
Safe navigation: space traffic management

The arrival of lower cost access to LEO, along with miniaturization of satellite components, has driven a dramatic increase in the number of spacecraft around Earth. As of the end of 2022, there were over 6,000 active satellites in orbit and that number is increasing exponentially.[12] In short, LEO is getting crowded, and fast.

Illustrating the risk that space poses to human spaceflight, the ISS has performed dozens of collision avoidance maneuvers over the past two decades, and they appear to be getting more frequent.[13] The maneuvers themselves are somewhat routine. However, you can't dodge what you can't see, and much of the hazardous debris in orbit is smaller than today's systems can identify and track.[14]

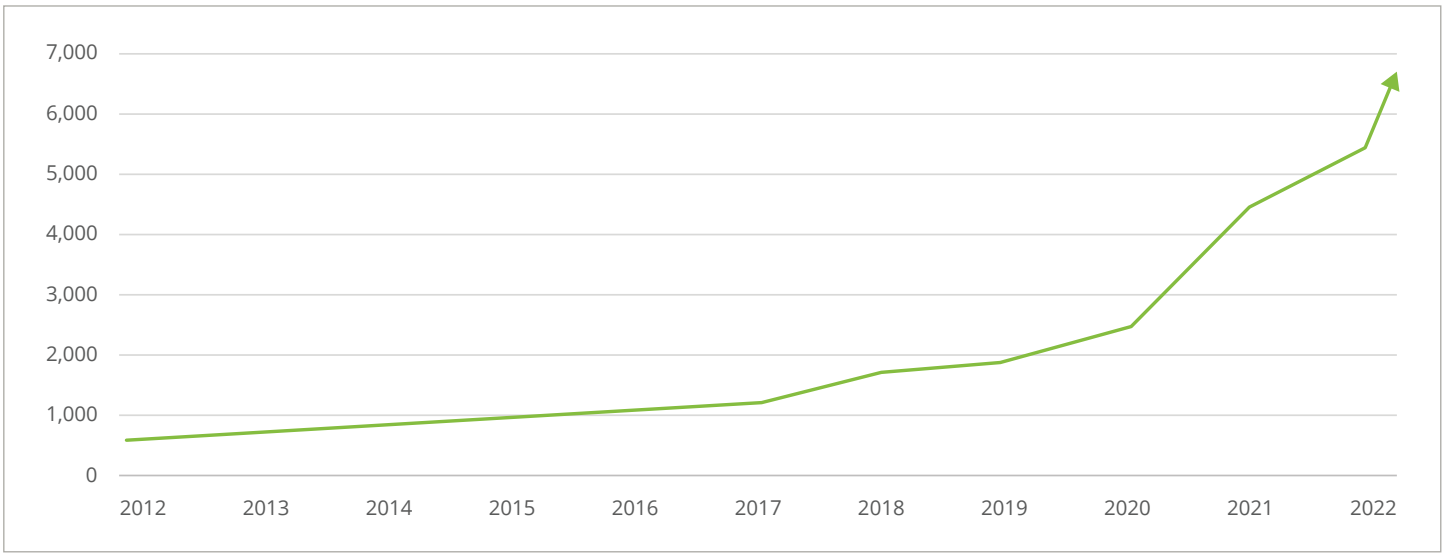
The discipline of space traffic management (STM) includes both space situational awareness (SSA) – or identifying, tracking, and communicating information about objects in orbit – and the rules and norms of behavior for mitigating collisions. With more and more objects in orbit, advancing STM is an important step towards enabling the commercial human spaceflight economy. The potential benefits extend beyond simply avoiding collisions. An effective STM system would also reduce uncertainty for human spaceflight activities, providing data that helps investors, operators, insurers, and astronauts make informed business *and personal* decisions about their activities in LEO.

I&S subsegments

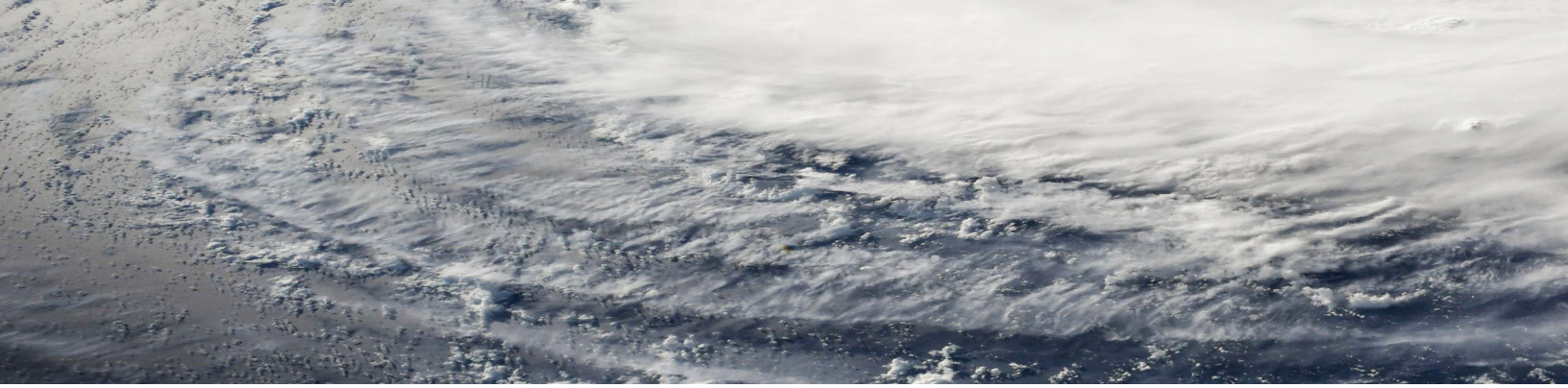


To advance STM, industry and government will likely need to work together. The Office of Space Commerce's request for industry input on the need for SSA data and services is a promising example of that collaboration.[15] Similar approaches may also help define the laws and regulations that serve as 'rules of the road' and enable coordinated and safe operations in space.

FIGURE 2 | **Satellites active per year (2012-2022*)**



**2022 data include active satellites as of April 30, 2022, plus an estimate for satellites added May 1, 2022 to December 31, 2022.*



Beyond the ISS: commercial destinations

Space stations serve as the base for most human spaceflight activity in LEO today and will likely remain the primary platforms to support government and commercial use cases over the next decade. Over the past quarter-century, the ISS has inspired countless enthusiasts and enabled massive scientific gains. Its success now culminates in a final "decade of results" before it is planned to be decommissioned circa 2030. As NASA has its sights set on the Moon and Mars, its Commercial LEO Destinations (CLD) program is aimed at supporting the creation of new, commercial space stations.[16]

New destinations on the horizon?

The CLD program is divided into two parallel lanes with unique providers to design commercial space stations. In the first, now referred to as the Commercial Destination on ISS (CDISS), NASA awarded up to $140 million and the use of a docking port on the ISS so that Axiom Space can attach a series of modules for commercial use.[17] The other, called Commercial Destination Free Flyers (CDFF), includes three awards with a combined ceiling of $415 million to teams led by Blue Origin, Nanoracks, and Northrop Grumman.[18] Figure 3 below illustrates the high-level timeline for phasing in the CDISS and CDFFs over the next decade.

I&S subsegments

Launch services		Communications & computing
Space traffic management		In-space servicing, assembly & manufacturing
Destinations (space stations)		Astronaut services & health

Computer-generated artists rendering of ISS
Image Credit: NASA

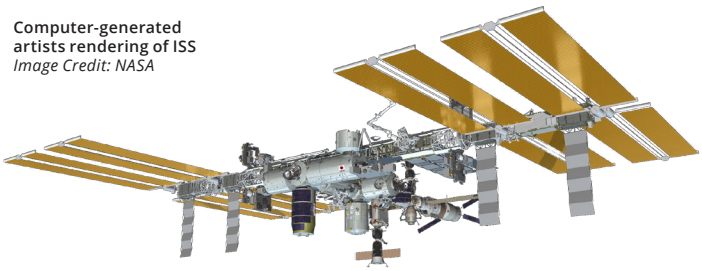
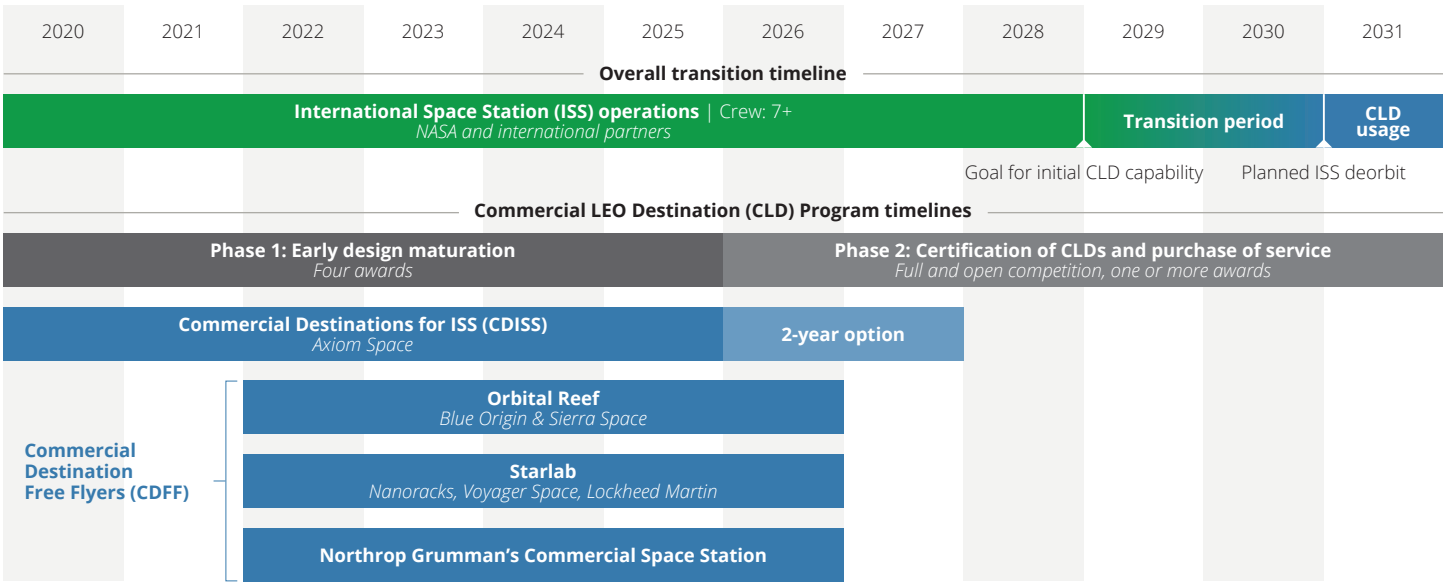
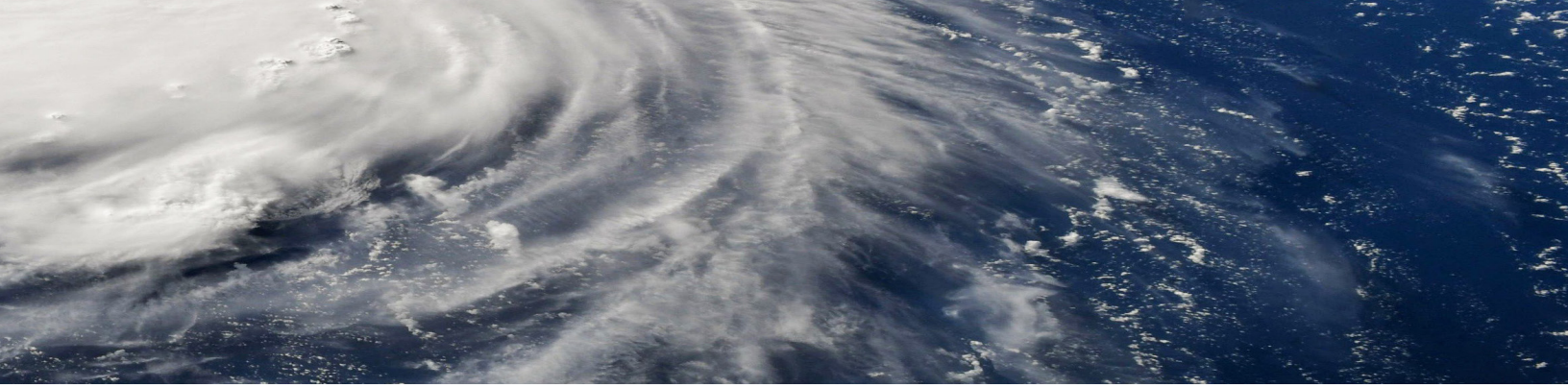


FIGURE 3 | **NASA's planned transition to CLD operations[19]**





These commercial destinations are intended to support NASA as one of many customers and will be critical to scaling commercial use cases that the ISS is able to support today. If the planned CDISS and CDFF stations were all successfully deployed, on-orbit crew capacity could more than quadruple (depending on final designs) that of the ISS. In theory, that level of growth would provide the physical space needed to expand commercial human spaceflight activities in LEO. However, the journey to market for commercial LEO destinations will be very challenging. Representatives from several of the teams vying to get their stations to orbit have acknowledged it is unlikely that all four will succeed.[20] If only one or two stations come online, growth of commercial human spaceflight activities in LEO will continue to face hard upper limits.

The initial federal investment provided a seed for the new destinations, but further funding is certainly needed as each team aims to mature their CLD concept. For reference, the ISS required over $150 billion to build and operate. Put in context of the CLD program, that is roughly 1,000x the size of phase 1 awards to each vendor team. NASA does plan to issue one or more awards for further development and certification, but the value of those 'phase 2' awards has not been announced. Even though CLD providers expect to reduce development costs by using new technology and building on lessons learned from the ISS, they will also need non-NASA capital investment to succeed in delivering hardware to orbit. For example, shortly after the Orbital Reef project was announced, Sierra Space announced a $1.4 billion raise intended to support development of critical components of the Orbital Reef architecture.[21] Similarly, Voyager Space recently completed an $80 million raise that may support development of Starlab.[22]

Fast-forwarding to 2030, when NASA plans to fully transition from ISS to CLD operations, making commercial destinations sustainable will require ample demand from NASA and other buyers. Again, looking to ISS operations as a benchmark, NASA currently spends more than $3 billion per year for maintenance, operations, and crew and cargo transportation services. NASA's forecasted budget for buying CLD services after the ISS is decommissioned is approximately $1 billion per year.[23] A grossly simplified analysis suggests that, in aggregate, future CLD provider(s) will need to make up the approximately $2 billion per year difference with a combination of non-NASA revenue and cost savings relative to ISS operations – just to break even.

Based on surveys of thousands of consumers, interviews with dozens of industry leaders, and extensive scenario modeling, our analysis suggests that potential commercial demand for R&D, manufacturing, space tourism, and media, entertainment, and marketing activities could range from $1.4 billion to $3.4 billion per year globally by 2030.[24] While that is in the ballpark of what is necessary, it also assumes that significant technological advancements and lower price points will be realized across other I&S sub-segments. As such, we believe CLD providers will need to find substantial cost efficiencies for building and operating next-generation space stations for the business case to close.

Not a one-size-fits-all approach

As we imagine how commercial destination concepts may take shape in the coming years, we first need to consider the different infrastructure needs of various use cases, as well as how they may evolve. Requirements for power, data, thermal management, crew time, and consumables will vary for each application. In a somewhat obvious example, a microgravity laboratory might not be what wealthy space tourists have in mind for an adventure vacation. Less visible differences, such as the quality of microgravity (e.g., vibration isolation and the procedures used for orbit-raising maneuvers), could become a critical differentiator among a small number of providers looking to support use cases like manufacturing.

The question for industry to answer through their design choices will be how to optimize for profitability and growth. NASA's requirements for CLD services will likely be a baseline for performance capabilities of future stations. From there, CLD providers will need to place bets and make strategic tradeoffs based on the non-NASA demand they aim to capture.

Continued leadership from NASA

Throughout the transition from ISS to CLDs and in the years that follow, NASA's role in shaping commercial destinations cannot be understated. With funded agreements in place, NASA is now iteratively defining and refining its expected concept of operations, service requirements, and demand forecasts for CLDs.[25] The agency is also working closely with CLD partners to transition vital lessons learned from 25 years of operating the ISS.[23] These 'phase 1' efforts are focused on early design maturation through 2025. As the agency enters phase 2, the decisions it makes to translate frameworks and forecasts into service contracts stand to dramatically reshape the competitive field. In doing so, NASA will need to consider tradeoffs associated with making one award or more; whether grouping or segmenting services may enable offerors to optimize their platforms; and how to balance the level of specificity in requirements to ensure mission goals can be safely met while allowing the flexibility commercial providers need to innovate.

Artemis I SLS at Launch Complex 39B
Image Credit: NASA

Data is king: communications and computing

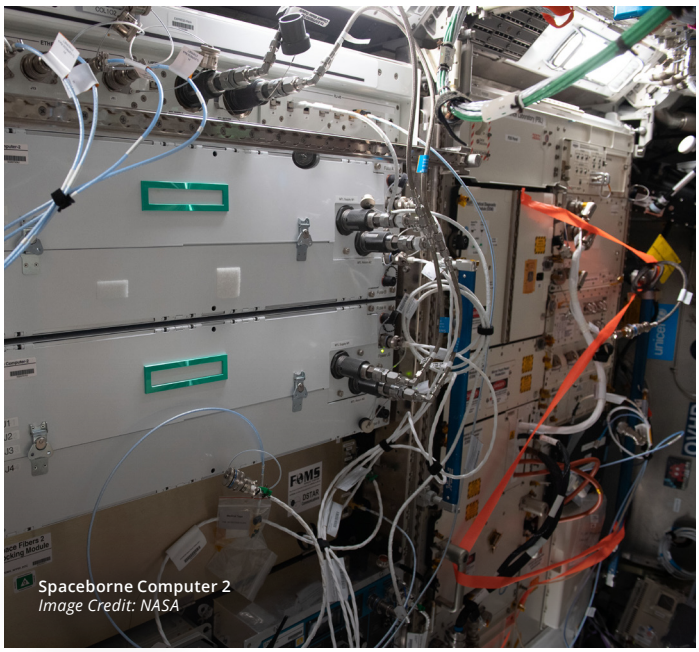
As with many other industries today, communications and computing are fundamental components of I&S for space. From ground-based facilities to space-based relays and the network layers in between, communications infrastructure not only supports critical operations like guidance, navigation, and control (GNC) for spacecraft, but is also a vital link in the value chain for commercial human spaceflight activities in LEO. Taking space tourism as an example, recent private astronaut missions shared the use of NASA's Near Space Network, which includes both direct-to-earth and space-to-space capabilities. When the network was prioritized for government use, there were big gaps in communication coverage. The lack of connectivity was cited as a reason the Inspiration4 mission did not have more live stream coverage,[26] which also signals a key infrastructure gap for media and entertainment use cases.

Like its goals for commercial launch services and orbital destinations, NASA also aims to move from being an owner/operator to a buyer of commercial space communication services, and they are not starting from scratch. "Ground station as a service" is a well-established business model and, with new entrants and investments, is expected to keep pace with near-term needs for direct-to-earth communications. And while the use of commercial satellites for the space-to-space segment for human spaceflight is a relatively new business model, the growing broadband constellations in LEO may provide the needed infrastructure for this service. In fact, testing this concept is a goal of the Inspiration4 mission's successor, Polaris Dawn (expected no earlier than summer 2023).[27] However, proving the technical feasibility of commercial SATCOM in this role is only part of the challenge. Industry and government will need to collaborate to define and adopt communications standards to allow the concept to scale across diverse customers and providers.

While improving space networks could make certain commercial human spaceflight activities more viable, data-heavy use cases like R&D may continue to be bandwidth-constrained. In these cases, edge computing provides an alternative approach to generate insights 'in situ.' Early experiments using in-space edge computing have shown up to 20,000x shorter time-to-insight compared with transmitting raw data to Earth for analysis. This added computing power onboard human-rated vehicles and destinations may also enable more autonomy and increase safety by detecting and characterizing hazards more quickly.[28]

I&S subsegments

Launch services	**Communications & computing**
Space traffic management	In-space servicing, assembly & manufacturing
Destinations (space stations)	Astronaut services & health



Spaceborne Computer 2
Image Credit: NASA

Efficiency in orbit: in-space servicing, assembly, and manufacturing

As the space industry grows, operators are continuing to look for ways to improve how they build and maintain space-based assets like satellites and space stations. Of course, one way to do this is using advanced manufacturing processes and new technologies while hardware is still on the ground. But constraints like the volume, mass, and rigidity of structures that can be readily launched to space, as well as the obvious challenges with accessing them once they are in orbit, create an imperative for in-space servicing, assembly, and manufacturing (ISAM).

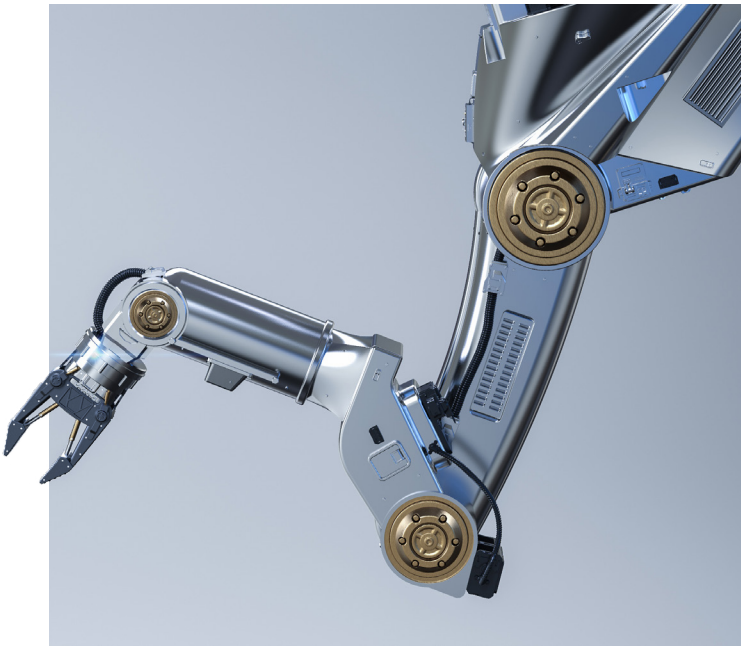
ISAM encompasses an array of different capabilities under one umbrella. *Servicing*, for example, includes extension of life, repair, orbit transfer and deorbit, and other functions. *Assembly* refers to construction in space from components made on Earth, while *manufacturing* refers to the production of new components in space from raw or recycled materials. Collectively, ISAM capabilities have the potential to support a more sustainable and resilient space infrastructure – a benefit emphasized in the White House's 2022 ISAM National Strategy.[29]

With applications ranging from LEO to the lunar surface, ISAM stands to benefit commercial human spaceflight activities in many ways. For example, removing hazardous debris could create a safer environment for astronauts and refueling existing satellites could provide a more robust communications infrastructure that in turn supports human spaceflight activities. However, these are indirect benefits. Given that ISAM is trending away from using humans *in* the loop, as was the case for repairing the Hubble Space Telescope, towards having humans *on* the loop but using automated and robotic capabilities,[30] is there still a direct link between ISAM and human spaceflight?

In short, yes. Some of the principal goals for ISAM focus on creating large structures like booms and solar arrays that will likely be needed for new commercial space stations. Additionally, transitioning maintenance activities from astronauts to robots may help reduce the cost to operate commercial space stations in the long run. However, while underlying technologies like precision robotics and AI are in development, automated assembly and maintenance capabilities are relatively immature. Continued investment in programs like NASA's On-orbit Servicing, Assembly, and Manufacturing 2 (OSAM-2) mission may help catalyze ISAM development, but commercial investment is still needed to accelerate growth over the next 5 years.

I&S subsegments

Launch services			Communications & computing
Space traffic management			**In-space servicing, assembly & manufacturing**
Destinations (space stations)			Astronaut services & health



The human factor: astronaut services and health

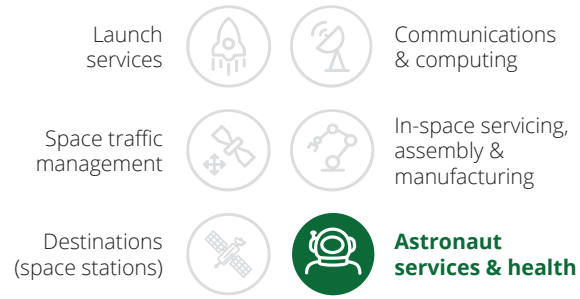
While there is significant promise and potential for human-centric commercial markets in LEO, early private astronaut missions of the 2020s have reinforced one of the biggest challenges facing the market: the human factor. As one space industry leader we interviewed put it, "humans are the weakest link in space exploration." There are considerable gaps to fill in terms of how private astronauts are trained to live and work alongside professional astronauts in space, and most importantly how we keep astronauts as healthy as possible.

There is a stark contrast between the extensive screening and training that NASA astronauts undergo and what non-professionals do to prepare for private astronaut missions (PAM). The unique considerations inherent to these missions have led to some lessons learned and new requirements. For example, future PAMs will require a former flown NASA government astronaut to serve as mission commander, and crews will be required to complete additional planning and training before launch.[31]

Given the unique challenges of living in microgravity and operating complex facilities like the ISS, NASA has long used simulated environments on Earth to prepare its astronauts for space. The next generation of training for private astronauts will likely employ simulations as well and may benefit from novel tools like augmented reality and virtual reality (AR/VR) to provide scalability and lower costs. NASA, for example, already has their own VR Laboratory at the Johnson Space Center that integrates AR/VR with robotics to prepare astronauts by simulating system rescue scenarios.[32]

Looking further ahead to the transition from the ISS to commercial destinations, we anticipate that what it means to be a "professional" astronaut will shift. Where government astronauts from NASA and other space agencies were once the core archetype, new roles and skills may be needed. For example, space companies providing commercial destinations "as a service" to both NASA and private customers may need crews that can simultaneously conduct cutting edge research, produce Hollywood-level media content, and cater to the needs of paying tourists – all while operating and maintaining the space station. There is a limited window of opportunity to leverage PAM missions and, within the next few years, commercial modules of the ISS to test and refine models to pull off that balancing act.

I&S subsegments



Finally, advancing commercial human spaceflight in LEO (and of course returning to the moon and traveling to Mars), will continue to require significant advancements in astronaut health. Spaceflight takes a massive toll on the human body and can also impact psychological health. After more than 50 years of research by NASA's Human Research Program (HRP) and related studies, we have a better understanding of the health impacts of radiation, confinement, microgravity, and living extended periods away from Earth.

However, the research to date is based on a relatively homogeneous sample population: professional astronauts who meet rigorous physical and mental health standards. As LEO becomes open to a more diverse population of potential private astronauts who have varying baseline health characteristics, the issue of astronaut health becomes central in making space responsible, equitable, and inclusive. New research protocols and studies will be needed to better understand how this more diverse population is affected by space. Even as we learn more about how spaceflight affects the body and mind, the science for preventing or mitigating those affects is still a relatively incomplete. NASA and commercial providers alike need to continue developing and testing ways to keep astronauts healthy and safe through all stages of space missions.

Delivering the future: What is it going to take to build the foundation for growth in LEO?

As we envision the future commercialization of human spaceflight in LEO, it's clear that I&S are foundational to growth. More capability and scale across I&S sub-segments are critical success factors in closing the business case for activities like space tourism, on-orbit R&D and manufacturing, and media, entertainment, and marketing. Each requires technological advancements, new platforms, and more maturity in the underlying industry architecture for commercial spaceflight. NASA is among the US government agencies striving to advance that vision, but private industry plays a central role. Collectively, they will need to leverage the right mix of policy, investment, collaboration, and innovation. If successful, building the next generation of I&S stands to not only make commercial human spaceflight economically viable, but also, in doing so, generate substantial value that cascades across the broader LEO market. With this in mind, we suggest the following strategies to advance key components of I&S over the next decade.

Government leadership to foster conditions for growth

While commercial providers are dramatically reshaping the space industry, NASA and other agencies continue to play a critical role in the commercialization of LEO. Each brings valuable capabilities, institutional knowledge, and unique levers that can help shape and advance the market. We suggest that US government agencies consider the following strategies:

- **Embrace the strategic imperative for commitment to the CLD program** and related programs that will help prevent a gap in US astronaut presence in LEO, promote competitiveness of US private industry on a global stage, and sustain the US position as a leader in human spaceflight.
- **Continue to refine and communicate a clear signal of demand for human spaceflight services in LEO**, including sufficient detail on the procurement strategy for severable services that may enable offerors to further optimize their platforms and refine their business case development for non-NASA demand.
- **Enact agency-level strategies for knowledge transfer in key technical and operational domains related to human spaceflight**, including to parties that are not currently engaged in commercial LEO programs (e.g., using space act agreements), to promote additional innovation and industry competition.
- **Continue to define and update strategies and policies at the Executive Branch level** to promote cohesive and synergistic action between NASA, the Federal Aviation Administration (FAA), Office of Space Commerce, US Space Force, and other relevant agencies. A focus on strategies that will advance safe, sustainable, and equitable access to space may help ensure that LEO (and beyond) remains accessible as a "commons" for commercial I&S.

Industry innovation where space meets 'Industry 4.0'

We anticipate that advanced technologies like additive manufacturing, digital engineering, and AI may serve as catalysts for growth in the space industry. Some of these technologies are already in use by leading agencies and companies in the space industry, but we expect their convergence will further amplify their potential. For example, NASA recently demonstrated the use of generative AI in concert with additive manufacturing to design stronger, lighter components than traditional engineering approaches have produced.[33] As such, both government and commercial players should consider:

- **Seeking more ways to adopt elements of Industry 4.0** including, but not limited to, using generative AI to design hardware and software with shorter cycle times and increasing the scope and scale of digital engineering to add flexibility and agility across the enterprise.

Commercial Crew Program
Astronaut Training - Nicole Mann
Image Credit: NASA

Public-private collaboration to enable a new industry architecture

While opportunities abound to apply emerging technology solutions to many of the problems outlined above, ensuring approaches are unified and interoperable may also help accelerate progress towards mature I&S segments. Considering that there are 10,000 companies focused on space globally,[34] many of which are entering into I&S sub-segments that have traditionally been government owned and operated, a new industry architecture is needed to foster collaboration, transparency, and new value-generating services. Close collaboration between government and industry is likely needed to realize that architecture. For example, we suggest that government and industry consider the following strategies:

- **Adopt a "middle-out" approach centered on commercial destinations** as the largest current gap in I&S to enable commercial human spaceflight. Map the barriers, enablers, and inter-dependencies from a perspective that places commercial destinations as the focal point of the broader I&S ecosystem.
- **Conduct trade studies and leverage cooperative agreements to create technology standards** that promote interoperability throughout the I&S ecosystem, particularly with respect to ISAM. For example, consider focusing on standards for communications protocols and hardware components that serve as interfaces between groups of suppliers and consumers.
- **Invest in key technologies and standards for STM** that promote safe and sustainable access to LEO and support trust and transparency for operators, investors, insurers, and consumers alike.

Investment at scale to overcome the tipping point for economic viability

The commercial human spaceflight market appears to be approaching an inflection point. Substantial demand likely exists but is constrained by the price and availability of today's I&S capabilities. The difference between a future state that resembles today's human activity in LEO and a future state with significant growth will largely depend on the level of investment over the coming five years. For example, if only one of the proposed CLD projects is successful by 2035, the capacity on commercial destinations would likely not exceed that of the ISS. Therefore, we suggest that US government agencies consider the following:

- **Sustain or increase funding for commercial destinations** at levels that reduce the risk of a gap in US access to LEO following the deorbit of ISS.
- **Explore additional acquisition strategies or incentives that will reduce uncertainty** for CLD providers during transition from early design maturation to certification and services phases.
- **Coordinate and fund a robust R&D portfolio** that sustains a floor of demand for human spaceflight services in LEO while advancing ISAM technologies that are critical to the success of commercial human spaceflight use cases. For example, consider a focus on ISAM capabilities with the most promising business cases for in-space manufacturing, or that enable cost efficiencies for assembling and maintaining future human spaceflight infrastructure.

At the same time, we anticipate that commercial players may benefit from:

- **Establishing partnerships that get "skin in the game"** from prospective customers early, such as agreements that reward co-investment with profit-sharing.
- **Investing in R&D and innovation projects for dual use capabilities** that may lend opportunities to spin-off or spin-in products from other industries. This may require more collaboration and engagement outside the space industry.
- **Focusing on operational discipline and capturing incremental and auxiliary revenue streams** for existing or near-term products in order to increase capital efficiency, reinvest cash in R&D, and justify new fund raises.

By 2035, our vision for a vibrant LEO economy includes multiple on-orbit destinations, regular human-rated access to space, and robust capability across other supporting I&S sub-segments. These are the foundations needed to close an increasing number of business cases for human spaceflight and accelerate growth towards a sustainable market driven by commercial demand. Given the rapid pace of change and investment within certain segments of the commercial space industry, we acknowledge that the critical path to a fully commercialized LEO will require continual analysis and reassessment. This is best done collaboratively, and we invite you to join us.

Let's talk

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