The Missing Link to Space Superiority: In-Orbit Refueling

White Paper

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NOVASPACE

About Novaspace

Novaspace is a leading space management and technology consulting firm dedicated to advancing the commercial and strategic development of space capabilities. With expertise spanning orbital operations, space logistics and emerging technologies, Novaspace drives thought leadership, provides actionable insights and fosters collaboration across government, industry and investment communities.

About the expert group

To address the challenges of in-orbit refueling investment and fielding of systems, a small, expert-level group of leaders in defense and commercial space, national security (USA and Europe), the private equity and venture investment community, futurists, strategists and cyber-space experts convened in October 2025 for 2.5 days at a remote location for a seminal "Chatham House Rules" roundtable discussion. These leaders were hand selected for their expertise in defense and commercial space systems, proven track records of seeing ahead into the future, designing asymmetric strategies to navigate around the difficult or impossible, stimulate technology and systems innovation, attract private equity and large programmatic management expertise.

What clearly emerged is that in-orbit refueling must be one of the key strategic priorities for space, both commercial and defense, and demands immediate attention.

About this paper

This paper is a **call to action**. It seeks to demystify in-orbit refueling, highlight emerging security vulnerabilities, and clarify the commercial and investment opportunities for policymakers, program leaders, operators, and investors.

This paper is intentionally comprehensive to cover the different facets of in-orbit refueling: technology, policy, operations, and investment. While longer than a typical brief, the content is designed to provide clear, practical insight across all these areas. A detailed table of contents is included for easy navigation, but readers may go directly to sections most relevant to them, though reviewing the full document will provide the strongest understanding of the strategic context.

Table of Contents

Figures

1. Executive summary

"If a society, a continent—in this case, Europe—does not maintain its own independent sources of data, information, and technology, it will inevitably lose out. That's why space is not only strategic but deeply embedded in the economic sector." — Josef Aschbacher, Director General of the European Space Agency (2025).

Space is becoming the decisive strategic domain for both economic prosperity and national security. The survivability and maneuverability of defense constellations, and the scalability of commercial satellite fleets, are still fundamentally constrained by finite onboard fuel. **In-orbit refueling (IOR)** is the missing capability that enables both military agility and commercial sustainability. Without scalable in-orbit servicing and refueling, space becomes more congested, more vulnerable and less investable.

The situation is reminiscent of the early space race. Sputnik in 1957 redefined the balance of power and catalyzed decades of U.S. leadership. A similar inflection point is emerging today, where **IOR is poised** to redefine space operations and market dynamics.

A significant inflection point occurred in June 2025, when China appeared to achieve an operational IOR event (Shijian-25 servicing Shijian-21) in the geostationary (GEO) orbit. While U.S. companies pioneered much of the underlying technology, China's ability to conduct a fluid transfer in-orbit suggests a shift from controlled demonstrations toward operational logistics. This development highlights that **refueling is progressing globally** regardless of U.S. pacing, and it reinforces the need for **deliberate Western investments** to avoid strategic and commercial disadvantage.

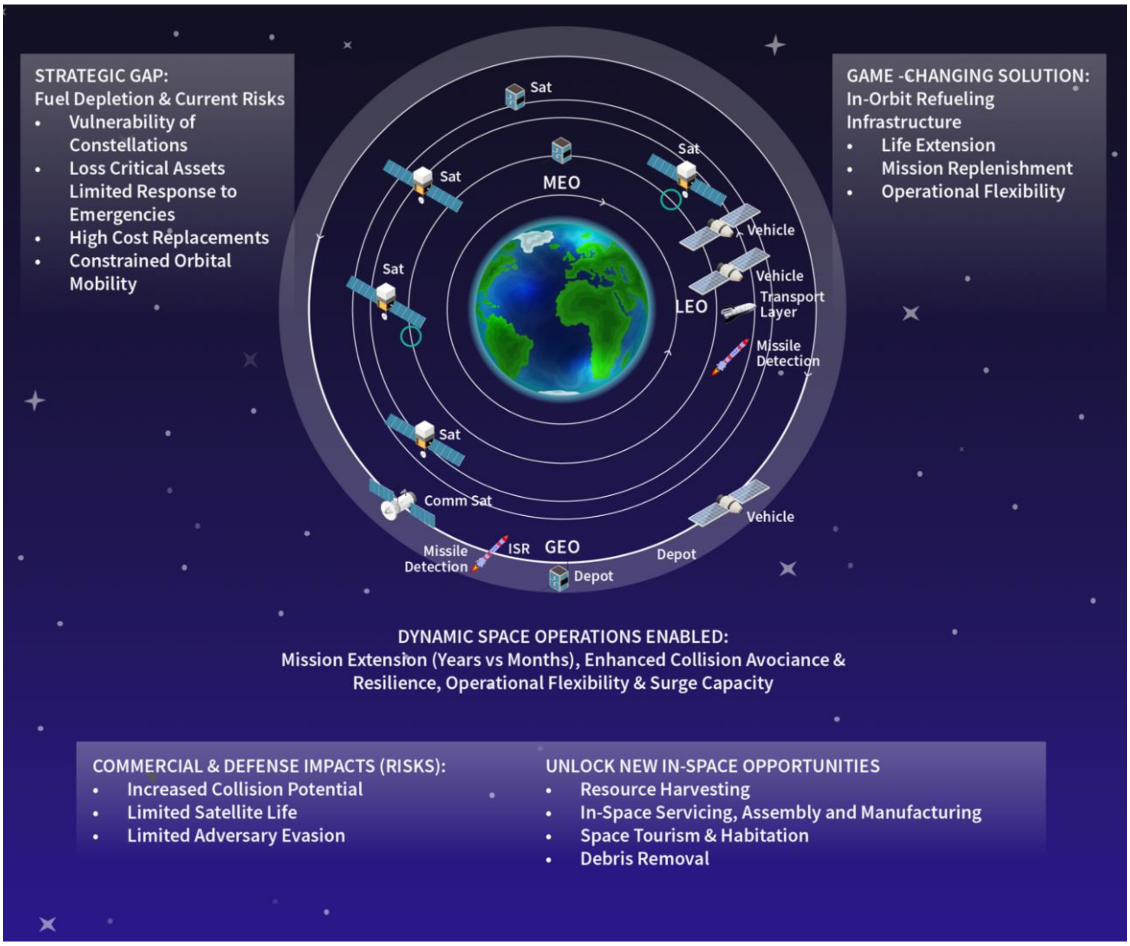
Whether or not China seeks to dominate space, the lack of shared standards, coordinated launch and orbital data, and accessible refueling infrastructure creates unnecessary risk for all operators—commercial and defense alike. In **alignment with the mandate** for a responsive national security architecture under **Executive Order 14369**, the U.S. is **accelerating the deployment of next-generation space capabilities, specifically IOR**, to ensure sustained operational dominance. Orbital maneuverability, **dynamic space operations (DSO)** and IOR are more critical than ever and are possible with IOR technology maturity. While military aircraft refueling is intuitive, many satellites lack the fuel to match the multi-system longevity of current and evolving space platforms, let alone conduct combat or logistics operations. China's nascent ability to refuel and resupply satellites signals a shift from episodic experimentation to operational space logistics—a game changer in a game which the West had created.

Now, and in years ahead, little will happen without **just-in-time, on-demand access to satellite fuel.** With deliberate investment, standards and education, IOR can transform a strategic vulnerability into a durable advantage, enabling robust defense capabilities while unlocking a space economy anticipated to reach trillions USD over the next decade.

The broader ability to refuel, reposition and repair satellites in orbit will determine which actors can sustain space superiority in crisis and unlock the full potential of the space economy in peacetime. IOR is not merely a life-extension toolkit, but it is a foundational infrastructure, critical to resilient, maneuverable and economically vibrant in-space operations.

Imagine how costly air travel would be if each aircraft could only fly once and had to be discarded because it could not be refueled. Space operations face the same challenge today—maneuver, a fundamental warfighting principle, is severely constrained without an on-orbit refueling backbone. Yet current private investment in IOR remains below $100 million USD, with government funding similarly limited. This level of **resourcing is increasingly misaligned** with the strategic importance of orbital logistics and with the accelerating efforts of foreign competitors. The gap underscores an **urgent need for coordinated public–private action now**, before others define the architectures, standards, and operational norms that the U.S. and allies will have to follow rather than shape.

Figure 1: Urgency and opportunity: In-orbit refueling for strategic and commercial advantage



10 main takeaways: 5 key findings and 5 recommendations

Key findings:

1. **Fuel, not technology, is the primary constraint on space power:** Across GEO, LEO (low earth orbit) and MEO (middle earth orbit), satellites are retired or operationally constrained not because sensors, processors, or power systems fail, but because propellant is exhausted. Today's satellites are operated conservatively to preserve fuel, limiting maneuver, training, testing and responsiveness. This constraint suppresses both military effectiveness and commercial value creation.

2. **In-orbit refueling is mischaracterized as "life extension" only,** masking its real strategic and economic value. Treating refueling primarily as a GEO life-extension tool dramatically understates its impact. The true value lies in enabling DSO: frequent maneuver, rapid repositioning, sustained presence, adaptive tasking and operational surprise, while enabling commercial companies to reduce replacement costs, respond to market demands and create new revenue streams through flexible, service-oriented space business models. Life extension is baseline, not the full business case.

3. **China is moving faster from demonstration to operational space logistics:** Observed Chinese activities involving Shijian-21 and -25 suggest not just refueling experimentation, but intent to deploy logistics infrastructure, including depots and tanker concepts, at scale. This indicates an evolution toward routine in-space logistics operations, with implications for deterrence, market access and orbital norms ahead of Western countries.

4. **Launch-dependent architectures can create strategic and commercial fragility:** Reliance on a small number of launch providers creates chokepoints that affect both defense readiness and commercial profitability. Weather, geopolitics, infrastructure outages and monopolistic pricing all introduce systemic risk. Without in-space logistics, operators are forced into conservative satellite designs and costly replacement cycles that constrain innovation, returns and operational resilience.

5. **The refueling market will not self-organize without coordination, standards and de-risking.** In-orbit refueling faces a classic coordination failure:
    1. Operators will not adopt refueling without standards and affordable infrastructure
    2. Investors will not commit capital without demand certainty and risk mitigation
    3. Manufacturers will not standardize interfaces without policy signals

Recommendations:

6. **Accelerate transition from technology demonstrations to operationally relevant refueling missions and infrastructure**: U.S. and European efforts should prioritize repeatable, multi-client, multi-orbit demonstrations that reflect real operational use, including inspection, relocation, servicing and sustained maneuver, rather than one-off proofs of concept. Programs such as the U.S. Tetra-5 and European ISOS (in-space operations and services), ASTRAL (advancing satcom technology with refueling and logistics) and Odyssey initiatives should be treated as steppingstones toward deploying dedicated refueling shuttles and orbital propellant depots, enabling a resilient, persistent logistics network in space rather than remaining purely R&D prototypes.

7. **Establish common refueling and servicing standards across allied ecosystems:** Interoperability is the single most important market accelerator. Governments should mandate or incentivize common mechanical, fluid and data interfaces for satellites above defined cost or mission thresholds and endorse supra-national working bodies like NATO/

other allied agencies to foster coordination of standardization, harmonization and interoperability. Standardization lowers insurance risk, unlocks secondary markets and enables infrastructure-as-a-service business models, accelerating commercial adoption.

8. **Create a joint U.S.–European space logistics investment framework wherever possible:** treat orbital refueling and servicing as civil infrastructure with assured military/public utility. Public capital should be applied deliberately to de-risk private investment through:
   - Anchor-tenant contracts
   - Cost-sharing for depots and servicing vehicles
   - Guaranteed demand for refueling and mobility services

   This mirrors how airports, fuel depots, ports and sealift were co-funded to support both commercial activity and standby military operations, creating resilient capability and bankable markets for private investors.

9. **Treat in-orbit refueling as a critical enabling service, not a niche capability:** Refueling, depots and servicing fleets should be viewed as strategic infrastructure, comparable to ports, pipelines and energy grids. Ownership concentration, access rules and resilience must be addressed early to prevent future bottlenecks or coercive leverage over commercial and defense operators.

10. **Reframe space operations culture—from fuel preservation to maneuver dominance:** As Lt Gen. (Ret.) John Shaw has argued, the mindset must shift *from "driving to church" to "operating for combat and competition."* Policymakers and operators should:
    - Budget fuel for dynamic maneuver and training, not just survival
    - Design constellations and satellites for refuelability/servicing by default
    - Reward operational agility, not just longevity

    This cultural shift is essential to unlocking both deterrence value and commercial upside, enabling a sustainable and investable space economy.

This white paper is a **call to action**. It seeks to demystify in-orbit refueling, highlight emerging defense vulnerabilities, and clarify the commercial and investment opportunities for policymakers, program leaders, operators and investors. Absent early government leadership, interoperable standards and public-private investment, the market will remain fragmented and bespoke, increasing operational, financial and insurance risk despite clear strategic and commercial benefits.

2. The space superiority context

"We should never be buying another satellite that is intended for a contested environment that isn't maneuverable... We need to be able to move our assets. We need to be able to refuel them."
— Lt. Gen. John Shaw, Deputy Commander, U.S. Space Command (2023)[1]

2.1. Defining space superiority

We define "space superiority" here as **the sustained, autonomous and independent two-pronged ability to access space, maneuver and operate in orbit across defense, civil and commercial domains**, while maintaining the option to exclude adversaries or deny that same freedom of action and use of space. It combines the **physical, cyber and electromagnetic aspects of space activity**, making sure that satellites and their supporting systems are protected, resilient and can be quickly restored or replaced if disrupted. Achieving and maintaining space superiority rests upon securing a constant presence in orbit, control of space infrastructure and ability to respond rapidly to new threats or operational challenges.

"Sovereignty in Space is a requirement for sovereignty on Earth" (Michael Schoellhorn, CEO Airbus Defense & Space, Handelsblatt Konferenz "Sicherheit & Verteidigung", Berlin 22 Jan 2026)

[1] At Schriever Spacepower Series event at the Mitchell Institute for Aerospace Studies (July 2023)

Figure 2: Key capabilities defining & enhancing space superiority

Key variables	Description	USA	Europe	China	Russia
Total Space Budget 2024	*Budget allocated for the year 2024 (civ+mil)*	**Ca. $80 Bn**	**$17 Bn**	**Ca. $20 Bn $38 Bn (PPP adjusted)**	**Ca. $6 Bn**
Number of Satellites Launched in 2024 (total tonnes)	*Total number of satellites launched in the year 2024 (in brackets the total mass of satellites launched)*	**2263 satellites (ca. 1700 t)**	**116 satellites (ca. 34 t)**	**276 satellites (ca. 134 t)**	**94 (ca. 28 t)**
Launch Capability	*N. of total orbital launches in 2024*	**154** (134 SpaceX)	**3** (2 Vega,1 Ariane 6 maiden)	**268** (primarily Long March family)	**11** (primarily Soyuz 2 family)
Human spaceflight & orbital lab. capability	*Active space stations*	ISS station (Lead partner), supporting US commercial stations	ISS station (Partner Via ESA), future tbd	Tiangong (National Station)	ISS station (Russia segment), uncertain future after its retirement
Moon / Mars Landing	*Human & robotics landings to date (success./unsuccess.)*	Moon **13/3** Mars **9/1**	Moon **0/0** Mars **0/2**	Moon **4/0** Mars **1/0**	Moon **8/6** Mars **0/4**
ASAT capabilities	*Current*	●	◔	◕	●
Refueling Capabilities	*Current*	◑	◔	◕	◔

Notes: ASAT Capabilities = Ability to detect, target and disable satellites whether though kinetic or non kinetic means; Source: Novaspace analysis

○ *No capability* ● *Fully operational*

Source: Novaspace analysis

Space has become an indispensable pillar of defense and security, shaping how nations communicate, navigate, observe, and exert influence across the globe. The ability to access, maneuver, and operate freely in orbit is now a determinant of national resilience and global influence. This **superiority is not only achieved through the possession of more satellites, but through the capacity to effectively sustain operations, defend critical assets and recover from disruption faster than adversaries**. The U.S., Europe, and China embody three distinct approaches to achieving this objective, while a growing number of emerging players make space a more multipolar domain, where power, capability and influence are shared among many nations.

The actors vying for space superiority are undoubtedly a select group of actors, with the US/Europe and China out in the lead, and to a lesser extent Russia and India, chasing the leaders. On the one hand, each current global spacefaring leader has long recognized the roles that **diverse independent capabilities** have on space superiority and have heavily invested human and financial resources in the development of key national space assets. These include a healthy variety of launchers and access to spaceports, autonomous global navigation satellite systems, Earth observation satellites, secure communication satellites, and more recently, observational and computational capabilities aimed at a **precise space situational awareness (SSA)**, including the tracking and surveillance of satellites.

On the other hand, major space powers are expanding their domestic space capabilities by investing in **advanced services such as IOR and other orbital logistics**. However, leading nations are taking different approaches to IOR and in-orbit services, such as life extension and orbital transfer vehicles, and these choices will determine who can sustain space superiority.

Foundations of space superiority: defense capabilities and operational concepts

The concept of space superiority, originally highlighted by the Soviet launch of Sputnik, has since evolved. Today, it includes not just launching and controlling satellites but also ensuring the **freedom to maneuver, service, upgrade and refuel** space assets at will. The rise of **DSO**, which emphasize adaptability, versatility and responsiveness across space systems, underpins modern space superiority. This expanded view recognizes that sustained operational advantage in orbit is essential for deterrence, national security and effective warfighting capabilities.

Maintain Space Superiority: On-Orbit Refueling Preserves Agility, Reach and Deterrence
Space superiority - the degree of control that allows forces to operate at a time and place of their choosing without prohibitive interference from space or counterspace threats.
Dynamic space operations - rapidly maneuvering, reconfiguring and sustaining assets in orbit.

In essence, space superiority on the defense side entails but is not limited to DSO, the end-to-end ability to service, upgrade, reposition, repurpose, and refuel satellites at will without interruption or observation and without concern for fuel or mission impact.

Commercial space operations and strategic market imperatives

Commercial space systems have expanded at an unprecedented pace, becoming **foundational to global economic** activity supporting aviation, autonomous systems, logistics, navigation, banking, communications, weather forecasting, remote sensing and even emerging markets like tourism. As reliance on these systems grows, leadership in space is increasingly a determining factor in national competitiveness and strategic resilience. In the commercial domain, success is driven by profitability, market capitalization, and the ability to outpace competitive threats thereby making sustained access to space and control of critical orbital infrastructure essential to both economic strength and strategic advantage.

In addition to **extending the operational life** of a revenue generating asset, IOR provides the ability to maintain custody of the orbital slot, prevent intrusion by commercial competitors or denial of service operations. IOR also enables asset management of depreciated satellites by creating a secondary market that can be an essential part of planned recapitalization.

Terrestrial companies like Amazon dominate through **superior logistics**. In space, IOR can play a similar role giving satellite operators the flexibility and endurance needed to outperform competitors. Launch monopolies create significant **economic leverage points** in the **space domain**. When a small number of providers control most of the launch capacity, they effectively dictate **cost**, schedule and access, constraining both government and commercial operators. Weather disruptions, geopolitical tensions, or facility outages can further amplify these vulnerabilities. This concentration also limits competition, slows innovation and incentivizes the design of conservative, long-duration satellites, which are typically very expensive to build and operate.

Expanding IOR and servicing infrastructure can **reduce dependency on the launch chokepoints**. By enabling satellites to operate longer, maneuver more freely and adjust to evolving operational needs, operators can defer or reduce replacement launches, optimize satellite design and increase operational agility. **Shared infrastructure**, including multi-operator depots and servicing shuttles, also reduces the strategic leverage of any single launch provider, encourages investment and unlocks more dynamic satellite operations. By combining multiple international launch options with robust IOR and servicing capabilities, operators can increase resilience, reduce operational bottlenecks and maintain strategic and commercial flexibility across both U.S. and European markets.

Ownership of in-orbit refueling and servicing infrastructure represents a critical strategic and economic lever. Control over depots, tanker fleets and servicing shuttles determines which operators can access fuel, conduct maintenance, or rapidly reposition satellites. A **distributed, shared and interoperable infrastructure model** mitigates these risks by enabling multiple operators to leverage common depots and servicing assets, fostering competition, lowering costs and increasing resilience. **Clear policies and standards** for interoperability, access and liability are helpful to maximize the value of this emerging layer of space logistics.

2.2. Current threat landscape and operational vulnerabilities

"The pace with which they [China] put counter-space capabilities into play is mind-boggling."[2] – Gen. B. Chance Saltzman (Chief of Space Operations, United States Space Force)

We face concurrent and accelerating hostile actions (terrestrial, on-orbit and cyber) that undermine space systems across all orbital regimes for the U.S. and its European allies. These threats restrict the freedom of action across all domains and can strike with little warning. Further, the orbital environment faces challenges from legacy, non-cooperative objects, debris and natural hazards such as solar activity, which can disrupt operations and limit flexibility. Events like the 2009 collision between Iridium 33 and the defunct Kosmos 2251 satellite, where neither had fuel or ability to move, illustrate the value of resilient, adaptable constellations.

These operational and environmental challenges highlight that **space superiority is not guaranteed by technical capability alone**; it depends equally on resilience, adaptability and the ability to respond dynamically to threats and hazards. Deliberate adversary actions, particularly by outpacing competitors, pose an additional, rapidly evolving risk to U.S. and Western space dominance.

China represents the pacing challenge. It is pursuing space-enabled kill chains and aims to rival the U.S. in all space technology by 2030, seeking preeminence by 2045. The People's Liberation Army has been ordered to be ready for invading Taiwan by 2027, which the West is taking seriously. China is developing counterspace capabilities to disrupt or destroy U.S. & European military space support, deploying on-orbit maneuverable satellites (e.g., Shijian-21) with dual-use offensive potential and ground-based ASAT (anti-satellite) systems such as missiles, lasers and jammers. It has also recently demonstrated in-orbit refueling, accelerating U.S. space-refueling requirements. [3]

Russia, despite sanctions and funding constraints, **continues to prioritize its space program**. Its efforts include a new space station, nuclear-power applications in space and expanded Arctic monitoring for military operations. Moscow maintains fleets of imaging satellites supporting global military and paramilitary operations, including enhanced ISR (intelligence, surveillance, and reconnaissance) for Ukraine since February 2022. Russia has declared commercial satellites used for

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[2] Source: Politico- Interview with General B. Chance Saltzman (U.S. Space Force Chief).

[3] Xin, L. (2025) China's landmark orbital refueling mission: why 2 US spy satellites hover nearby; Zhang, P. (2025) China's Shijian satellite pair appears to dock in orbit for historic refueling mission; Young, C. (2025) China's satellites may have pulled off world's first in-orbit fuel refill, beating US, Interesting Engineering

military operations are valid targets and is advancing electromagnetic warfare, directed-energy, cyber and both ground-based and co-orbital ASAT capabilities. Most concerning, it is reportedly pursuing a possible in-orbit nuclear weapon, which if deployed would threaten the global use of space for all nations[4].

Deepening collaboration among China, Russia, Iran and North Korea amplifies the threat. In June 2024, Russia and North Korea signed a comprehensive strategic partnership treaty that includes space cooperation. In October, Iran sent satellites to Russia for launch services. China and Russia continue joint efforts on the International lunar research station (ILRS), BeiDou-GLONASS integration and space-debris monitoring, all of which strengthen their collective space and missile capabilities and raise strategic risks of misperception or escalation[5] These developments underscore the accelerating erosion of U.S., Europe and allied freedom of action in orbit.

Historical American space superiority is under direct challenge, creating a sense of urgency for leaders in security. U.S. and allied forces remain limited in **conducting DSO** due to logistical constraints, particularly in refueling, in-orbit servicing and replenishment. **Bold and decisive leadership** is needed to deliver, scale then normalize these capabilities across operational units, rather than pursuing prototypes and demonstrations that sequentially to budgeting after months or years

For example, in the U.S., while the recent U.S. National Defense Authorization Act (NDAA) increases the latitude for the Office of Strategic Capital, at the same time, it does not include a renewal for the Small business innovation research (SBIR) and Small business technology transfer (STTR) programs. This sends a strong message to existing and emergent leaders in space that advancing U.S. space capabilities and early-stage innovation in the face of clear and present threats to our overall defense and commercial posture may simply not be that important. The omission of the **SBIR and STTR from the recent NDAA**, as does continuing resolutions and the **inability to do new starts**, sends precisely the opposite signal necessary to early-stage investors in space, especially for IOR.

"*It is our job to contest and control the space domain, to fight and win so that we assure freedom of action for our forces while denying the same to our adversaries*" *(Gen B. Chance Saltzman).*

[4] Berkowitz, M. and Williams, C. (2024) Russia's Space-Based, Nuclear-Armed Anti-Satellite Weapon: Implications and Response Options; Plumb, J.F. (2024) Statement of Dr. John F. Plumb, Ass't Secretary of Defense before the U.S. House of Representatives,
[5] Kuramitsu, S. (2024) Security Council Rejects Second Russian Space Resolution, Arms Control Association.

3.In-Orbit Refueling (IOR): the game-changer

3.1. What basic principles drive space system design?

In-orbit refueling enables satellites to replenish finite onboard propellant, extending mission duration, enhancing maneuverability and preserving the operational and economic value of space assets. Satellites rely on two essential resources in orbit: **electrical power**, generated by solar arrays and stored in batteries and **propellant** (which may include fuel, oxidizer, or both) to support station-keeping, orbital maneuvers and attitude control. While power can be generated, in orbit fuel is finite and loaded at launch, calculated to balance mass, volume and performance requirements and constraints.

In many cases, particularly for GEO satellites, the depletion of fuel is the main factor limiting operational lifespan. Satellites are often retired not due to system failure, or space technology obsolescence, but because they run out of propellant or no longer have enough to safely deorbit - a critical requirement for responsible operations and sustainable norms in space.

Because fuel cannot currently be replenished in orbit, operators must **meticulously plan and approve every maneuver,** whether to avoid collisions or adapt to mission changes. This leads to a **trade-off between risk management and mission optimization** - preserving propellant often takes priority over pursuing mission enhancements or adapting aggressively to changing conditions. Ultimately, the inability to refuel in space significantly restricts the full capabilities and lifespan of otherwise functional satellites.

3.2. What key capabilities does IOR entail?

IOR is the **process of transferring fuel/ propellant between two spacecraft, already in space**, allowing satellites, space stations, or servicing (or transport) vehicles to extend their operational life, maneuver and reduce the need for costly replacements or new launches. More importantly, IOR is expected to give operators unprecedented flexibility, ending the era when propellant reserves largely determined a satellite's **operational lifetime** and the feasibility of long-distance/duration space missions.

Enabling IOR at scale requires an integrated stack of technologies on both the satellite to be refueled (i.e., the client) and on the refueller, mastery of orbital mechanics and the laws of physics and a robust logistics and infrastructure layer that supports continuous, flexible and versatile operations in a contested and congested space domain[6]:

A scalable IOR ecosystem requires three tightly linked elements: **technology, orbital mechanics and logistics**. Standardized refueling interfaces and autonomous RPO (rendezvous and proximity operations) systems must enable safe and reliable docking across diverse spacecraft without custom hardware, supported by precise GNC (guidance, navigation, and control) frameworks that manage fuel slosh and orbital perturbations. These technical capabilities must align with the realities of orbital mechanics, where every maneuver consumes delta-v and shapes depot placement, service-vehicle trajectories and rendezvous timing. **To scale, refueling must operate as a logistics network** with depots supplying servicers and servicers refueling clients, supported by command and control, real-time space domain awareness and debris-mitigation practices.

Together, these elements form the foundation of a sustainable and expandable orbital logistics architecture. Developing and fielding these capabilities is essential to achieving a resilient, maneuverable space enterprise that can adapt to operational challenges while supporting both commercial and defense objectives.

3.3. Where do main actors stand in IOR development?

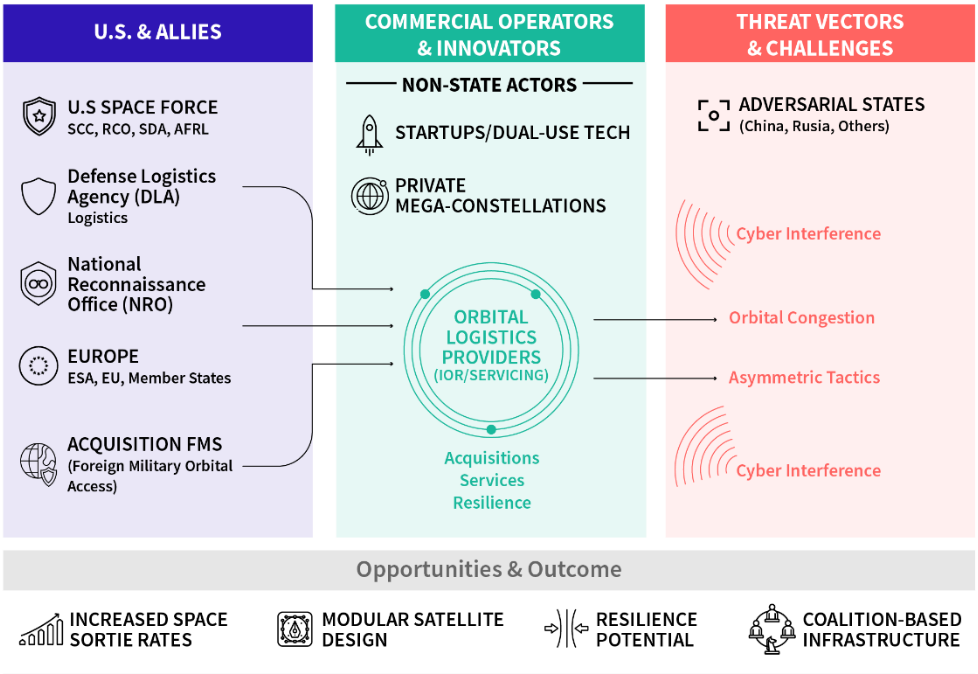
The technical capabilities required for scalable IOR in section 2.2, directly shape which nations and commercial operators can project sustained presence and influence in space. Leading space powers have recognized that mastery of these capabilities is not only a matter of operational efficiency, but a strategic differentiator: independent access, rapid maneuverability and the ability to sustain satellites on orbit underpin both national security and commercial competitiveness.

As a result, in-orbit services and particularly IOR, have become a focus area for global leaders in space. **Countries and companies that can deploy and operate scalable IOR architectures**, integrating logistics, orbital mechanics and advanced servicing technologies, will gain a clear advantage in maintaining orbital resilience, responding to emerging threats or opportunities, and extending mission duration. By contrast, **actors lacking** these capabilities risk being constrained by

[6] Galbreath, D. (2025) A broader look at dynamic space operations: creating multi-dimensional dilemmas for adversaries. Mitchell Institute for Aerospace Studies, 6 November

fuel limitations, maneuvering restrictions and the **operational fragility** of their satellite constellations.

Figure 3: Wildcards, non-state actors and the evolving space refueling landscape



Different architectures and technologies are being explored for the development of IOR capabilities, primarily led by Chinese, European and US public and private actors.

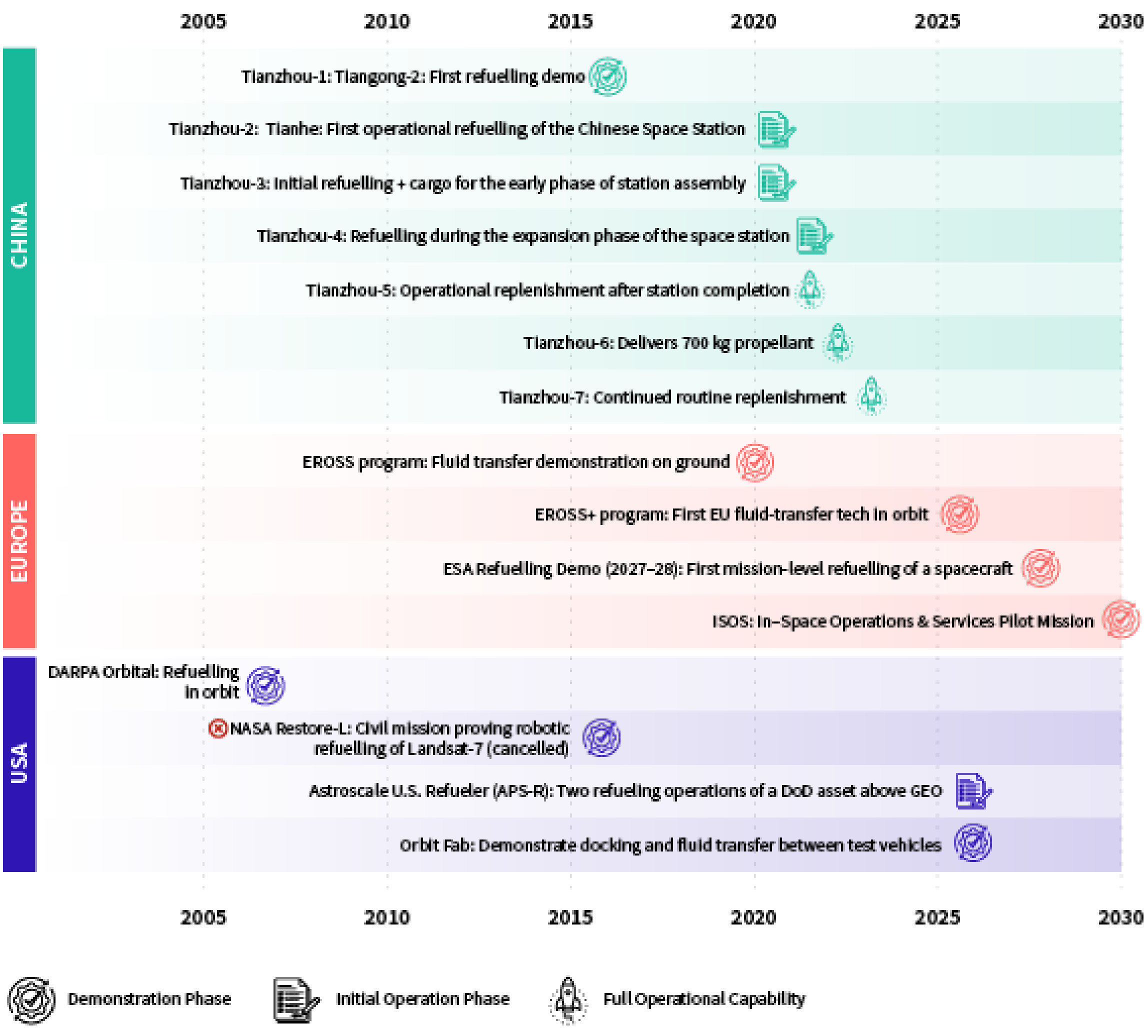
China has invested heavily in refueling technologies, specifically through its Tianzhou program, successfully demonstrating orbital refueling operations in GEO through the Shijian-21 and Shijian-25 satellites, having separated in November 2025 after being docked for several months.

NASA's **Fly Foundational Robots (FFR) demonstration** in late 2027 aims to support in-space operations through a robotic arm demonstration, which could lead to a variety of applications including in-space assembly and manufacturing as well as satellite refueling. The **grip coupling approach** uses mechanical clamps or grapples to attach a servicing vehicle to a client satellite, enabling propellant transfer or component servicing, especially for cooperative spacecraft with standardized grapple points. The **U.S. Kamino program**, funded by the **Defense Innovation Unit** (DIU), will place a hydrazine-carrying satellite into orbit to serve as an on-orbit fuel depot for refueling operations in geostationary orbit. It too uses the grip coupling approach.

Furthermore, the European Space Agency (ESA) has invested in in-orbit technology demonstrations addressing multiple aspects of in-space transportation through the **InSPoC** (in-space proof-of-concepts) activities within the **Future Launch Preparatory Program**. InSPoC coordinates the maturation of key technologies such as RPO, docking, refueling and spacecraft operations in orbit. The proof-of-concepts developed under InSPoC, and a similar IOR demonstration mission named ASTRAL planned by the ESA Satcom team now form the technical foundation for Odyssey, an ESA initiative envisioned not just as a single propellant depot but as a flexible ecosystem supporting the growth of in-space logistics products and services. In addition, the EU, through Horizon Europe funding, has launched ISOS Pilot Programs to advance operational concepts and commercial integration for in-orbit servicing and refueling.

"China has proven that can dock with other satellites and tow them away: (Maj Gen Traut German Command in Süddeutsche Zeitung 14 Jan)

Figure 4: Timeline of development for China, Europe and U.S. (examples of missions)



United States – commercial strength, strategic and financial hesitation

The United States combines proliferated constellations, unmatched launch cadence and deep integration with commercial operators. The US Space Force and Space Development Agency are building resilient, layered architectures designed to fight through disruption. Yet **most US systems remain effectively single use once on orbit**: limited fuel, constrained maneuver and little provision for refueling at scale. IOR is progressing via prototypes (e.g., primarily the **Tetra** programs) and experiments rather than as a coordinated operational capability, leaving a **gap between launch strength and long-term endurance.** U.S. policy and targeted funding, through co-invested depots, anchor-tenant contracts and guaranteed demand, could rapidly turn demonstrations into a scalable, resilient IOR ecosystem, strengthening both commercial competitiveness and military advantage.

China – logistics as a deliberate source of advantage

China pursues space power through state control and military–civil fusion, integrating space, cyber and electronic warfare under the PLA's (people's liberation army) Strategic Support Force. Demonstrated rendezvous and proximity operations, alongside early refueling-related activities, point to a deliberate strategy: logistics and sustainment as a source of asymmetric advantage. In a future conflict, the ability to refuel, reposition, shield, or disable satellites in orbit could allow China to out-maneuver competitors even if it does not match them in raw satellite counts.

Europe – policy-driven autonomy, gaps in operational missions

The European Union anchors its security posture in dual-use, policy-driven programs such as Galileo, Copernicus and emerging secure connectivity initiatives. Europe has strengths in regulation, data sovereignty and advanced manufacturing, but **fragmented governance** and launcher constraints **limit rapid operationalization**. In-orbit servicing and refueling efforts, through EU-Horizon Europe's EROSS (European robotic orbital support services) initiatives and pilot programs (ISOS), the EDF (European defence fund) -funded demonstration mission, ESA InSpoC and ASTRAL for refueling and member-state initiatives such as ASI's (Italian space agency) Italian government-led mission, remain largely in early R&D or proof-of-concept stages to date. Without a more coordinated and assertive approach to orbital logistics, **Europe risks securing autonomy** on the ground while remaining dependent on external actors for in-orbit maneuvering, servicing and satellite life extension.

Emerging spacefaring nations – getting ready to strengthen strategic cooperation

India, Japan, South Korea, Australia, the UAE and others are rapidly building space commands, sovereign constellations and secure links. Few will field full IOR architectures soon, but they will be pivotal customers and partners. Their reliance on a small set of providers for relocation, life extension and refueling will create enduring strategic dependencies. Whether they align their orbital logistics with U.S./European providers, Chinese systems, or mixed models will help define future alliance structures and norms in the security domain.

Private actors- pushing their standards and approaches

United States appear to be trailing China in their IOR capabilities, with NASA having seemingly deprioritized the development of some key capabilities, such as by cancelling the in-orbit servicing, assembly and manufacturing 1 (OSAM-1) mission. On the upside, different private actors are developing solutions targeting different approaches to IOR, such as Orbit Fab and Northrop Grumman.

Two approaches to IOR have emerged in the commercial sector. One approach, exemplified by **Orbit Fab**, organizes operations around clients, depots and shuttles. In this model, client satellites are spacecraft in orbit requiring propellant, depots act as fueling stations in space to store and supply propellant and shuttles transport fuel between depots and clients. These operations take place within a RPOD (rendezvous, proximity operations, and docking) framework, which supports identifying the client satellite in orbit (rendezvous), approaching it safely (proximity operations) and attaching and docking (docking). Orbit Fab has also developed a **rapidly attachable fluid transfer interface (RAFTI),** a cooperative docking and refueling interface that can replace a satellite's existing fill and drain valve to enable in-orbit and ground fueling.

A second approach, illustrated by **Northrop Grumman**, uses an **active servicer and passive client interface**. The active servicer, known as the **mission robotic vehicle (MRV),** carries propulsion, navigation sensors and a robotic arm to approach, dock with and transfer propellant to satellites equipped with compatible interfaces. The **passive refueling module (PRM),** installed on client satellites prior to launch, provides the plumbing for propellant transfer but does not actively pump or control fuel flow.

Both approaches demonstrate different ways to extend satellite life and provide in-orbit servicing, illustrating the diversity of emerging IOR architectures.

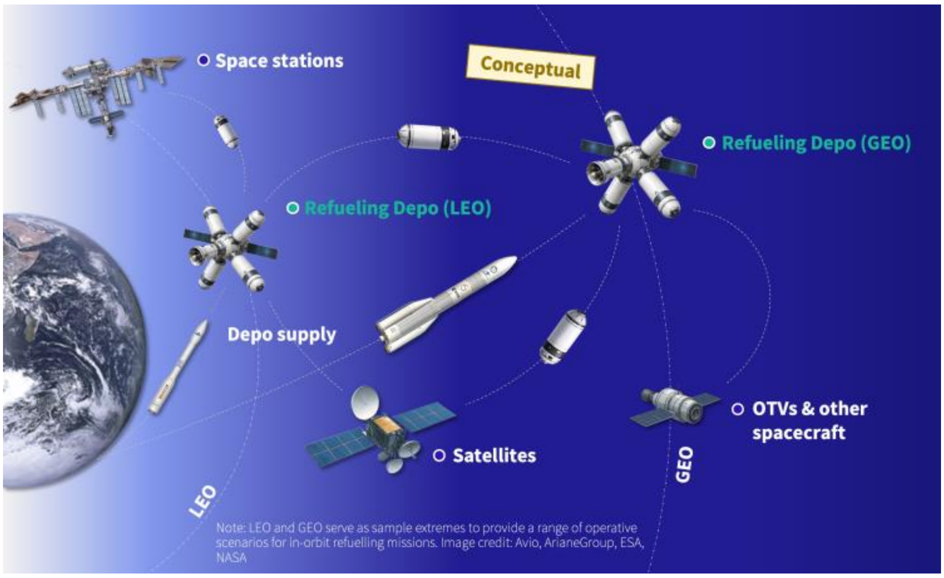
Two logistics architectures are emerging

Two logistical architectures are emerging for IOR. The first is **mission-based** (targeted refueling launches), in which a refueling servicer is delivered precisely to the customer location, performs rendezvous and docking, and transfers propellant to the target satellite, extending the respective attitude and orbit control system (AOCS) & orbital maneuvering capabilities. After the mission, the servicer is either disposed of, or if designed for reusability it is put in standby for the next service. The figure below illustrates a mission-based IOR concept of operations. Implementing an IOR service relying on this approach is achievable in short- to mid-term, targeting selected use cases such as life and maneuvering capability extension of satellites in Earth orbit.

Figure 5: Conceptual overview of mission-based IOR architecture

The second approach is **infrastructure-based** IOR, which relies on centralized (e.g., one refueling station) or decentralized propellant depots in orbit. These depots act as on-orbit fuel storage, from which servicing or shuttle vehicles transfer propellant to client satellites. This model allows **multiple spacecraft to be refueled** without each carrying excess launch fuel and is being pursued through a range of commercial and agency-led demonstrations and pilot programs. The figure below provides a conceptual overview of an infrastructure-based IOR concept of operations. Compared to the mission-based, the infrastructure-based approach relies on a consolidated network of assets and supply-service routes, boosting refueling efficiency for a wide variety of spacecraft and use cases, even beyond Earth orbit. The infrastructure-based approach can be seen as a natural long-term evolution of the mission-based approach.

Figure 6: Conceptual overview of infrastructure-based IOR architecture



Establishing a **minimum viable infrastructure**, including interoperable depots in high-value orbits, shuttle fleets equipped for RPO and docking and robust command/control systems, **enables rapid, repeatable servicing**, strengthens strategic and commercial resilience and reduces reliance on single-launch solutions. U.S. and European public and commercial partners are already developing potential concepts to enhancing both strategic and economic capabilities.

3.4. What new in-space applications can IOR unlock?

"The way we' ve traditionally operated—with a few, very expensive, high-capacity satellites that are effectively sitting ducks once they run out of gas—is a recipe for disaster in a contested domain." – Gen. B. Chance Saltzman, Chief of Space Operations (Paraphrased from CSO's Theory of Success).

IOR is transforming satellite operations by **unlocking endurance, mobility and mission flexibility**. Beyond life extension, it enables repeated debris removal, more capable payloads and new business models like orbital depots and cislunar logistics. These capabilities **enhance resilience, responsiveness and strategic advantage** for both civil and defense space operations.

GEO satellite life and revenue extension

In-orbit refueling is often framed narrowly as a life-extension tool, but this understates its strategic value. While GEO communications satellites can generate up to $1 million per additional day of operation, **life extension is only the baseline benefit**. Traditional alternatives such as mission extension vehicles (backpacking) tie up capital and constrain flexibility for years. Refueling, by contrast, allows a single servicer to support multiple satellites, **enabling repositioning, adaptive operations and rapid response** to changing conditions. The true value lies in shifting satellites from static, fuel-limited assets to maneuverable, resilient elements of space operations.

Enhanced mobility

Enhanced mobility is a critical use case enabled by refueling. China's reported Shijian-21/ Shijian-25 activities - including refueling followed by a large inclination change equivalent to years of GEO station-keeping—demonstrated how **added propellant can complicate tracking and counterspace planning**. Additional fuel enables satellites to maneuver unpredictably, reducing observability and increasing survivability.

New missions and business models

Refueling enables entirely new missions and business models beyond today's constraints. Concepts such as propellant depots at Lagrange points could support more direct transfers in cislunar space, avoiding slow, low-energy trajectories. Many orbit-raising missions currently rely on efficient but time-consuming electric propulsion spirals; refueling could **significantly shorten commissioning timelines.** For government operators, this translates into **higher sortie rates, greater agility and improved resilience**. Reduced dependence on launch cadence supports a shift toward dynamic, maneuver-centric space operations.

Active debris removal (ADR)

Active Debris Removal addresses the growing risk posed by defunct satellites, upper stages and long-lived debris in congested orbits. Even small objects can cause catastrophic damage at orbital velocities, as evidenced by impacts on ISS (International space station) systems and near-misses involving crewed spacecraft. ADR missions are currently constrained by limited onboard propellant, restricting the number of objects that can be removed per vehicle. Rather than deorbiting a single (defunct/ compromised) object per mission, a refueled ADR vehicle can service multiple targets, dramatically improving cost efficiency and mission viability. In-orbit refueling is **a key enabler, allowing servicers to conduct repeated deorbit missions** and maintain operational readiness.

Expanded mission capabilities

Refueling fundamentally expands the mission design envelope. Today, satellites trade maneuvering capability for endurance, often devoting up to half their mass or volume to propellant. As a result, sensors, power systems and onboard computing are frequently down-scoped or omitted entirely. Refueling reduces this constraint, allowing designers to **prioritize payload performance, processing power and resilience**. The shift is analogous to designing a vehicle without dedicating half its volume to fuel storage. This **unlocks more capable, adaptable spacecraft** without sacrificing operational longevity.

Figure 7: Emerging in-space economy and key enabling capabilities like refueling

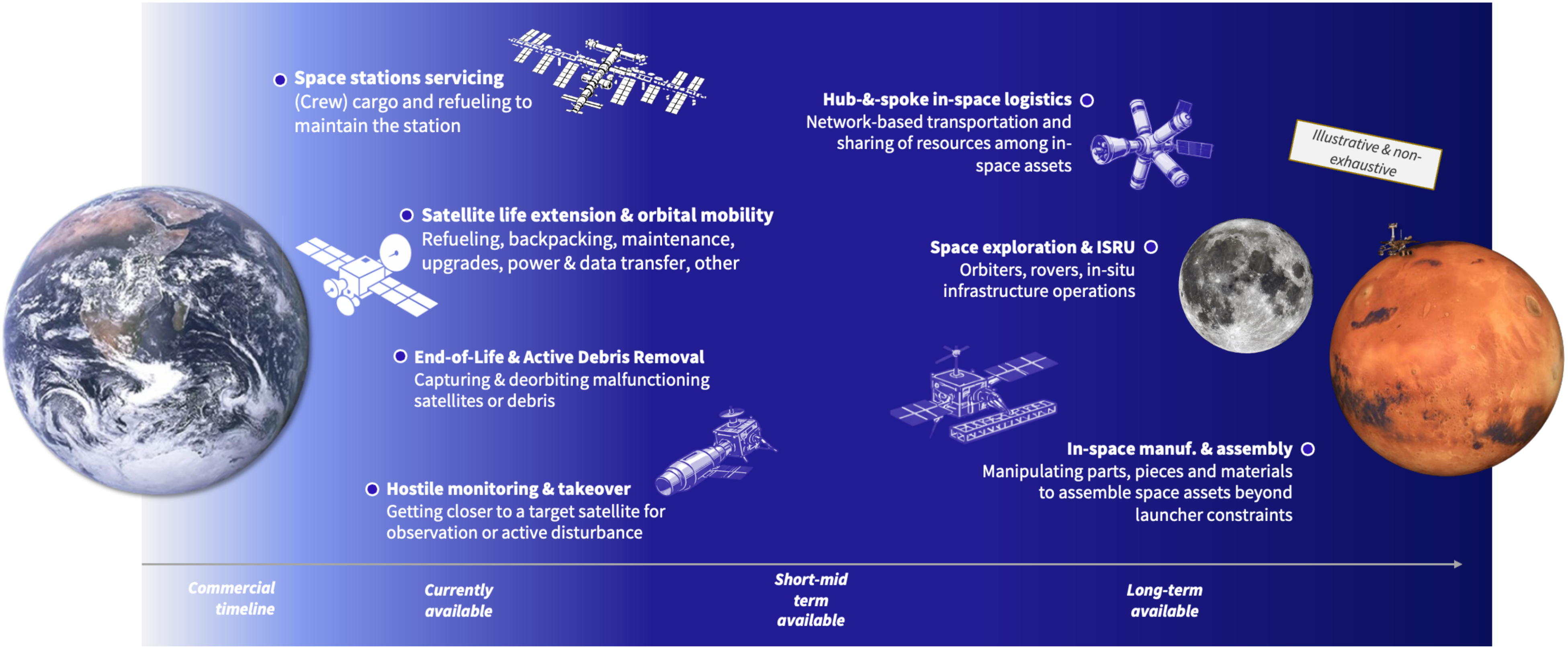


Image courtesy: NASA, ESA. ISRU= In-space resource utilization

3.5. What is the rationale of IOR for defense and for commercial clients?

Defense user perspective

IOR has a growing strategic importance for the defense domain. It gives military and dual use satellites the **ability to maneuver, reposition, replenish and operate for longer periods**, without depending on replacement missions. This added operational **agility allows defense forces to adapt quickly to changing threats** or emerging situations in space.

IOR also **reduces reliance on specific launch windows and ground resupply operations**. Refueled satellites can stay active in orbit for years beyond their design life, maintaining persistent coverage for communication, intelligence, or surveillance missions. This endurance enhances a **country's ability to defend its critical assets and maintain a credible deterrence in space**. Additionally, IOR unlocks a long-term and enhanced maneuverability and responsiveness of critical assets in space, allowing them to retain their role in the overarching defense posture of the space actor.

As mentioned before, for governments and defense actors, the benefits of IOR extend far beyond cost savings. IOR directly supports **DSO,** enabling national assets to maneuver freely, reposition when needed and remain active for long periods. With refueling, a satellite can approach a target, avoid tracking, escape a threat, or adapt coverage over sensitive regions, optimize imaging and communication link.

IOR also enables mission extension for key government functions such as reconnaissance, Earth observation, GNSS (Global navigation satellite system), military communications and satellite inspection among others. In the face of procurement delays, budget pressure, or evolving operational needs, refueling provides **valuable flexibility** and ensures **continuity of service.** It also **supports capability gap bridging**. When new satellites are delayed or when an unexpected operational requirement emerges, refueled satellites can be repositioned to fill gaps temporarily. The fact that refueled satellites can be launched with less fuel and more payloads makes them capable of offering a greater range of services too. This operational agility becomes increasingly important as geopolitical tensions rise.

Due to the variety of applications introduced in the paragraphs above, IOR is anticipated to become a key element of next-generation defense space architecture. Defense organizations are expected to **integrate IOR into their formal planning and budgeting structures**, including U.S. and European budgetary cycles.

IOR directly supports the shift toward **maneuver warfare in space**. Maneuver warfare emphasizes freedom of action, operational unpredictability and the ability to **impose cost and complexity on an adversary**. In the orbital domain, these objectives have historically been constrained by finite propellant and tightly bounded delta-v budgets, **forcing** space assets into largely **predictable orbits** and operational patterns. With assured access to propellant through IOR, national space assets are no longer tied to fixed maneuver limits. Instead, they can maneuver more frequently and over longer durations, sustain dynamic orbital positioning and reconstitute delta-v (i.e., re-fuel) margins as missions evolve. This enables **persistent yet adaptive surveillance**, responsive repositioning and the ability to **complicate adversary targeting and planning**. From a maneuver-warfare perspective, IOR shifts space operations from a model of positional endurance to one of **continuous operational movement**, increasing ambiguity for adversaries and raising the cost of counterspace actions.

More specifically, several defense concepts are expected to benefit directly from emerging IOR capabilities. One example is the proposed U.S. Golden Dome concept, which envisions a large, resilient satellite architecture designed to **disrupt, complicate and increase the cost of an adversary's kill chain.** The U.S. recognizes the potential value of such a concept, as it could provide rapid and reliable protection against missile threats, helping defend critical infrastructure, military assets and civilian populations. However, a common critique is that implementing this type of system would require thousands of fast-moving satellites, each with limited fuel, making them potentially vulnerable to adversary actions and leaving only a small fraction able to be in the right place at the right time. Still, this **weakness exists mainly because traditional satellites have limited fuel**. With IOR, these satellites could stay in orbit much longer, keep the right positions and move quickly to where they are needed. In other words, refueling turns a system that might otherwise be costly and impractical into one that is far more achievable and sustainable.

In the same way, fast-deployable **satellite constellations used for intelligence, space awareness**, or missile warning become more useful when they can be refueled. With extra fuel, they can move into new positions, react quickly to new threats, or temporarily replace satellites that are delayed or not yet launched.

Beyond U.S. initiatives, **European defense programs** in Earth observation, GNSS resilience, secure communications and space domain awareness **would similarly benefit**. IOR enables capability gap bridging, allowing refueled satellites to support continuous service when new launches are delayed, satellites fail earlier than expected or when strategic requirements suddenly shift.

Commercial user perspective

IOR **unlocks** commercial value by extending spacecraft lifetimes, enabling life extension services (LES), improving **maneuverability** and enhancing both **collision avoidance and mission security**. When combined with software-defined payloads and flexible satellite architectures, refueling enables rapid **repositioning**, dynamic market targeting and **recovery from insertion anomalies** that would otherwise degrade or end a mission. Operators can also **trade fuel mass for payload mass at launch**, increasing payload capacity and opening new revenue streams that competitors without refueling access cannot pursue. These advantages compound: greater maneuverability expands markets, thus higher revenue and higher revenue supports further investment in orbital logistics, creating a self-reinforcing cycle of commercial and strategic advantage.

IOR also increases **return on investment** by allowing operators to keep **amortized assets productive** rather than procuring new satellites when demand does not justify replacement. It **defers large capital expenditures** in uncertain markets, reduces launch costs by lowering required onboard propellant and enables operators to wait for complementary technologies to mature before committing to new platforms. Refueling also **mitigates** the financial impact of **orbital anomalies**, restoring maneuverability and preserving mission value. Beyond these direct benefits, IOR accelerates the emergence of a broader orbital logistics economy built on depots, shuttles and servicing vehicles. Interoperable standards such as **Northrop Grumman's PRM and Orbit Fab's RAFTI, now recognized by the U.S. Space Force's Space Systems Command**, help reduce market barriers and increase commercial viability, positioning refueling as a cornerstone of long-term commercial growth and space-domain resilience.

Figure 8: Summary of rationale for IOR by type of customer

RATIONALES FOR ADOPTING IOR	
RATIONALE	**DESCRIPTION**
	DEFENSE USERS
Strategic reinforcement	Enhancing the strategic enabler of resilience, deterrence and space superiority
Dynamic Space Operations (DSO)	Enclosing satellite stealth (avoiding tracking by enemy SSA systems), ability to approach a target for close-up observation, or escape a threat in orbit.
Mission extension	Extending the yields of a government capability (EO, reconnaissance, GNSS etc.), either in addition to a new generation follow-on, or in anticipation of its delay, or to help with pressure on public budgets
Capability gap bridging	Repositioning and potentially extending mission duration to transfer available satellite capacity (e.g., satcom, GNSS, EO) to pain points.
	COMMERCIAL AND CIVIL USERS
Spacecraft value increase	Trading fuel mass for payload mass, hence increasing the commercial value potential
Business extension	Extending the yields of an already amortized satellite to keep addressing a declining market which does not justify buying a new satellite.
Enhancing flexible asset management	Delaying acquisition of a follow-on satellite for a few years, enabling a "wait-and-see" strategy in the face of market uncertainty, waiting for new technology to mature, and gaining time to finance next generation
Mitigate new satellite failure risk	In the event of a launch failure, operators are typically left with about two years to launch a replacement or suffer a capability gap. Life extension of the to-be-replaced satellite buys more time to replace it.
Make up for partial launch failure	In case of a partial upper stage malfunction resulting in imperfect injection orbit, the satellite will have to use its own propulsion to correct course, resulting in lower lifetime which LES can compensate.
Second-hand monetization	LES allows operators to sell or lease satellites reaching design EOL, instead of decommissioning them, to third parties that cannot afford their own satellites or require additional capacity rapidly.

3.6. What is the business case for IOR and how to make it more sustainable?

"Our entire business model is constrained by fuel limitations. We launch birds with a fraction of the fuel necessary for the lifespan of the satellite – we don't maneuver because of fuel concerns – if we could refuel them, we unlock the entire business model" - Daniel Faber, CEO Orbit Fab

Our research highlights that the commercial viability of in-orbit refueling is shaped by four key factors: **hardware interoperability** (spacecraft and interface designs), **infrastructure scale** (depot and shuttle numbers and capacity), **client specifications** and **launch costs**. Early government support is essential to mitigate upfront investment risks and stimulate private sector participation. Over time, **reusability, scalable depot architectures and standardized interfaces** will drive down costs and enable sustainable business models.

LEO: low-cost entry, faster payback

In LEO, the business case for IOR, specifically single-mission hydrazine delivery, is driven by a lean cost structure and high-value asset targeting. Benchmarked against recent industry demonstrators and operational shuttles, the total mission cost for a single-refuel deployment is primarily concentrated in spacecraft manufacturing and RPOD systems.

Unit economics are optimized by a **higher propellant-to-dry-mass ratio**. If the required propellant mass remains relatively low, the servicer can utilize smallsat-class architectures, which significantly reduces launch and mission operations overhead compared to traditional heavy-satellite development. This cost profile identifies **LEO as the most immediate domain** for commercial viability, particularly for extending the life of high-value assets.

Market scalability in this region is further de-risked by institutional support, such as ESA's InSPoC-1 or ASTRAL missions. By **standardizing docking interfaces and autonomous rendezvous protocols**, these initiatives lower the technical barriers to entry and ensure multi-mission interoperability. Our estimates reflect an integrated view of current program budgets, established RPOD performance benchmarks and extrapolated launch costs for the smallsat class, positioning refueling as a sustainable and scalable service.

GEO: premium market with strategic ROI

In geostationary orbit, the economic profile shifts from the high-volume model of LEO to a premium service model. Total mission costs in GEO are significantly higher, reflecting the technical demands of deep-space transit, increased spacecraft dry mass and substantially larger propellant requirements. On the other hand, larger servicers for these operational scenarios translate into a **favorable scale factor for GEO** missions, potentially contributing to lowering price per kg of propellant delivered compared to LEO use cases.

Consistent with the logic applied to LEO, dedicated refueling shuttles offer a more compelling Return on Investment (ROI) than multipurpose servicing vehicles. **By focusing strictly on fuel transfer, the mass penalties and mission complexities** associated with robotic manipulation are minimized, as well as in general the mass constraints for additional mission and sensor capabilities not supporting IOR and factors that might also drive-up launch costs and risk profiles.

Because of this higher capital expenditure base, the **GEO market demands a strategic pricing approach**. Profitability in this domain is potentially achieved through three primary levers: reduced risk by increasing **technology readiness levels** (TRL) and maturing concepts of operations through **synchronous prototype** activities, commanding **premium service fees** for high-value mission-critical assets, and utilizing a multi-client architecture where a single servicer supports multiple satellites per deployment with potential replenishment itself from an in-orbit depot. This ensures that the increased cost of operating in GEO is offset by high-margin revenue streams.

IOR vs replacement: strategic trade-off

A key consideration in the IOR business case is the trade between refueling and replacement costs. Launch cost, access to launch capacity and associated timelines directly affect the value proposition of refueling versus satellite replacement. While refueling can extend operational life, operators must weigh the time and cost savings against the expense of launching replacement satellites, particularly in GEO where replacement can take months or years—time being another less tangible cost. Delays in launch availability or extended build times increase the opportunity cost of waiting, whereas in-orbit refueling provides more immediate operational continuity. **These factors—launch cost, timing and satellite replacement cycles—must also be incorporated into economic models** to fully capture the sustainability and strategic value of IOR. As shown below replacement becomes significantly less desirable to IOR once refueling infrastructure is in place.

Metric	Replacement (new launch)	IOR (refueling)
Capital outlay	100% (full manufacturing+ launch)	~ 35% (service fee)
Time to readiness	2-3 years (build/launch)	3 months (mission planning)
Operational risk	Medium-High (launch failure/ delay) depending on launcher reliability	Currently high but de-risked once persistent IOR infrastructure in place (proximity ops with healthy sat)
Revenue impact	Potential gap during transition	Continuous service

Pairing persistent refueling mission spacecraft with multiple sequential refueling services prior to its own resupply, improves the economics of IOR in both LEO and GEO. Analysis of mission scenarios indicates that dedicated refueling services - separate from more complex satellite servicing tasks - offer the most cost-efficient approach. By **isolating fuel transfer from more advanced robotic operations**, servicing vehicles can remain simpler, lighter and lower cost, while complex robotic or non-cooperative servicing operations incur higher development, operational and risk costs. This distinction is critical when shaping program requirements and evaluating potential government or commercial RFPs, as it allows mission planners to optimize **both price and operational efficiency**.

Depending on the bus used and any number of variables associated with design, refueling a geostationary satellite for extra **five years can easily save more than $100 million** compared to launching a replacement where replacement costs include launch price and availability, schedule constraints and time. In many cases, the time required to commission/acquire, build, launch and test a replacement satellite represents a **significant opportunity cost**, because the on-orbit asset continues to generate revenue or provide essential government services during the extended period a replacement would take to arrive. In this context, IOR delivers value not only by avoiding the capital cost of replacement, but by preserving continuity of operations and preventing revenue or mission-service gaps.

Key takeaways:

- LEO refueling enables near-term **commercialization** with small servicing vehicles and lower infrastructure requirements
- GEO refueling supports **long-term value** by extending satellite lifespans and reducing replacement costs, especially where launch availability is constrained
- Dedicated refueling services - decoupled from robotic or complex operations - offer the best economics across both orbits
- Standardized interfaces and government-backed programs will be critical to **de-risk the market.**

For investors and policymakers, we underscore the importance of **mission planning efficiency**, **standardized interfaces** and **persistent refueling missions** to reduce costs and support a viable business model across orbital regimes.

3.7. What are the key operational enablers?

IOR introduces a new class of operational, financial and systemic risk that must be deliberately managed. Refueling requires close-proximity operations between high-value spacecraft, increasing exposure to inadvertent contact, fuel leakage, or damage to the client vehicle. A failure during such operations can result not only in the loss of the serviced satellite, but also in the generation of debris that threatens other nearby spacecraft, potentially amplifying risk across a congested orbital regime.

For investors, this translates into asset loss, insurance exposure and portfolio-level risk; for policy makers, it raises concerns about shared infrastructure, space sustainability and cascading economic impacts.

The long-term viability of IOR therefore depends not only on **technical feasibility, but on disciplined operational practices, demonstrable risk mitigation and governance frameworks** that reduce both the probability and consequences of on-orbit incidents[7].

Critically, mitigating these risks requires more than access to fuel or the ability to perform one-off refueling demonstrations. A viable space refueling market **depends on standards, interoperability and a scalable logistics infrastructure** that supports end-to-end servicing across multiple platforms, missions and operators. Without common interfaces, refueling remains bespoke, capital-intensive and difficult to insure, much like a terrestrial fuel system in which every vehicle requires a different nozzle and fueling procedure.

Because refueling hardware and interfaces must be integrated prior to launch and cannot be retrofitted on orbit, adoption depends on **coordinated action across manufacturers, operators, regulators, funding and capital providers**. This creates a classic coordination problem: industry is unlikely to converge on standards without regulatory clarity and demand signals, while private capital remains constrained without evidence of government commitment and risk sharing.

As a result, meaningful progress in in-orbit servicing and refueling demands that governments move beyond passivity to aggressively de-risk early deployments, enforce standardization and inject strategic capital alongside private investment[8]. This decisive action is critical to catalyze a sustainable market before adversaries and global economic competitors outpace our capabilities. **Time is of the essence**: government and industry leaders must synchronize imminently to accelerate infrastructure funding. If the current inertia persists, the U.S. and its allies might lose their strategic edge in space.

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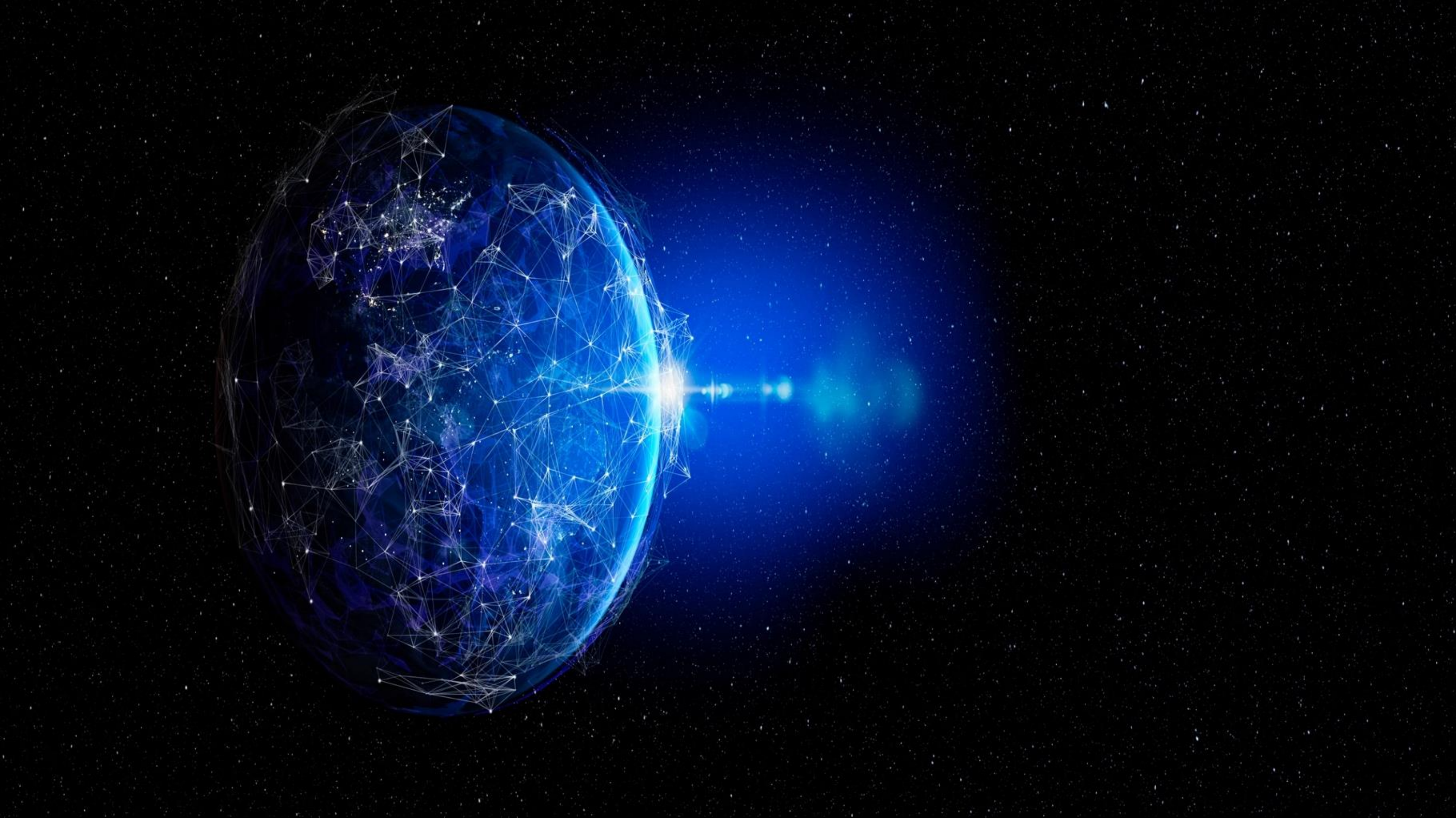
[7] Fehse, W. (2003) Automated rendezvous and docking of spacecraft; Klinkrad, H. (2006) Space debris: models and risk analysis; National Research Council (2011) Limiting future collision risk to spacecraft; OECD (2020) Space sustainability and the economics of space debris

[8] National Research Council (2011) Limiting future collision risk to spacecraft; Saleh, J.H., Lamassoure, E., Hastings, D.E. and Newman, D. (2006) 'Flexibility and the value of on-orbit servicing'; CONFERS (2018–2022) Guiding principles for on-orbit servicing and rendezvous operations; DARPA (2017–2020) Robotic Servicing of Geosynchronous Satellites (RSGS) Program documentation



4. The near future: strategic implications

4.1. IOR in defense: next 1–5 years

Over the next five years, **IOR and servicing** will become a cornerstone of **maneuver-centric space operations** and a **resilient space economy**. Integrating IOR planning and procurement into U.S., European and allied budget cycles will enable satellites to reposition rapidly, operate with agility under threat and support **modular, optimized designs** across GEO, MEO and cislunar domains. Beyond life extension, this capability underpins **deterrence** by sustaining maneuverable, resilient forces while strengthening space-enabled industries critical to commerce, security and national infrastructure.

Shared, interoperable infrastructure (e.g., depots, servicing vehicles, and standardized interfaces) reduces reliance on single launch providers, mitigates operational and financial risk and increases the viability of a **commercial space logistics market**. Governments can accelerate adoption by rigorously engaging with commercial providers to ensure defense requirements for responsiveness, endurance and maneuver are incorporated into design, service standards and contractual models.

The U.S. Golden Dome, a proposed multi-layered missile defense system, illustrates the strategic necessity of IOR. Space-based interceptors (SBIs) have finite propulsion reserves. High-tempo engagements against ballistic or hypersonic threats could deplete fuel within days. **Refueling allows satellites to reset**, maintain station and sustain sensor-to-shooter coverage without repeated replacement launches. Similarly, the planned European Union (EU) Space Shield flagship program relies on continuous in-orbit maneuverability to maintain persistent defensive coverage.

Current and emerging military constellations stand to benefit immediately. This includes **geostationary wideband global satcom** (WGS), **Defense support program** (DSP), **Space-based infrared system** (SBIRS) and inspection/response satellites like **Geosynchronous space situational awareness program** (GSSAP) and Defense advanced research projects agency (DARPA) robotic servicing of geosynchronous satellites (RSGS). No **prioritized roadmap** exists in the public domain at this time, making it difficult for industry, congress, or even the US government and its allies to move forward with **IOR planning** and investments. This change in practice is critical. For operators, the trade between IOR and replacement is clear: launch access, acquire/build schedules, test and time-to-orbit can create operational gaps that **refueling directly mitigates** often at lower cost than satellite replacement.

Cost considerations reinforce these operational benefits. As highlighted earlier, LEO IOR missions offer lower entry barriers and faster commercial viability, while GEO servicing is justified for high-value satellites where savings from extended life exceed the combined cost of launch and mission operations. Incremental reusability, scalable depots and standardized interfaces improve economics and reduce per-service cost over time, enabling governments and commercial actors to plan strategically across orbital regimes.

Policymakers should **align budgets now** to enable phased IOR capability development in parallel with on-going prototyping. U.S., European and allied defense allocations can prioritize first-of-a-kind demonstrators, depot development and shared-servicer models that maximize cost-effectiveness. Coordinated investment signals to the commercial sector which capabilities are mission-critical, supporting robust public-private partnerships and ensuring that defense needs drive technical standards rather than being constrained by them. This parallel approach ensures decisive agility in contested space. IOR programs can become sustainable, strategically relevant and commercially viable, reinforcing a **competitive advantage** over potential adversaries.

4.2. IOR in commercial/civil: next 5–10 years

Over the next decade, commercial space markets are poised to shift from launch-limited, single-use missions to persistent, refuelable operations that support manufacturing, resource utilization and sustained economic activity in orbit. **Refuelable constellations and on-demand servicing** extend asset lifetimes, enable continuous repositioning/replenishment and reduce capital tied to replacement launches. In proliferated LEO, where many satellites are currently designed as “throwaway” systems, IOR introduces a strategic trade: operators can either continue cycling short-lived satellites or invest in fewer, refuelable platforms.

Space-based Infrastructure-as-a-Service models (shared fuel depots, tanker fleets, servicing vehicles and logistics hubs) will create the foundation for scalable orbital supply chains, lowering barriers to entry for new business lines such as in-space manufacturing, assembly, repair and the harvesting and transport of natural resources. By reducing operational risk and decoupling growth from launch availability, these logistics capabilities **unlock new revenue models**, attract long-term private investment thereby transforming space from a project-based industry into a durable, self-sustaining commercial marketplace.

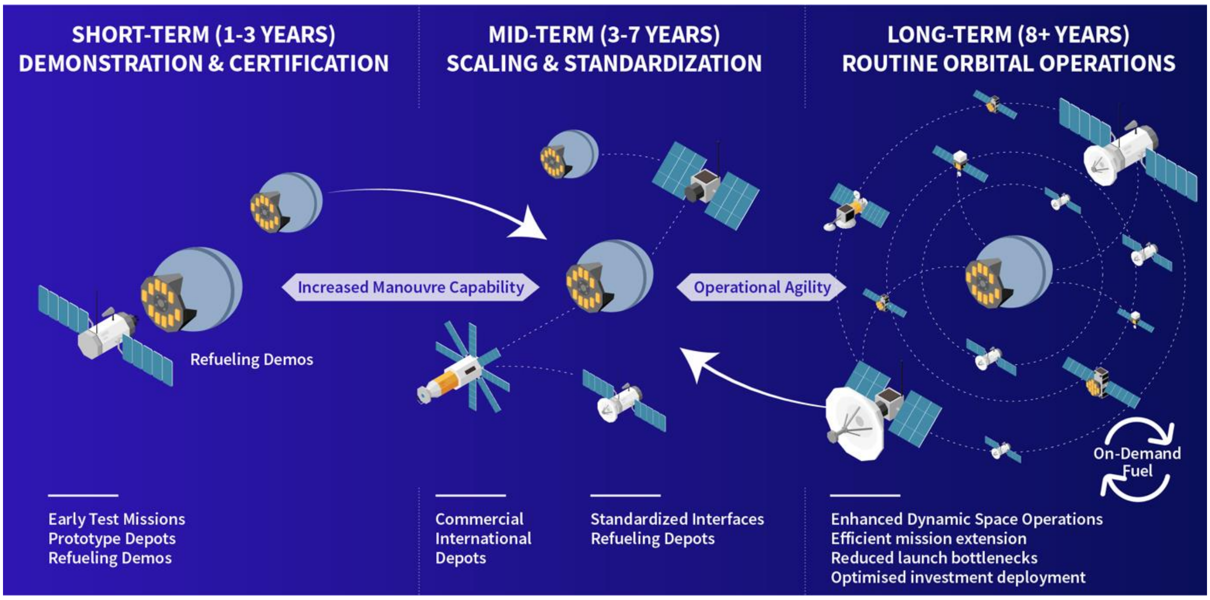
Commercial programs also benefit significantly. **LEO mega-constellations** such as SpaceX Starlink and Eutelsat-OneWeb can reduce replacement costs, improve collision avoidance and manage congested orbits dynamically. GEO communications satellites like SES and Eutelsat fleets can preserve orbital slots and extend operational lifetimes, while Earth observation platforms such as Planet, Maxar and ICEYE can conduct longer missions with flexible repositioning to meet market demand.

In-space manufacturing and resource-harvesting platforms, including Redwire and Astroscale, can remain operational longer, transport components and perform multiple maneuvers without returning to Earth. Tourism and research satellites, such as those operated by Axiom Space and other emerging commercial space stations, can sustain operations and service client satellites, unlocking new revenue streams.

Across civil and military sectors, programs requiring frequent repositioning or adaptive mission planning, such as NOAA (National oceanic and atmospheric administration) weather satellites, European Commission's Copernicus satellites, or debris mitigation constellations, benefit from enhanced flexibility and resilience, while high-capital platforms gain economically through extended asset life, reduced launch dependence and access to shared infrastructure like depots or refueling shuttles.

Policymakers should support the shift toward persistent, refuelable space operations by enabling **shared infrastructure, encouraging standardization, and creating a regulatory environment** that fosters investment and long-term commercial growth.

Figure 9: In-orbit refueling & servicing: a decadal vision



5.Path forward: key recommendations

5.1. From policy to practice

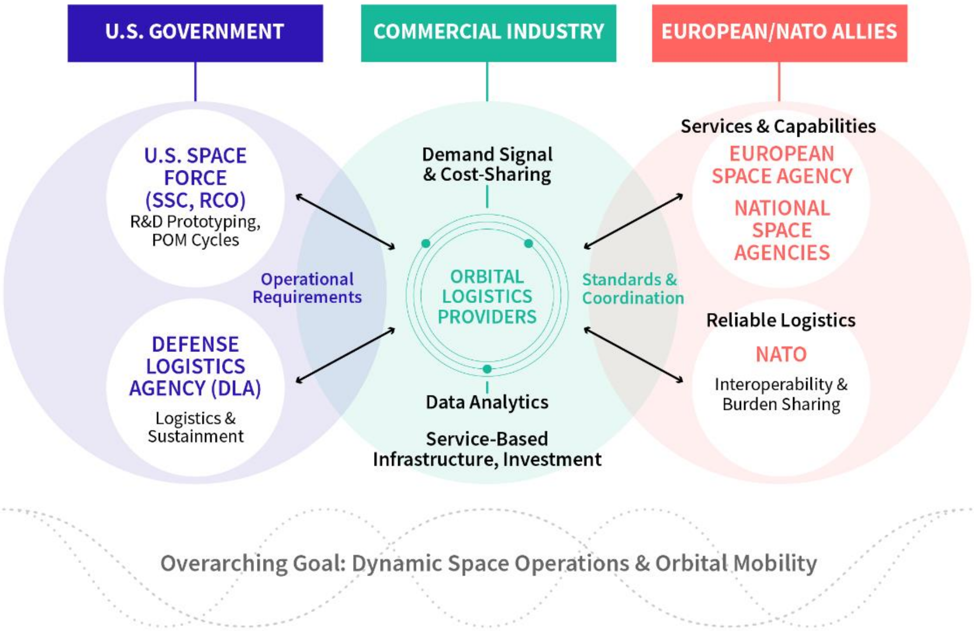
Responsibility for advancing IOR should be clearly anchored within specific government organizations rather than treated as a diffuse futuristic interest as is shown in **the figure** below.

In the **U.S.**, this includes integrating IOR R&D, prototyping and early fielding into the Program objective memorandum (POM) cycles of the U.S. Space Force—particularly programs within Space systems command (SSC), Combat forces command (CFC) and Space rapid capabilities office (Space RCO)—with coordination and emphasis from U.S. Space command to define operational priorities and demand signals. The Office of the Secretary of War (OSW), including Under secretary of war for research & engineering (USWR&E) and Office of cost assessment and program evaluation (CAPE), plays a critical role in aligning analysis, budgeting and acquisition pathways, while the **Defense logistics agency (DLA)** is a natural partner for framing refueling as a logistics function rather than a bespoke satellite program.

In **Europe**, parallel roles fall to EU, ESA, national space agencies and European defense ministries, with coordination through EU and NATO structures to ensure interoperability and burden sharing.

Across government organizations with regard to large space doctrine should be updated to explicitly prioritize orbital mobility & sustainability, and maneuver-centric operations should be institutionalized within operator training, exercises and readiness assessments. Governments should collaborate and work together to gain synergies on the defense side through for example the **Multinational Force**, Operation Olympic Defender led out of U.S. Space Command.

Figure 10: IOR Global stakeholders & synergies



For investors, IOR and orbital logistics mark the emergence of a capital-efficient infrastructure layer in space, one that shifts returns from episodic, launch-driven revenue toward predictable, **service-based cash flows**.

Near-term participation (1–3 years) benefits from **government-anchored demand and cost-sharing** that compresses technical and market risk, while **mid-term scaling (3–7 years) supports recurring** revenue, higher asset utilization and expanding margins as standards and throughput with IaaS improves. Over the **longer term**, ownership or access to refueling infrastructure creates durable competitive advantage through network effects, potentially exceedingly high switching costs and long-lived assets with depreciation profiles more akin to air refueling infrastructure and terrestrial energy markets. By reducing replacement risk and extending productive satellite lifetimes, refueling also lowers volatility in downstream markets—improving risk-adjusted returns and increasing the probability of a deeper, more liquid space economy overall.

Some practical actions include:

- **Update doctrine and operations for orbital mobility:** Space doctrine and the associate operations must shift from fuel-limited assets to maneuverable systems supported by logistics. IOR and servicing should be defined as foundational enablers of DSO, not niche life-extension tools. Legacy programs require modifications to accommodate the new age capabilities.
- **Institutionalize maneuver and sustainment in training:** Training pipelines must assume refueling availability as a baseline condition. Operators should routinely train on proximity operations, rapid maneuver and coordination with refueling and servicing assets, with fuel expenditure treated as a planned operating cost and a procurement requirement. Embedding these assumptions into simulations, exercises, and allied training normalizes refueling readiness, reduces perceived RPOD risk, and normalizes maneuvers.

- **Strengthen international cooperation**: Coordinated collaboration among allies and like-minded spacefaring nations can accelerate IOR by expanding demand, sharing development risk, and enabling interoperable refueling architectures. International partners can contribute complementary capabilities—such as propellant production, depots, servicing vehicles, rendezvous and docking technologies, and ground command-and-control—while aligning requirements to avoid fragmented, non-compatible solutions.
- **Establish clear, coordinated funding and procurement pathways** across multinational institutions, civil space agencies and national defense organizations will enable joint IOR demonstrations, harmonized refueling and docking standards, and coalition-ready orbital mobility capabilities that support shared civil, commercial and defense missions.
- Establish dedicated **Space Logistics Task Force** to synchronize requirements, share data and coordinate industry participation across refueling, servicing and mobility technologies.
- **Enhance education**: Universities should develop specialized courses on IOR, orbital logistics, and maneuver-enabled operations to prepare the next generation of engineers and operators. Examples include the University of Colorado Boulder, University of Strathclyde, and KTH Royal Institute of Technology in Stockholm, which offer relevant academic programs.
- **Modernize regulatory and standards frameworks** for IOR: In close collaboration with industry, governments should update licensing, safety, and space traffic management regimes to explicitly cover IOR and servicing. In the U.S., this requires coordination among the FAA (Federal aviation administration), FCC (Federal communications commission), Department of Commerce (Office of Space Commerce), and Department of War. In Europe, alignment is needed across ESA, the EU, and national authorities, while other allied nations should harmonize standards and regulatory approaches.

5.2. The role of private investment

Emerging competitive dynamics indicate that **private capital, across venture, growth equity, infrastructure funds and strategic investors, will be essential** to scaling IOR, particularly in the United States and allied markets. Early investment positions both nations and firms to shape technical standards, secure first-mover advantage and anchor leadership in a foundational layer of the future space economy.

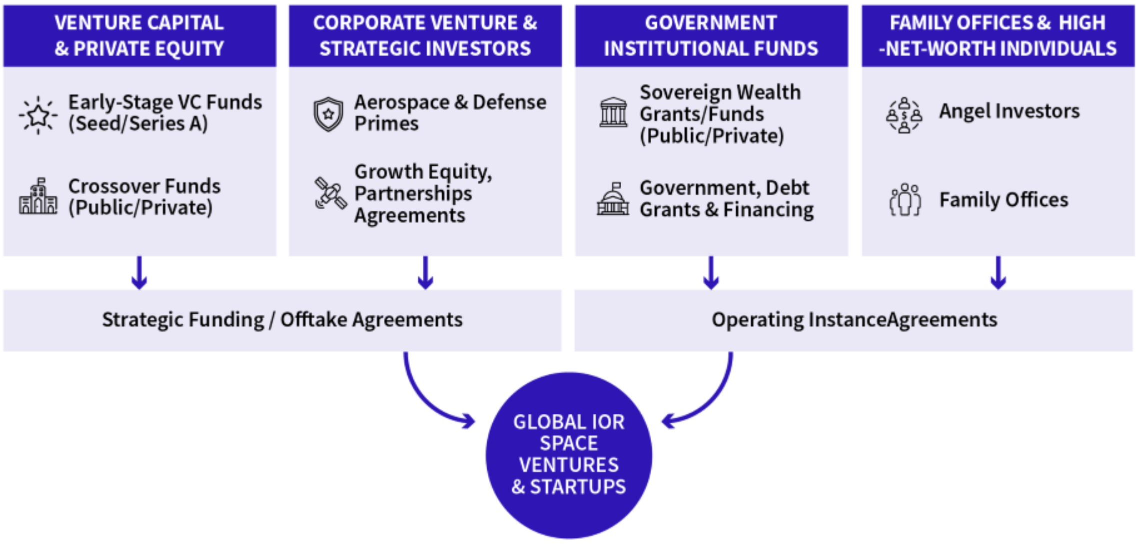
IOR presents a dual-track investment profile that is difficult for capital markets to ignore. Early-stage capabilities (e.g., refueling interfaces, autonomous rendezvous and proximity operations, tanker vehicles, and servicing platforms) map to **venture-style, power-law returns (5–10x+ invested capital)** driven by **winner-take-most dynamics**, where a small number of technical standards and flight-proven systems become embedded across government and commercial fleets. Over a **5-7-year horizon**, credible exit paths include **strategic acquisition by primes, vertical integration by constellation operators and government-backed scale-up contracts**.

As capabilities mature, IOR transitions into a **long-duration infrastructure asset class**, characterized by contracted demand, predictable utilization and stable cash flows. Government de-risking through anchor tenancy, milestone funding and early service contracts is critical to unlocking this shift. Once deployed, fuel depots, tanker fleets and logistics nodes behave less like speculative technology bets and more like **orbital utilities**, supporting recurring revenues from defense, civil and commercial customers.

The investment case is increasingly clear across institutional investors, venture capital and family offices. IOR extends satellite lifetimes, preserves orbital slots, reduces replacement and disposal costs and maximizes returns on high-capital assets. Much like lithography enabled the semiconductor industry, **IOR acts as a force multiplier**, catalyzing downstream markets in launch services, component manufacturing, in-space assembly, logistics and operations—driving durable economic growth and high-value employment across the aerospace sector.

The figure below illustrates how coordinated public and private investment can de-risk IOR, **establish time critical scalable infrastructure** and enable on-demand space services across defense, commercial and civil sectors—critical because these investments create the foundation for operationally resilient, maneuverable and economically sustainable space operations.

Figure 11: Global investor landscape: space economy (non-exhaustive)



5.3. The role of governments and critical technology funding

Government funding plays a crucial role in enabling critical technology investments by providing the foundational capital and strategic direction needed to advance high-priority space technologies. Through dedicated financial support, governments (e.g., Department of War in USA, EU/ESA/Member States Ministry of defence in Europe) can help **de-risk early-stage innovations and attract additional private sector** participation, accelerating the pace at which IOR capabilities mature. This collaboration not only strengthens national security interests but also ensures that robust infrastructure and cutting-edge solutions are available to support both defense and commercial operations in space.

Leverage tax and incentive programs to accelerate private capital inflows: Governments can accelerate private investment into IOR and space logistics by treating them as **strategic infrastructure**, not experimental programs. This means reducing early-stage risk, improving after-tax returns and shortening time-to-revenue, three levers that directly influence capital allocation decisions. Specific strategies include:

- Apply **targeted tax credits and accelerated depreciation** to refueling depots, servicing vehicles and standardized interfaces to improve early cash flow and investor IRR (internal rate of return)
- Use **government demand signals** (advance purchase commitments or service guarantees) to reduce market risk and enable project-finance style investments.
- Establish **public–private co-investment structures/ partnerships** that absorb early risk, lower cost of capital and attract institutional investors.
- Align **insurance, export and regulatory incentives** to recognize refueling as a risk-reduction capability, expanding the investor base and market liquidity.

5.4. Creative financing approaches

Developing IOR and related space capabilities requires coordinated investment across government and private sectors as is discussed above. Early-stage technologies, long development timelines and dual-use requirements create structural gaps in capital markets. The U.S., allied nations and innovation agencies should further leverage a combination of funding mechanisms to de-risk technology, accelerate commercialization and ensure strategic leadership in space. A discussion of some creative approaches follows.

Defense and critical technology funds: funding mechanisms and levers: The Department of War, via the U.S. Space Force, Office of Strategic Capital and allied innovation agencies, use debt, equity, milestone-based contracts and anchor tenancy to accelerate critical space technologies. These tools lower capital costs, provide predictable demand and support dual-use domains like IOR, on-orbit servicing and resilient space architectures.

Critical technology funds (CTFs): CTFs mobilize private capital for national-security-relevant technologies where commercial demand alone is insufficient. With $4 billion across 1,700+ portfolio companies, they absorb early risk, validate technical feasibility and signal long-term demand. In space, CTFs fund propulsion, refueling interfaces, cryogenic storage, autonomous robotics and other technologies for service-oriented orbital operations.

Small business investment company for critical technologies (SBICCT): SBICCT partners with the Small Business Administration to license funds focused on security-relevant technologies, offering up to $175 million in government leverage per fund. Beyond capital, SBICCT provides technical guidance and demand signals to reduce investor risk, blending federal policy goals with private-sector investment discipline for emerging space and advanced manufacturing technologies.

Defense innovation unit: Complementing these funds, DIU accelerates commercialization through rapid contracting, prototype demos and early operational validation. Using commercial solutions openings (CSOs), other transaction authorities (OTAs) and anchor tenancy, DIU reduces technical and market risk and signals credible demand, often turning promising space concepts into commercially viable capabilities.

Integrated Financial Architecture: Together, these mechanisms create an investable ecosystem from R&D through deployment. By combining public and private capital with milestone-based incentives, the Department of war and allied partners foster a resilient, competitive industrial base that underpins next-generation space capabilities, including critical IOR infrastructure.

5.5. Accelerating private capital for IOR

Private investment is essential to scale IOR infrastructure and make it commercially sustainable. While government funding can de-risk early technology development, targeted **policy levers**—tax incentives, regulatory reform, standards, PPPs and modernized export controls - can unlock **long-duration capital**, accelerate adoption and ensure U.S. and allied leadership in the emerging space logistics economy.

Expanding **federal tax incentives** to include space logistics and IOR infrastructure could shift early-stage investment economics. Extending tools like **Private activity bonds (PABs)** and direct-pay credits to orbital depots, servicing vehicles and refueling interfaces unlocks **long-duration, low-cost capital** from **pension funds, insurance companies** and other institutional investors. These mechanisms help transition refueling from **high-risk R&D** to **bankable infrastructure assets**.

Regulatory friction remains a major barrier to scaling IOR. Current **licensing processes** are fragmented across agencies, creating **uncertainty** and long approval cycles. A **unified, streamlined framework** led by a designated authority would shorten timelines, enable **multi-mission planning** and support **risk-based oversight** while ensuring **national security and safety compliance**.

Standardized refueling interfaces are critical for a **scalable, competitive market**. Without common standards, each mission becomes bespoke, increasing **costs and integration risk**. Policymakers can accelerate adoption by embedding **standards in procurement**, offering **tax incentives for compliant designs**, or sponsoring **industry-government working groups**. Standardization creates a virtuous cycle, where more refuellable satellites justify investment in depots, tankers and logistics networks.

Public-private partnerships (PPPs) can **de-risk early infrastructure** by aligning incentives, sharing technical and financial risk and providing **predictable demand signals**. Tools like **milestone-based payments, anchor tenancy and guaranteed procurement contracts** give investors' confidence in revenue streams. Proven in terrestrial infrastructure and launch markets, these models can support depots, servicing vehicles and orbital logistics networks for IOR.

A **modernized export control regime** is essential for global competitiveness. Current **ITAR** (International traffic in arms regulations) **and EAR** (Export administration regulations) **frameworks** restrict access to widely available technologies, limiting **market reach** and complicating international partnerships. Clearer **categorization, technical thresholds and predictable licensing** would expand the addressable market, strengthen the investment case and maintain national security safeguards.

5.6. 5 key actions to take today

Space superiority will not be preserved by intent or rhetoric alone; it requires decisive action now to operationalize IOR and space logistics at scale.

1. Transition from technology demonstrations to operationally relevant refueling missions:

Current U.S. and European refueling efforts have largely focused on proof-of-concept demonstrations—single-mission, experimental operations that validate basic technical feasibility. While these milestones are important, they do not reflect the operational realities of a **fully functioning orbital logistics system** nor are they being conducted on a fail-fast timeline sufficient for space superiority over the long term. Further, there are no architecture studies conducted in parallel or budgetary programs of record looking to adopt this capability and make it a reality.

To advance IOR from experimental capability to **mission-critical infrastructure**, programs must prioritize repeatable, multi-client, multi-orbit missions that demonstrate sustained utility. This includes routine operations such as satellite inspection, repositioning, servicing and fuel transfer across multiple orbital regimes.

Programs like the **U.S. Tetra-5, Tetra-6 and the European ISOS, ASTRAL and Odyssey should be viewed not as endpoints, but as steppingstones** that progressively build operational logistics, operational confidence and cross-mission interoperability. Too often are prototype missions left in the sandbox and never transitioned into programs of record. By moving beyond one-off tests, governments and operators can validate procedures, reduce operational risk and create the foundation for scalable commercial and defense applications.

2. Establish common refueling and servicing standards across allied ecosystems

Interoperability is the single most powerful driver for accelerating the adoption of IOR. Currently, satellites and servicing platforms often have bespoke mechanical, fluid and data interfaces, making each operation custom, costly and difficult to insure. By developing and mandating when possible or otherwise coordinating **common standards across allied nations**, governments can reduce technical risk, enable multi-mission servicing and facilitate the creation of shared orbital infrastructure. Standardization not only lowers costs overall but also **enables secondary markets for refueling and servicing**, supporting sustainable infrastructure-as-a-service (IaaS) business models. In practice, this means defining interface specifications, fuel transfer protocols and data communication standards for satellites above certain cost or strategic thresholds, while creating incentives for compliance through procurement and funding mechanisms.

3. Create a joint U.S.–European space logistics investment framework

Scaling IOR capabilities requires a deliberate coordination of public and private capital which is discussed in detail earlier in this paper. A joint U.S.–European/EU investment framework can reduce financial risk for early-stage infrastructure and create predictable demand signals that attract private investment. Key levers include anchor-tenant contracts with government satellite operators, co-investment in refueling depots and servicing vehicles and commitments for guaranteed demand for refueling and orbital maneuver services. These initiatives should be **guided by national-level**

space policy in the U.S. and aligned with equivalent policy frameworks among allied nations, with implementation supported through **targeted public investments starting immediately**. This mirrors the historical development of terrestrial logistics, aviation and maritime networks, where strategic public investment created bankable markets for private actors. By applying these lessons to space, allied governments can accelerate infrastructure deployment, expand the addressable market and ensure that both defense and commercial requirements are met efficiently.

4. Treat IOR as strategic space infrastructure, not a niche capability

IOR, depot operations and servicing fleets should be regarded as core enabling infrastructure for both defense and commercial space activities. **Just as air refueling extends the range and flexibility of military aircraft,** orbital refueling enables satellites to maneuver, sustain operations and adapt to dynamic conditions, transforming them from fuel-limited assets into resilient, persistent systems. Like terrestrial ports, pipelines, or energy grids, these capabilities underpin broader system resilience and operational agility. Early strategic planning is critical to address ownership, access protocols, redundancy, operational resilience and preventing chokepoints. By **treating refueling as strategic infrastructure (i.e. roads, bridges, tunnels)**, policymakers, investors and operators ensure that availability, security and long-term sustainability are prioritized, rather than relegating it to an optional or experimental capability.

5. Reframe space operations culture—from fuel preservation to maneuver dominance

Effective use of IOR requires a **cultural shift within space operations**. Traditionally, satellites have been operated conservatively to conserve fuel, limiting training, experimentation and operational agility. As Lt Gen. (Ret.) John Shaw emphasizes, the mindset must move from “driving to church” to “operating for combat and competition.” Policymakers and operators should:

- Budget propellant as an operational resource, enabling dynamic maneuvers without regret and training, not merely survival.
- Design satellites and constellations for refuelability and servicing from inception, rather than retrofitting capabilities after launch.
- Reward operational agility and flexibility, prioritizing mission effectiveness over mere longevity.

This cultural and procedural shift is critical to unlocking the full strategic and economic value of IOR. It transforms satellites from fuel-limited assets into maneuverable, responsive systems, enhancing deterrence, sustaining operational advantage and creating commercial opportunities in the rapidly expanding space economy.

6. Conclusion: IOR as a strategic imperative

IOR is rapidly emerging as a cornerstone capability for the next era of space operations, with profound implications for national security, commercial markets and scientific exploration. By transforming satellites from fuel-limited, single-mission assets into maneuverable, serviceable systems, IOR extends mission lifetimes, enables dynamic repositioning and allows operators to adapt to evolving mission needs across defense, civil and commercial domains.

From a strategic perspective, IOR strengthens deterrence, enables persistent coverage and mitigates operational gaps for high-value defense and allied constellations. Space-based interceptors, inspection satellites and maneuver-reliant communications and observation platforms all benefit from extended life, rapid repositioning and resilience in contested environments. **Commercially, refuelable satellites reduce capital tied to replacement launches, improve orbital traffic management and unlock new service-based business models** - including on-orbit manufacturing, assembly, repair and resource utilization.

The long-term viability of IOR depends on more than technology readiness; it requires interoperable standards, scalable logistics infrastructure and coordinated action across manufacturers, operators, regulators and investors. Governments must actively de-risk early deployments, integrate IOR into doctrine and acquisition cycles, harmonize regulatory frameworks and provide strategic funding and anchor demand to catalyze the market. Standardization and shared infrastructure accelerate adoption, lower insurance and operational risk and enable infrastructure-as-a-service models that benefit both public and private stakeholders.

Private capital is equally critical. Early-stage investments in refueling interfaces, autonomous servicing platforms and depot infrastructure carry power-law upside potential, while mature IOR assets behave like long-lived, infrastructure-like systems with predictable cash flows. Public-private partnerships, milestone-based incentives, tax levers and regulatory modernization can unlock private investment, ensuring that strategic and commercial imperatives align to sustain a competitive, maneuverable and resilient orbital ecosystem.

Ultimately, IOR is not merely a niche capability or life-extension tool but the foundation for a sustainable, dynamic and economically vibrant space future. The opportunity is clear: move from demonstration to operational missions, establish interoperable standards, align public and private investment and embed refueling and orbital logistics at the core of strategy and operations. **Those who act decisively will shape the structure, competitiveness and sustainability of the global space economy, and the trajectory of national security and commercial space leadership, for decades to come.**

Annex: Examples of operational scenarios unlocked by IOR

Satellite inspector scenarios: enhancing mission effectiveness with in-orbit refueling

IOR is more than a technical advancement—it is a **strategic enabler for both national security and commercial space operations**. For defense operators, access to fuel in orbit allows satellites to maneuver rapidly, extend mission duration and maintain a persistent presence in contested or congested environments, directly supporting U.S. and allied space superiority objectives. For commercial operators, it provides the flexibility to **maximize asset utilization**, **reduce replacement costs** and **respond** quickly **to changing market** or operational **conditions**. The following scenarios illustrate how refueling transforms the mission of a satellite inspector, turning single-use satellites into reusable, mission-ready assets capable of sustained, multi-target operations while supporting broader strategic, operational and economic goals.

Scenario 1: Extended observation of multiple satellites

A satellite inspector tasked with examining multiple target satellites can leverage IOR to stay on station longer. This **extends operational endurance and reduces interruptions** or the need for replacement spacecraft.

By accessing propellant from service satellites or nearby fuel depots, the inspector gains greater maneuver flexibility. It can **adjust orbit, approach multiple targets, or respond to unexpected events without running out of fuel**. Refueling also enables repeated visits within a satellite constellation, supporting frequent inspections and maintenance while avoiding the high cost and delay of launching replacements.

Ultimately, IOR transforms the inspector mission from single use to reusable operation, improving both efficiency and return on investment.

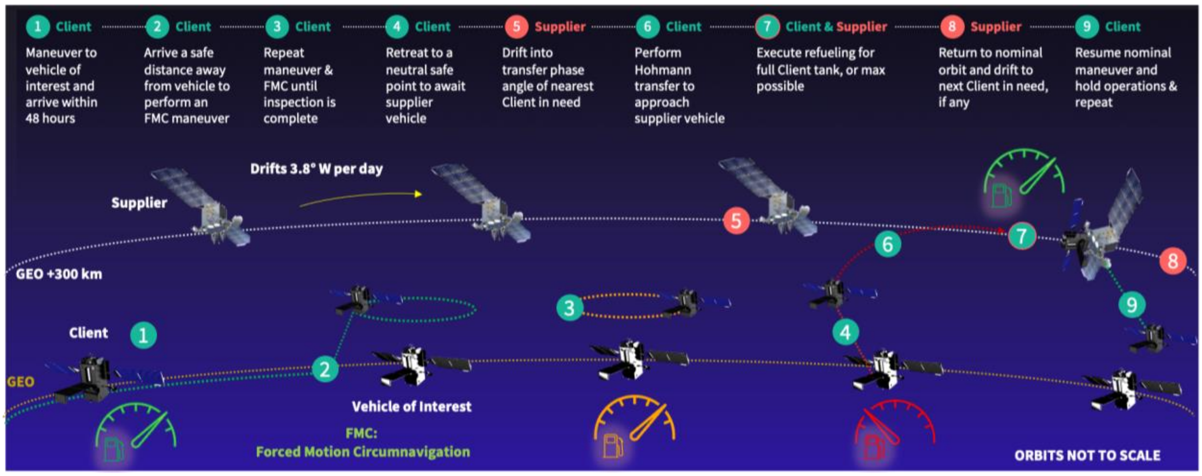
Scenario 1A: Response to a new foreign launch

In this scenario, the inspector observes a newly launched foreign satellite, using **IOR to extend mission duration and operational flexibility**.

Starting from its “home” position at 150°E in geostationary orbit, the inspector maneuvers within 48 hours to reach the new satellite at 120°E. Using a circumnavigation pattern, it **inspects the target** while **maintaining a safe distance to avoid collisions**. After completing the observation, the inspector returns to a neutral holding point and waits for refueling from a nearby shuttle.

Refueling allows the inspector to continue monitoring multiple targets over time without returning to Earth or launching replacements. This capability enables **extended mission duration, repeated inspections and rapid response to new satellites** like a surveillance drone that can refuel mid-air to stay on station longer.

Figure 12: Scenario 1A, Response to a new foreign launch



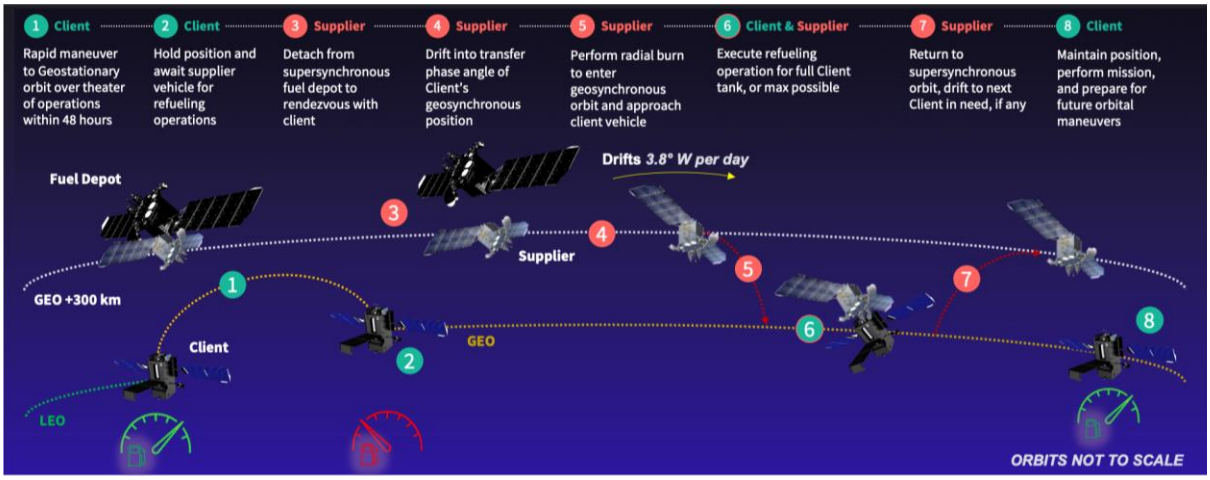
Scenario 2: Rapid relocation and refueling

In this scenario, a client satellite moves quickly into geostationary orbit over its area of operations, reaching position within 48 hours. Once on station, it holds its orbit and waits for a supplier vehicle to arrive for refueling.

The supplier, departing from a super-synchronous fuel depot above GEO, maneuvers carefully to rendezvous with the client. It aligns its orbit and performs a burn to enter geostationary orbit and approach the satellite.

Once in position, the supplier refuels the client's tanks to full or maximum capacity. After completing the transfer, the supplier returns to its super-synchronous orbit to service the next satellite. Meanwhile, **the client continues its mission with enhanced flexibility and endurance**, now able to perform future maneuvers without the constraints of limited fuel.

Figure 13: Scenario 2, Rapid relocation and refueling



Annex B. Abbreviations and acronyms

ADR	Active Debris Removal
AOCS	Attitude And Orbit Control System
ASTRAL	Advancing Satcom Technology with Refueling and Logistics (ESA-ARTES mission)
ASAT	Anti-Satellite
ASI	Italian Space Agency
CAPE	Cost Assessment and Program Evaluation
CFC	Combat Forces Command
CSOs	Commercial Solutions Openings
CTF	Critical Technology Funds
DARPA	Defense Advanced Research Projects Agency
DIU	Defense Innovation Unit
DLA	Defense Logistics Agency
DSO	Dynamic Space Operations
DSP	Defense Support Program
EAR	Export Administration Regulations
EC	European Commission
EDF	European Defence Fund
EROSS	European Robotic Orbital Support Services
ESA	European Space Agency
EU	European Union
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FFR	Fly Foundational Robots
GEO	Geo-stationary Orbit
GNC	Guidance, Navigation, and Control
GNSS	Global Navigation Satellite System
GSSAP	Geosynchronous space situational awareness program
IaaS	Infrastructure-as-a-service
ILRS	International Lunar Research Station
InSPoC	In-Space Proof-of-Concepts
IOR	In-Orbit Refueling
IRR	Internal Rate of Return
ISOS	In-Orbit Services and Operations
ISR	Intelligence, Surveillance, and Reconnaissance
ISS	International Space Station
ITAR	International Traffic in Arms Regulations

LEO	Low Earth Orbit
LES	Life Extension Services
MEO	Medium Earth Orbit
MRV	Mission Robotic Vehicle
NATO	North Atlantic Treaty Organization
NDAA	National Defense Authorization Act
NOAA	National Oceanic and Atmospheric Administration
OSAM	On-orbit Servicing, Assembly, and Manufacturing
OSW	Office of the Secretary of War
OTAs	Other Transaction Authorities
PABs	Private Activity Bonds
PLA	People's Liberation Army
POM	Program Objective Memorandum
PPPs	Public-Private Partnerships
PRM	Passive Refueling Module
RAFTI	Rapidly Attachable Fluid Transfer Interface
R&D	Research and Development
RCO	Rapid Capabilities Office
ROI	Return on Investment
RPO	Rendezvous and Proximity Operations
RPOD	Rendezvous, Proximity Operations, and Docking
RSGS	Robotic Servicing of Geosynchronous Satellites
Satcom	Satellite Communications
SBI	Space-based interceptors
SBICCT	Small business investment company for critical technologies
SBIR	Small Business Innovation Research Small Business Innovation Research
SBIRS	Space-Based Infrared System
SSA	Space Situational Awareness
SSC	Space Systems Command
STTR	Small Business Technology Transfer
WGS	Wideband Global Satcom

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