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COSMIC

CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES

A CROSS-DISCIPLINARY STUDY OF ON-ORBIT REFUELING FOR GEOSTATIONARY SATELLITES

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Abstract

Through collaboration within the In-space Servicing, Assembly, and Manufacturing (ISAM)-focused consortium, the Consortium for Space Mobility and ISAM Capabilities (COSMIC), representatives from U.S.-based industry, academia, and government organizations identified a high-priority ISAM use case, refueling for Geostationary (GEO) satellites, and interrogated the use case from four distinct perspectives aligned with Focus Areas within the consortium. This interdisciplinary use case report identifies linkages between the four focus areas (Missions and Ecosystems, Research and Technology, Policy and Regulation, and Demonstration Infrastructure), establishes the current state of the art, identifies gaps in current capability to realize the use case, and suggests methods for gap closure. The intent of this interdisciplinary report is to provide a holistic overview of GEO refueling to further understanding of the methods of implementation, feasibility with current technology, and timeline for technology, testing, policy, or regulatory maturity.

1. Introduction

As the space industry continues to flourish and future space endeavors expand in ambition, pre-integrated spacecraft, which are never interacted with after launch, may become too limited in capability to meet the needs of civil, national security, and commercial space interests. In-space Servicing, Assembly, and Manufacturing (ISAM) offers the solution through a suite of capabilities which expand spacecraft performance, availability, resilience, and lifetime. Although ISAM capabilities have been in use for decades through activities such as the Hubble Space Telescope Servicing Missions or International Space Station Assembly, only recently has this suite of capabilities been coalesced and advanced as a unified entity. In 2022, the White House's Office of Science, Technology, and Policy (OSTP) released two documents, the ISAM National Strategy and National ISAM Implementation Plan, to establish this technology area and chart a course towards U.S. leadership in ISAM developments.

To further collaboration within the ISAM community and to fulfil requirements within the OSTP National ISAM Implementation Plan, NASA established the COSMIC consortium in 2023 with participation from U.S.-based industry, academia, and government organizations. As of August 2025, the consortium boasts more than 1200 members from 306 organizations across the U.S. and is responsible for enriching collaboration between member organizations, developing products to identify the benefits of ISAM technologies, and working together to further the state of domestic ISAM endeavors. The consortium offers five focus areas for participation, each with unique perspectives and products under development.

In 2025, the COSMIC consortium identified the need for Integrated Use Case Reports as a product intended to describe an ISAM use case, its value proposition, and the corresponding gaps that must be closed to be able to implement the use case. COSMIC defines a use case as a scenario where ISAM capabilities are employed to enhance or enable a mission. For example, a scenario in which a mission planner has a need to launch a spacecraft that requires extremely high power, the spacecraft could be designed to unfurl very large solar panels post-launch, increasing mission complexity. In this scenario, an

ISAM use case exists in which the spacecraft's large solar panels are assembled after launch, on-orbit, foregoing the complexities of folding large panels into the launch fairing.

The report is intended to inform decision makers on the feasibility and value of implementing a specific use case in future mission planning and operations. This report involves participation from four of the COSMIC focus areas: Missions and Ecosystems (ME), Research and Technology (RT), Demonstration Infrastructure (DI), and Policy and Regulation (PR). Engagement from each of these focus areas offers unique perspectives tuned to the current efforts and challenges specific to each and brings in a wealth of focus-area knowledge from participant expertise and products previously developed within those focus areas. The Missions and Ecosystems Focus Area is responsible for describing the use case and its value proposition, and for providing a detailed Concept of Operations (CONOPS). The Research and Technology Focus Area is responsible for defining the current state of the art and existing technology gaps in any technology area required by the use case. The Demonstration Infrastructure Focus Area is responsible for describing the U.S.' current capability and gaps to perform digital, ground, or in-space testing of the technologies required by the use case. Finally, the Policy and Regulation Focus Area is responsible for describing the U.S. regulatory framework that would be required to implement the use case. An outline of these activities is shown in Figure 1.

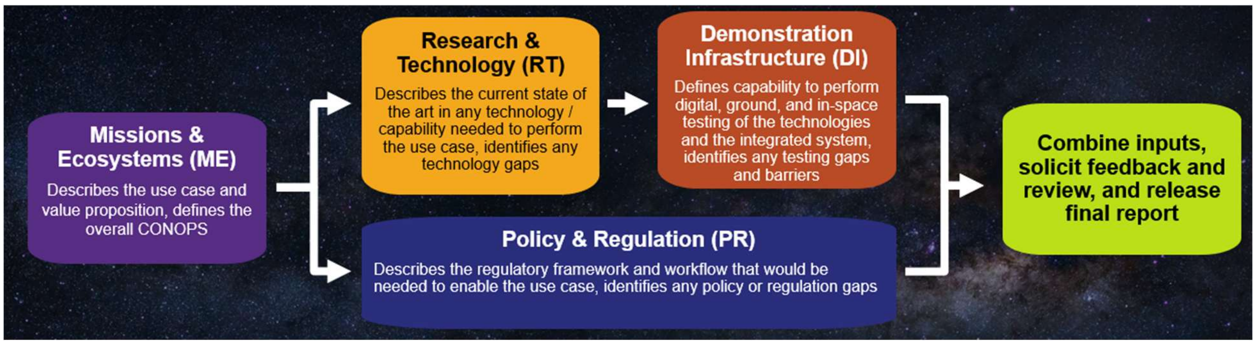

Figure 1. Cross-Focus Area Process Overview.

After a consortium-wide prioritization of use cases, the refueling of Geostationary (GEO) satellites use case was selected primarily due to its expected near-term implementation. Refueling of GEO satellites will provide a critical capability to ensure assets remain viable throughout their project lifespan and unlock novel applications of GEO satellites.

2. Use-Case CONOPS and Value Proposition

Historically, refueling activities in space have been leveraged to support human spaceflight activities, particularly refueling of the International Space Station (ISS). To date, visiting vehicles, including the Russian Progress spacecraft and ESA's Automated Transfer Vehicle (ATV), have provided tens of metric tons of propellant to the ISS in low Earth orbit (LEO). This has allowed the ISS to perform necessary station-keeping or debris-avoidance maneuvers. In 2007, DARPA's Orbital Express program demonstrated transfer of propellant and tank-venting between the ASTRO and NEXTSat spacecrafts within LEO, marking the first refueling operation between uncrewed spacecraft. Since this historic demonstration, only one development has occurred involving the Chinese spacecraft Shijian 25, which may have performed an in-orbit refueling operation [1]. In the near future, the United States Space Force (USSF) will perform multiple in-space refueling and augmented maneuver demonstrations. These demonstrations will involve Rendezvous Proximity Operations and Docking (RPOD) using several on-orbit partners including but not limited to the Air Force Research Laboratory (AFRL), Defense Innovation Unit (DIU), and Space Systems Command (SSC). These demonstrations will utilize the commercial capabilities of Astroscale U.S., Northrop Grumman, Orbit Fab, and Starfish Space to provide a unique capability, further enabling the mission area of all involved partners.

Propellant capacity is one of the limiting factors for maneuverability and lifespan of GEO satellites. Without on-orbit refueling (OOR), a satellite must launch with sufficient propellant to meet both projected and unexpected maneuvering demands within its design life. If fuel consumption is higher than projected, as could happen if orbital insertion is inaccurate or more frequent maneuvering becomes desirable, operators would be forced to trade between mission lifetime and the number and frequency of maneuvers. GEO OOR is also a key enabler for dynamic satellite operations, which require significant propellant consumption. Dynamic satellite operations utilize large amounts of propellant, enabling faster and persistent responses at tactical timelines and increasing national security capabilities. On-orbit refueling at GEO can provide a critical capability to ensure critical space capabilities are continuously poised to achieve effects rapidly, repeatedly, and without regret to future utility in critical moments, and to sustain those effects as long as they are required. While refueling capabilities enable other ISAM use cases and mission architectures, this report is solely focused on refueling activities related to satellites in GEO.

2.1 Concept of Operations

For the purposes of this Integrated Use Case report, a single CONOPS is developed to reduce the potentially expansive scope of the use case. The total scope of GEO refueling can range from prepared client spacecraft, such as performed by Orbital Express, to unprepared client spacecraft, such as that planned by OSAM-1 [2]. For the purposes of this report, prepared client spacecraft was determined to be the most critical to investigate due to the prevalence of commercially available refueling interfaces and the expected direction of the industry as informed by recently published standards and the demand signal being sent by the United States Space Command (USSPACECOM) [3] [4] [5] [6] [7].

The potential scope of the use case also includes a wide variety of possible propellants, including storable and cryogenic chemical propellants, electric propellant, and even water. For this report, the scope was limited to storable chemical propellants, in either a bipropellant or monopropellant configuration, specifically MMH/NTO (monomethylhydrazine and nitrogen tetroxide) or hydrazine, as these are the most prevalent propellants on-orbit and are compatible with many of the currently available refueling interfaces. The inclusion of both monopropellant and bipropellant storable chemical refueling are considered by the authors to be similar enough to not affect the remaining portions of the report or the overall refueling CONOPS. The trade tree for this use case is shown in Figure 2. The stars on the diagram indicate the portions of the trade tree considered in this report.

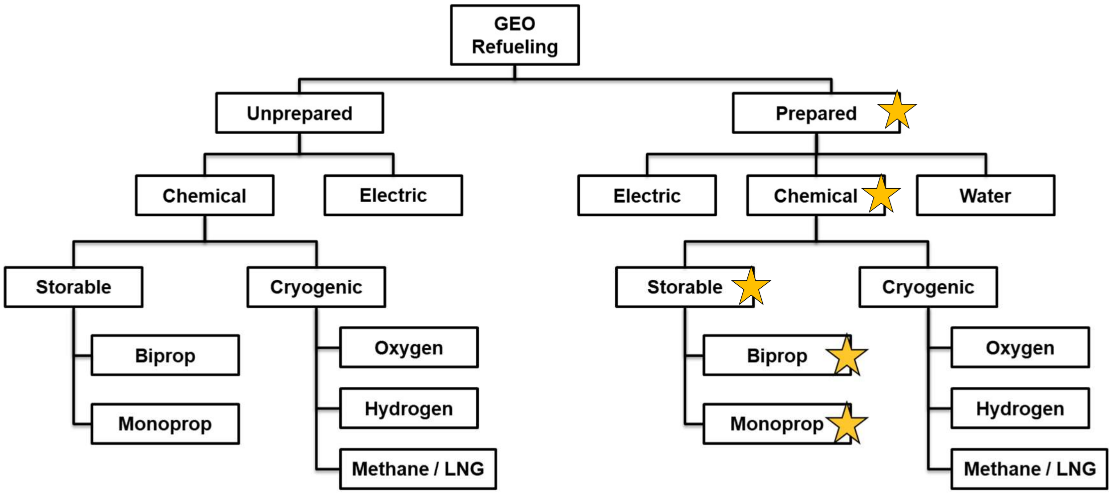

Figure 2. Refueling of GEO Satellites Trade Tree.

The details to be captured in this report can be visualized within the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS) On-Orbit Servicing (OOS) Mission Functional Diagram, as found in Figure 3. CONFERS is an international, industry-led consortium focused on establishing satellite servicing best practices and publishing voluntary consensus standards [8] [9]. Within the diagram, this report is focused on all activities between the request for refueling from the client through the return of the refueling spacecraft to its parking orbit. This includes a RPOD ingress to the client; docked initial checkout, refueling operations, and final checkout; and servicer egress and return to its parking orbit.

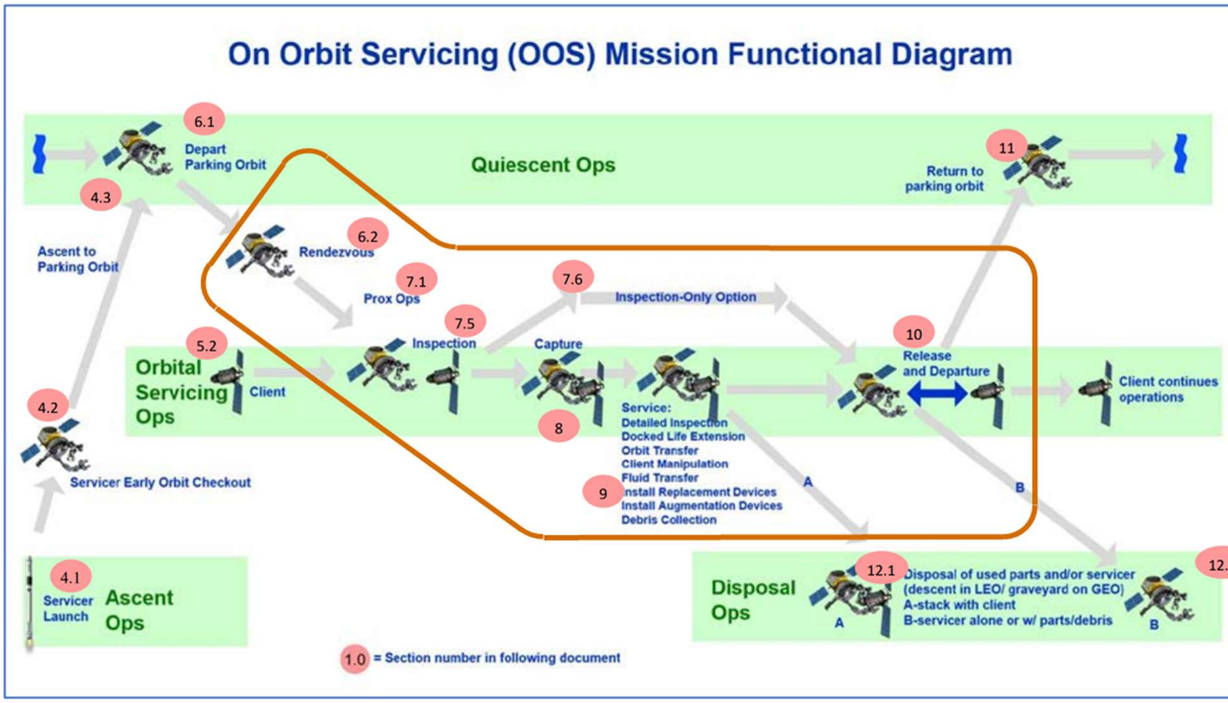

Figure 3. CONFERS On-Orbit Servicing (OOS) Mission Functional Diagram [9].

These five high-level mission phases are further decomposed into more specific activities to provide more insight into the technical details of the use case. The following is a breakdown of the CONOPS as defined for this study, with a bulleted sequence view and key considerations detailed in Appendix A: GEO Satellite Refueling CONOPS. This CONOPS describes best practices for nominal operations.

<u>RPOD ingress</u>: After an initial request from the client, the servicing spacecraft will perform long range RPO, ingress, and dock with the client spacecraft. Prior to docking activities, the client spacecraft will configure the necessary systems for the servicing spacecraft and client spacecraft to behave as a combined stack. This may include temporarily disabling elements of communications, ADCS, or any active propulsion system on the client spacecraft.

<u>Docked – Initial Checkout</u>: After docking, initial checkouts will provide the servicer with state knowledge critical to providing services, such as assurance of successful docking and proper alignment.

<u>Docked – Refueling</u>: The refueling phase will begin with mating of the fluid interface between the servicing spacecraft and the client spacecraft, if this interface is separate from the initial docking interface. Next, the servicing spacecraft will perform interface leak checks, evacuate the interstitial volume in the interface, and prime the interface with the necessary fluids. If necessary, the client spacecraft will then vent ullage gas from the tanks to be refueled to ensure no over-pressurization of the tanks during refueling operations. The servicing spacecraft will then transfer the appropriate amount of propellant to the client spacecraft, which may be measured by flow sensors or system pressure. After refueling, the interface will be depressurized and de-mated.

Docked – Final Check-Out: While still physically connected in a combined stack, the servicing spacecraft will perform another round of system checks, such as checking for leaks, over-pressurization, or excessive contamination of sensors.

Egress and Return to Parking Orbit: After decoupling of the mechanical interface between the servicing spacecraft and the client spacecraft, the servicing spacecraft will egress to a safe distance, and the client spacecraft will re-configure the necessary systems for the client spacecraft to behave as an independent free-flyer. Each spacecraft will then perform independent system checks, including validating the functionality of re-configured systems, performing leak checks, over-pressurization checks, and contamination checks. Each spacecraft will also perform center of gravity measurements to update propellant estimates and refine the estimated amount of transferred propellant. Finally, with verification of the proper amount of propellant being transferred, the servicing spacecraft will return to its parking orbit.

2.2 Value Proposition

This section provides an overview of the expected value of GEO refueling to potential users and the expected methods to be used to compare this ISAM use case to alternative non-ISAM methods.

With OOR capabilities, satellites that have depleted fuel reserves may be refueled to continue operations, allowing them to stay in mission, extend their lives, or be dispatched to new missions. The value of OOR varies greatly amongst potential users. The civil space sector, such as NASA, could use refueling in GEO to enable extended mission duration for future telescopes and observatories or other science spacecraft that operate in GEO. The existence of a GEO refueling ecosystem could influence the initial design and orbit selection for these observatories, which are currently deployed to LEO (Hubble Space Telescope) or Sun-Earth Lagrange point L2 (James Webb Space Telescope, planned for Habitable Worlds Observatory). Refueling also enables launching of spacecraft with less propellant than is required for the full mission duration, which provides more launch capacity for science instruments or the spacecraft bus. Refueling can be used to recover full capability when a satellite is inadvertently launched into a low orbit and must use its own propellant to get to GEO. Finally, civil space could use a refueling capability to enable a spacecraft to relocate to a new orbit due to desires such as observational coverage, data gathering in a new location, or replacement of a decommissioned spacecraft in that orbit.

The primary interest in GEO refueling for national security space is to enable new mission areas that require high maneuverability and long lifetimes. National security assets in GEO are preferred to be able to maneuver on tactical timelines, enabling rapid response to changing mission needs, environmental conditions, or adversary activity. Current command structures treat on-orbit propellant as a scarce commodity, often requiring multiple levels of approvals before executing any maneuver out of concern that doing so will reduce the operational life of the spacecraft. In a world where refueling is safe, reliable, and effective, operational commanders could maneuver more rapidly to perform missions that require mobility without having to worry about running of out fuel and shortening lifespan. These significantly higher levels of performance can enable Sustained Space Maneuver (SSM), an attribute of missions performing Dynamic Space Operations (DSO), which USSPACECOM has advocated for as an extremely valuable attribute of military space capabilities. As secondary considerations, national security space also shares some similar uses of GEO refueling with civil space, including reducing launch mass to increase spacecraft dry mass and refueling to extend spacecraft lifetime or correct for launch insertion anomalies.

Based on substantial feedback, COSMIC anticipates that commercial satellite operators will be fast followers and adopters using the infrastructure made available to enhance their missions but, to date, operators of commercial clients are not incentivized to pursue development of the basic infrastructure without significant demand signal or investment from the government sector.

The value of OOR to a specific use case becomes apparent when highlighting the differences between completing a use case through ISAM capabilities versus traditional means. An oft-postulated alternative to GEO refueling typically involves the replacement of spacecraft which have fully depleted their propellant or involves launching additional in-space assets to allow for desired operational flexibility. With OOR, old-but-functional or defunct spacecraft may be refueled to continue operations, and operational flexibility can be achieved by refueling spacecraft after redeploying to new orbits.

In the future work of quantitatively establishing the value of GEO refueling, it is expected that the OOR alternatives are evaluated with consistent metrics including cost, schedule, risk, performance, and flexibility. The cost/value comparison should also include an assessment of different levels of performance/functionality for the same cost and different levels of cost for the same performance/functionality. As each potential user may have different relative value of these metrics, the overall benefit to each user of the ISAM use case is expected to be different. In the current mission paradigm, generally the value of refueling increases as the orbit altitude or the spacecraft complexity increases. In other words, there is potentially less obvious market space for refueling short-lived satellites in LEO as launch prices continue to fall. There is a more substantial business case for MEO or GEO spacecraft, as these orbits are slightly more difficult to get to and have fewer throw-away assets. There is high value in refueling for L2, lunar, planetary, etc., as these require exquisite spacecraft. However, as launch prices decrease, the price of in-orbit propellant may decrease, enabling more refueling cases to close in lower orbits. Ultimately, more analysis is required. The full definition of the value of this use case is future work of the COSMIC Missions and Ecosystems Use Case and Value Proposition Integrated Product Team.

3. Technology State of the Art and Gap Analysis

3.1 Overview

The CONOPS from Section 2 were used to determine the current state of the art of technology required for the use case and identify technology gaps that need to be closed. This was done by first identifying technology categories that are relevant to the use case from the COSMIC ISAM Technology Taxonomy and then assessing availability of needed technologies in those categories from the COSMIC ISAM Technology Inventory [10] [11].

The ISAM Technology Taxonomy, a 2024 COSMIC product developed by the Research and Technology (RT) focus area, was central to this effort. Heavily adapted from the NASA Technology Taxonomy, it excludes NASA categories not applicable to ISAM and introduces new, ISAM-specific categories. The taxonomy contains 270 entries at the third level, ensuring inclusive coverage of all relevant space technologies. These third-level categories were prioritized according to relevance to the use case and grouped into three broad technology areas to streamline the discussion of the state of the art and to highlight current gaps. These are summarized in Table 1.

Table 1. Prioritized Technology Taxonomy Categories Identified as Relevant to the Use Case.

Broad Technology Areas	Taxonomy Number	Title	Priority
Robotic Manipulation, Capture, and Interfaces	04.3.2	Grappling Technologies	1st
	04.3.1	Dexterous Manipulation	2nd
	04.5.6	Robot Control for Vehicle Capture and Berthing	3rd
	04.5.5	Capture Mechanisms and Fixtures	10th (tied)
	04.6.1	Modularity, Commonality, and Interfaces	12th (tied)
Guidance, Navigation, and Control (GNC) and Sensors for RPO	04.5.2	Rendezvous and Docking Algorithms	4th (tied)
	17.4.3	Attitude Estimation Sensors	7th
	05.7.3	Active and Passive Sensors (e.g., Geophones and Seismic Receivers)	8th
	17.3.5	GNC Actuators for 6DOF Spacecraft Control During RPOC	9th
	17.1.1	Guidance Algorithms	10th (tied)
	04.5.4	Capture Sensors	12th (tied)
Fluid Transfer and Propellant Management	01.5.1	Storable Propellant Refueling	4th (tied)
	01.5.3	Client Prop System Design for Refueling	6th
	14.1.1	In-Space Propellant Storage and Utilization	14th

3.2 Existing Technology

The prioritized taxonomy categories in Table 1 were cross-examined against the COSMIC ISAM Technology Inventory [11]. This inventory provides an extensive list of available and in-development ISAM technologies. Technology entries for this inventory were collected from a wide range of sources, including NASA's TechPort database, the ISAM State of Play, and direct inputs from COSMIC members [12] [13].

Subject matter experts evaluated each technology for relevance to the use case on a scale of 1 (irrelevant or inaccessible) to 5 (highly relevant and available) and noted gaps either due to low Technology Readiness Level (TRL), absence from the inventory, or broader market unavailability. A full list of identified technologies applicable to this use case can be accessed by COSMIC members within the *ISAM Technology Appendix: GEO Refueling Use Case* [14]. The inventory technology count and TRL range for each broad category is summarized in Table 2 below, showing general technology maturity across the board. A deeper dive into each category is provided below.

Table 2. TRL Range of Relevant ISAM Inventory Technologies.

Category	Relevant Technology Count	TRL Range
Fluid Transfer and Propellant Management	20	2-7
Robotic Manipulation, Capture, and Interfaces	105	1-9
GNC and Sensors for RPO	42	2-8

3.2.1 Robotic Manipulation, Capture, and Interfaces

3.2.1.1 Robotic Arms and Grappling

Key Technologies: Robotic arms and grappling mechanisms

Producers: KMI, Maxar, Motiv, MDA Space, NASA, Northrop Grumman, GITAI Corp, HoneyBee Robotics (Blue Origin)

Assessment: Autonomous robot control systems for vehicle capture and berthing have been demonstrated in space. MDA's Shuttle Remote Manipulator System (SRMS) and ISS Mobile Servicing System (MSS) are space-qualified, having been used extensively for satellite missions and ISS assembly and maintenance. MDA also provided the Orbital Express Demonstration Manipulator System (OEDMS) sized for mated servicing from an uncrewed servicing spacecraft and is much smaller than SRMS and MSS. ISAM relevant robotic arms are TRL 7 at best, as none have been successfully used in space, but many have been tested extensively on the ground. This category shows the strongest integration outlook, supported extensively by both commercial and government technological advancements, but each company's proposed solution needs flight heritage to show it is safe, reliable, and effective in the operational environment.

Current robotics technology is based on a single-arm, single-task approach, mimicking a human and mimicking the tasks the Canadarm has done (grappling to replace a part, docking, etc.). More complex ISAM missions could benefit from collaborative robotics (multiple robots working in concert with human in the loop as oversight). A simple example of a collaborative robotic system includes using one robot to handle a task while a partner robot provides the counter torques and forces necessary to operate in microgravity.

3.2.1.2 Docking, Latching, and Compliant Interfaces

Key Technologies: Docking mechanisms, latching systems, compliant interfaces

Producers: Enduralock, iBOSS, Voyager, Astroscale U.S., Orbit Fab, NASA GSFC, Moog, Sierra Space, Redwire, Arrow Science & Technology, Northrop Grumman

Assessment: Secure physical connections between servicing and client spacecraft are vital for mission success. Standards for docking and berthing are well defined for ISS but not for uncrewed spacecraft. Standards have been defined through CONFERS and AIAA, but these are functional standards, not design standards with form and fit requirements. Most of these docking/latching mechanisms need to be tested in space. Orbit Fab's RAFTI/GRIP will achieve TRL 9 with a successful flight in 2026. Also, two of Northrop Grumman's Mission Extension Vehicles have successfully docked with three GEO satellites using the client spacecraft's apogee kick motor nozzle as the mating interface, which puts it at TRL 9. Efforts are underway to improve flexibility and adapt interfaces to a wider variety of vehicle designs.

3.2.2 GNC and Sensors for RPO

3.2.2.1 Sensing and State Estimation

Key Technologies: Passive sensors (optical cameras, IR cameras), active sensors (LIDAR, radar, structured light, laser rangefinders), and sensor processing for relative navigation and pose estimation

Producers: Visible & IR cameras with flight heritage have come from Ball Aerospace, SAIC, Malin Space Science Systems, MDA, Neptec, Boeing, Ecliptic Enterprises, Space Dynamics Laboratory, DRS Sensors, L3 Communications, Lockheed Martin, and Carthage College, plus many others. LIDAR and Laser Rangefinders come from Neptec, L3 Communications, Teledyne Optech, MDA, Advanced Scientific Concepts, and Ball Aerospace, plus many others. Sensor processing for relative navigation and pose estimation is provided by Lockheed Martin, Northop Grumman, Ball Aerospace, Honeywell International, Draper Laboratory, and many others.

Assessment: Modern sensor technologies and state estimation software support precise navigation, thereby ensuring safe and effective proximity operations. While several existing sensing solutions are highly mature, integration and data fusion remain key focus areas to fully exploit sensor capabilities in complex operational environments. A robust sensor suite needs a mix of active and passive sensors with overlapping operating ranges, providing operational flexibility and robustness. Each contractor's end-to-end relative GNC solution must be tested in orbit, because the sensors, filters, and actuators have interlocking performance characteristics that cannot be adequately simulated or tested on the ground.

3.2.2.2 GNC Systems and Algorithms

Key Technologies: High-performance processors, advanced algorithms, adaptive control systems

Producers: NASA JSC, Northrop Grumman, Astroscale U.S., Starfish Space, Rogue Space, Utah State University, Microchip (NASA HPSC), Obruta, and many others.

Assessment: Starting with a relative state estimate from an onboard sensor, the relative GNC processing chain forms the backbone of spacecraft operations during rendezvous, proximity operations, and docking. Although reliable in many flight applications, the complexity of on-orbit servicing and docking demands enhanced algorithms with improved fault tolerance. Incremental advancements in this area are essential to ensure full mission resiliency under unexpected conditions, and exhaustive ground-based simulation and hardware-in-the-loop testing are necessary precursors to on-orbit operations.

3.2.3 Fluid Transfer & Propellant Management

3.2.3.1 Fluid Transfer Systems

Key Technologies: Fluid transfer couplings and interfaces, on-orbit pumps and compressors, variable system pressure regulation

Producers: Enduralock, Northrop Grumman, Orbit Fab, iBoss, Creare, Flight Works, Inc., Moog, Allatherm, NASA, VACCO

Assessment: While several promising solutions are emerging—such as high-cycle rate valves and innovative fluid interfaces—there is a notable shortfall in technologies that have achieved full maturity as an integrated system. VACCO developed the Orbital Express refueling coupler (TRL 9). Orbit Fab's RAFTI is the most mature storable propellant transfer interface at TRL 8. VACCO also has a cryocoupler concept (TRL 4) with both oxygen and hydrogen lines in a single interconnect that was included in Boeing's Cryogenic Propellant Storage and Transfer (CPST) Demonstration Mission in 2013 before NASA redefined the project.

Refueling and managing high-pressure systems remains a challenge. This area will benefit from targeted investments to accelerate the development and testing of robust, repeatable propellant handling systems. Systems that are currently being designed need both extensive ground-based testing under nominal and off nominal conditions, as well as on-orbit demonstrations for heritage.

3.2.3.2 Leak Detection & Management while On-Orbit

Key Technologies: Pressure sensors, ultrasonic leak detectors

Producers: NASA

Assessment: This technology focuses on the development and integration of leak detection and evacuation capabilities during on-orbit refueling operations. Its primary function is to ensure operational safety and prevent the contamination of the servicing environment. Given its critical safety implications, robust leak detection mechanisms are needed to promptly identify and mitigate any propellant leak, thereby preserving mission integrity and reducing risks to both servicing and client spacecraft. Hardware currently available on the commercial market can be used to adequately perform an interface leak check; the challenge is designing the system and creating the CONOPS to properly enable a suitable leak check. AIAA S-157 provides some guidelines for this, with more detail in Section 3.3. Active monitoring for a leak at the interface during the fluid transfer is a shortfall; only the ammonia leak detector used on ISS is known technology for this area.

3.2.3.3 Fuel Quantity Measurement in Microgravity

Key Technologies: Capacitance-based sensors, ultrasonic and radar sensors, flow sensors (e.g., turbine, Coriolis), cavity acoustic resonance, acceleration of mass measurements, volume by acoustic reverberation decay, inductive sensors

Producers: Innovative Scientific Solutions LLC, VACCO Industries, Moog, Marotta Controls, Hoffer Flow Controls, CU Aerospace, Eaton Mission Systems, Emerson Electric Co., Carthage College, Creare, Sierra Lobo

Assessment: This technology addresses the challenge of accurately tracking fluid levels during transfer operations in a microgravity environment, and after the transfer is complete. Reliable fluid quantity measurement is crucial for managing propellant resources effectively, ensuring that refueling operations meet both performance and safety requirements. Integration of flow rates from meters provide a means of gauging transferred and remaining volume but are inherently prone to error due to cumulative nature of measurement error and potential for two-phase flow during transfer. Direct volume measurements are thus likely more desirable. Some key factors determining suitability of the direct volume measurement technologies include electromagnetic environment (in consideration of generation of EM as well as sensitivity of the technology to externally generated EM), storage vessel configuration and ullage (e.g., rigid or flexible wall and resulting, likely non-uniform headspace), and tolerance of application to vibration or other accelerations. The state of maturity of technologies like cavity acoustic resonance, volume by acoustic reverberation decay, and acceleration of mass measurements requires additional development and testing prior to field use.

3.3 Gap Assessment

As can be seen in Table 2 above, the technology categories most essential to perform GEO refueling are well-developed and mature, with the notable exception of leak detection. However, while some technologies identified as critical to execution of this use case have been successfully demonstrated in space, many critical systems still lack flight heritage. The absence of on-orbit validation increases the risk for mission planners, operators, and clients, making it difficult to justify investment or purchase of refueling services. The demonstration opportunities and infrastructure required to advance refueling technology is discussed in the next section.

The challenges we see in interoperability are also significant. Efforts underway at AIAA and CONFERS highlight the enterprise response to a need for coordination. AIAA S-157-2024 "In-Space Storable Fluid Transfer for Prepared Spacecraft" was released in early 2025 [6]. It is a voluntary consensus standard that incorporates recommendations from CONFERS on how vehicles should prepare for on-orbit refueling, although it has not been incorporated as a compliance document on many missions yet. CONFERS has also set up a new task force on Interoperability that will expand on CONFERS' previous development of functional standards to enable interoperability of mechanical interfaces for use on unmanned spacecraft engaged in ISAM activities [8].

3.4 Recommendations

Most of the technologies needed for OOR are already in development, but they need to be integrated, tested, and demonstrated in a way that builds confidence in their reliability and effectiveness. There are a few things that can be done to help close the gap between technology development and market demand.

Contribute to and Adopt Standards for a Unified Refueling Architecture: While historically it is not typical for standards to be designed before a market is established, refueling technology developers can benefit by adopting standards that support a unified refueling architecture. Developers should work with standards bodies to ensure their needs, concerns, and own wisdom can be incorporated into future standards. There are also opportunities for developers to create their own open standards so the ecosystem can build around their development path, giving them a competitive advantage in market dictation.

Improve Commercialization Gaps seen in Refueling Systems: There is a need to help build confidence and intuition about emerging ISAM technologies and approaches, and that starts with the developer educating the market. Developers should work closely with potential clients to educate them on their approach, inform them on developments regularly, and consider creative financial agreements or partnerships that can not only share the risk, but also provide additional incentives for clients to be early adopters and help close the gap between technology development and market demand. This could include leasing arrangements, pay-for-performance contracts, or other innovative financial structures that align incentives between providers and clients.

4. Demonstration Infrastructure State of the Art and Gap Analysis

4.1 Overview

The set of technologies identified in Section 3 as being critical to the refueling of GEO spacecraft were used to determine what testing activities are required to prove out a technology, component, or mission. The closing of identified testing gaps helps increase TRLs, decrease risk, and encourage mission adoption. The primary types of technology categories identified in Section 3 were evaluated for existing testing methods and gaps. The results are summarized in Table 3.

Table 3. Technology Categories, Testing Methods, and Gaps.

Taxonomy Categories Summarized	Testing Gaps Identified
Robotic Manipulation, Capture, and Interfaces	No major testing gaps on ground; ISS enables testing of robotic control algorithms, end effectors, and interfaces, but not new arms or capture/docking/grappling mechanisms. An on-orbit testing platform could mature component hardware faster and more reliably than standalone demo missions.
GNC and Sensors for RPO	Environmental simulation at system level; Infrastructure to test in space.

Fluid Transfer and Propellant Management	Zero-g simulation for fluids for long duration; Infrastructure to test in space; Methods for measuring propellant volume transfer while in space.

4.2 Existing Demonstration Infrastructure and Demonstration Missions

While there is very little demonstration infrastructure in space for testing OOR systems, demonstrations of refueling and RPOD capability have occurred over the last 25 years. Demonstrations over the next few years are expected to build upon the successes of the past and help reduce actual and perceived risk of OOR. Past, current, and future demonstrations are as follows:

4.2.1 NASA's Robotic Refueling Missions (2011-2023, LEO)

The Robotic Refueling Mission (RRM) included three hardware phases for demonstrating tele-operated robotic servicing tasks. The first module was launched on the last shuttle flight in 2011 and installed as an external payload on the ISS. Its primary goal was to demonstrate the robotic tools and techniques required to refuel an unprepared client satellite. The RRM payload contained multiple fill/drain valves complete with redundant caps lock-wired shut. It also flew four custom tools compatible with the ISS Special Purpose Dexterous Manipulator (SPDM). The SPDM was used to telerobotically cut lockwire, remove and stow caps and then engage a nozzle tool with an attached hose to a plumbed fill/drain valve. A hydrazine simulant (ethanol) was successfully transferred across the interface and the valve resealed. Additionally, robotic evaluations were completed in thermal blanket cutting, tool and tool adapter stowage, fastener removal, and machine vision algorithms. Additional launches in 2013 and 2014 delivered replacement task boards and a new visual inspection tool installed on RRM by SPDM which enabled new demonstrations of electrical connector manipulations, cryogen tank cap removal, and internal plumbing line inspections. RRM3 was an entirely new module launched in 2018 and focused on storage and transfer of cryogenic fluid (liquid methane). While electrical issues prevented an actual methane transfer demonstration, significant evaluations were completed on the pre-transfer robotic installation and management of the transfer hoses. It also featured a robot-compatible cryogenic valve interface and a Xenon Cooperative Servicing Valve. Across all RRM demonstrations, eight custom robotic tools and nine tool adapters were successfully evaluated, and three add-on components were robotically integrated to the main payload. The RRM demonstrations were critical to development and risk reduction for NASA's OSAM-1 mission.

4.2.2 Orbital Express (2007, LEO)

A mission by DARPA and NASA that launched in 2007, Orbital Express demonstrated in-space refueling through a series of autonomous and semi-autonomous operations conducted by two spacecraft: the ASTRO (Autonomous Space Transport Robotic Operations) servicing satellite and the NEXTSat (Next Generation Serviceable Satellite) client satellite. During the mission, ASTRO approached NEXTSat, connected to it using a specialized robotic arm, and after fully docking, transferred propellant to and from NEXTSat's fuel tank. The mission successfully showcased the capability to refuel satellites in orbit, extending their operational lifespans and reducing the need for launching new satellites. This demonstration included multiple dockings and undockings, the transfer of hydrazine fuel, and the exchange of batteries and other components.

Orbital Express operated in LEO approximately 492 kilometers (about 305 miles) above the Earth's surface. This orbit was chosen to facilitate the demonstration of autonomous rendezvous, docking, and refueling operations between the ASTRO servicing satellite and the NEXTSat client satellite.

4.2.3 ISS Refueling (2000-present, LEO)

The ISS has been refueled by Russian Progress vehicles since 2000 and by European Automated Transfer Vehicles (ATVs) from 2008 to 2014. The Progress vehicle was notably first used in 1978 for refueling the Salyut 6, a Soviet space station. Each vehicle delivers around 850 kg of propellant per mission [15].

4.2.4 MEV (2020, GEO; servicing not refueling)

Northrop Grumman SpaceLogistics' Mission Extension Vehicle-1 (MEV-1), produced by Northrop Grumman, launched in 2020 and docked with Intelsat-901 to provide propulsion services and extend its operational life. This was the first successful life-extension servicing mission in GEO using an in-space servicing vehicle. MEV-2 provided life extension services to Intelsat 10-01. While it did not provide refueling of the client spacecraft, it did demonstrate successful RPO and docking technologies and CONOPS that will enable future refueling GEO missions.

4.2.5 Tanker-001 Tenzing (2021, LEO)

Orbit Fab is actively working to establish a refueling infrastructure in space, with a particular focus on supporting satellites in various orbits, including GEO. Their approach involves developing fuel depots, known as "Gas Stations in Space," and tanker spacecraft that can deliver propellant to client satellites as needed.

Orbit Fab launched Tanker-001 Tenzing to LEO in 2021 as a fuel depot. Although it has not yet been used to transfer fuel, it serves as a demonstration of their refueling technology and provides a foundation for future missions. Orbit Fab plans to expand its network of fuel depots and tanker spacecraft, enabling regular refueling services for satellites in various orbits, including GEO.

4.2.6 Chinese SJ-25 (2025, GEO)

It has been reported that China recently demonstrated refueling in GEO when Shijian-25 docked with Shijian-21 in GEO to transfer approximately 142 kg of hydrazine fuel [1]. If confirmed, this would be China's first in-orbit fuel transfer in GEO.

4.2.7 MRV and RSGS (anticipated 2026, GEO)

The Mission Robotic Vehicle (MRV), developed by Northrop Grumman SpaceLogistics, will host the Robotic Servicing of Geosynchronous Satellites (RSGS) payload developed by the Defense Advanced Research Projects Agency (DARPA) and the Naval Research Laboratory (NRL). This mission aims to demonstrate on-orbit servicing capabilities. While MRV is not intended to perform refueling on client spacecraft, the technologies it will demonstrate are enabling for future GEO refueling architectures.

Planned for launch in 2026, the MRV is equipped with robotic arms and other specialized tools to perform various tasks such as inspection, maintenance, repair, and life-extension services for satellites in

GEO. The MRV is prepared to be refueled, but it is not designed to be a refueling vehicle. However, RSGS is a flexible robotic platform, and refueling payloads and tools could be developed and launched to GEO to be picked up by the MRV and used to refuel other satellites. The MRV is also capable of installing a refueling pod (or tank exchange) on a client satellite like the Mission Extension Pods (MEPs). The MRV includes a Northrop Grumman Passive Refueling Module (PRM) within its chemical propulsion system, so that a future refueling mission (not currently funded) could dock with MRV and refill the hydrazine propellant.

4.2.8 Astroscale U.S. Refueler, Kamino, and Tetra-5 Architecture Demonstration (anticipated 2026, GEO)

The Astroscale U.S. Refueler is a commercial refueling shuttle developed by Astroscale U.S. to conduct hydrazine fuel transfer operations of commercial and government clients in GEO. Kamino is a Defense Innovation Unit (DIU) effort to stage hydrazine fuel for transfer and use by other satellites in GEO. Tetra-5 is a United States Space Force (USSF) effort, in partnership with the Air Force Research Laboratory (AFRL), to demonstrate autonomous RPOD, on-orbit inspection, and refueling.

Together, these three programs will be employed by USSF to demonstrate an end-to-end GEO refueling architecture and supply chain.

4.2.9 LEXI (anticipated 2026, GEO)

Astroscale's LEXI (Life Extension In-Orbit) Servicer is a full-scale commercial servicing vehicle for life extension and mobility services in GEO. It is equipped with Orbit Fab's RAFTI interface for in-orbit refueling of the servicer itself. It is scheduled for launch in 2026.

4.2.10 ROOSTER-5 (anticipated 2027, GEO)

The ROOSTER-5 mission (Rapid On-orbit Space Technology Evaluation Ring) is a USSF initiative focused on demonstrating in-orbit satellite refueling capabilities. It involves a spacecraft designed to act as a "space gas station," enabling the refueling and life extension of other satellites in higher orbits, particularly GEO. The mission is part of a broader effort to develop a new space economy and address issues like space debris. USSF is currently targeting a 2027 launch date.

ROOSTER-5 will test Northrop Grumman's GAS-T (Geosynchronous Auxiliary Support Tanker) through a Northrop Grumman Passive Refueling Module (PRM), which will be fitted on the receiving spacecraft.

4.2.11 OSAM-1

While the future of OSAM-1 (On-orbit Servicing, Assembly, and Manufacturing-1) is currently uncertain, the mission planned to demonstrate advanced capabilities in satellite servicing, including refueling of an unprepared client spacecraft. OSAM-1 planned to dock with the Landsat 7 satellite and transfer propellant using its robotic arm and specialized refueling equipment. This demonstration would have showcased the ability to autonomously refuel satellites that were not originally designed (i.e., not prepared) for in-space refueling. NASA cancelled the mission in 2024 and released an RFI asking for input on alternate use cases for the OSAM-1 spacecraft, flight hardware, ground test facilities, and/or other parts of the mission, but has not publicly announced the next steps for the mission.

4.3 Gap Assessment

One key set of technology demonstration infrastructure gaps revolves around the testing of fluid transfer in space. This ranges from testing components that demonstrate leak detection, propellant filtering, and long-duration performance in vacuum and microgravity environment to testing integrated, end-to-end fluid transfer systems for performance related to spillage, measurement of fluid transfer quantity and rate, and system degradation over time. The performance is both around the parts themselves and the quality of fluid or potential contamination or spoilage. This latter element was identified as important for the development of certain storable propellants which are in their early stages, and since different propellants have different degradation rates. The duration of microgravity needs to be long enough for sloshing and other fluidic behaviors to damp out, which is not met by ground test options such as drop towers (2-9s of microgravity), parabolic flights (<30s of microgravity), or sub-orbital rockets (<4 min). As a result, the key challenges arise from the cost of building a specific mission around demonstrating this, because on-orbit demonstration of the end-to-end fluid transfer system is required.

Leakage testing in terrestrial vacuum chambers is also challenging, as a “dirty” vacuum chamber which can accept the leakages is required. Given how important outgassing is during vacuum testing, this type of testing requires a dedicated vacuum chamber that is not used for other purposes, which greatly increases the cost of testing. A small (approximately 50 cubic feet) chamber can be built that is compatible with propellant for about $100,000, so the demonstration gap is accessibility to such chambers.

Additional barriers for in-space testing included the fact that propellants required for GEO refueling, such as hydrazine and nitrogen tetroxide, are highly hazardous to human health, so testing on crewed space stations is not possible. However, there are adequate (and much less toxic) simulant fluids that do exist that can be used for testing instead of the actual propellants.

A second set of demonstration infrastructure gaps revolve around rendezvous and proximity operations (RPO). Some testing elements are solved, such as using air-tables to demonstrate 2D behavior and contact dynamics, as well as variable light simulation testbeds that allow camera systems to test the stark light contrast they would experience in space. However, full 3D testing of RPO and contact dynamics which include the full 6-degree-of-freedom behavior requires in-space flight missions to demonstrate. Elaborate ground-based testbeds with robotic arms (like those that exist at NASA Goddard, Naval Research Lab, and Northrop Grumman SpaceLogistics) can emulate 6DOF orbital motion driven by simulators, but there are discrepancies between the fidelity of any ground-based testbed and what is experienced when the spacecraft gets into orbit.

Grappling technologies had also been raised as being critical for GEO refueling, but for the most part ground tests were judged sufficient to demonstrate most interactions they needed to perform. The exception was a mating seal interface, especially when the docking interface and the fluid interface are combined into a single unit. In addition to the leakage aspects already mentioned, electrostatic differences between spacecraft as well as cold-welding in vacuum were raised as concerns that need to be mitigated in the design phase and validated through ground-based requirements signoff.

4.4 Recommendations

The primary solution suggested for the gaps in fluid transfer and RPO was the development of an in-space testbed in the style of a "persistent platform." The advantage of this platform is that it could host multiple different types of experiments from multiple government, commercial, or academic organizations over the course of its life, instead of each of those organizations needing to develop entire space missions to test their own technologies. Compared with a single mission, the orbital testbed platform could be far more capable in terms of power, robotics, computing, and communications. The additional capabilities expand the range of possible tests and missions while reducing costs by an order of magnitude because the costs are spread over a wider range of customers. Communication is particularly important because it allows for more information on the ground during RPO, including more frequent and higher-quality images to confirm a test is performing as expected. A persistent platform would need to be designed to comply with RPO and manipulation safety standards.

Additional suggestions including placing the testbed in unpopular or non-commercially valuable orbits, such as graveyard orbits, to reduce the risk to other spacecraft if space debris was accidentally created. This approach would also expand and help democratize the GEO refueling market beyond organizations that can afford to perform all the testing through one-off missions to validate their technology.

5. Policy and Regulation Proposed Framework

5.1 Overview

The successful implementation of on-orbit refueling for GEO satellites is contingent not only on technological advancement but also on the establishment of a clear and enabling policy and regulatory landscape. A robust framework is essential to provide industry with the certainty required for investment, ensure safe and sustainable operations, and foster international collaboration. The COSMIC Policy and Regulation (PR) Focus Area analyzed the GEO refueling use case and identified key gaps in the current regulatory environment.

Based on this analysis, the working group has developed and prioritized a series of recommendations. The following section details the highest-priority recommendations, divided into domestic and foreign policy, which are considered critical-path items for enabling a thriving GEO refueling ecosystem. A subsequent discussion section explores other important policy considerations that will need to be addressed to ensure long-term success and sustainability.

5.2 Recommendations

The following recommendations represent the most urgent and impactful actions that can be taken to facilitate near-term progress in GEO satellite refueling.

5.2.1 Domestic Policy Recommendations

5.2.1.1 Establish a Unified Domestic Mission Authorization Framework

The complexity of on-orbit servicing missions, particularly those involving rendezvous and proximity operations (RPO) and propellant transfer, does not fit neatly within existing domestic licensing structures. To avoid lengthy and uncertain regulatory reviews that stifle innovation, it is imperative to develop and implement a clear, efficient, and timely domestic licensing and "mission authorization" framework. This framework should be managed by a single lead agency and specifically tailored to the unique operational and safety considerations of GEO refueling depots and servicers. A unified framework will provide regulatory clarity, reduce administrative burden on commercial operators, and ensure a consistent approach to safety and sustainability.

5.2.2 Foreign Policy Recommendations

5.2.2.1 Establish An International Framework for ISAM

ISAM missions, including OOR, will undoubtedly become international in nature with services between U.S. operators and operators from other States. The Outer Space Treaty establishes rules on signatory States for items like registration, authorization, supervision, and liability that all can be intertwined within a servicing mission. Today, each such service could require bilateral agreement(s) between the State, which can take time and create business uncertainty. An agreed international framework for ISAM would ease the burden on States and provide business assurance to commercial entities that deliver or use ISAM services. The U.S. should lead the development of such a framework for ISAM services, including OOR, such that if the ISAM service is contracted or performed within the boundaries of such framework, it can be assumed that each State approves the operation without requiring new bi-lateral agreements.

5.2.2.2 Harmonize & Streamline Export Controls (ITAR/EAR)

Current U.S. export control regulations, namely the International Traffic in Arms Regulations (ITAR) and Export Administration Regulations (EAR), can present significant hurdles to collaborating with international partners on refueling missions. The transfer of servicing technology, the provision of refueling services to foreign satellites, and the use of foreign components can trigger complex licensing requirements. The U.S. should continue efforts to streamline ITAR and EAR regulations to facilitate these activities with allied and partner nations, ensuring that security concerns are appropriately balanced with the need to foster a competitive and collaborative global market for on-orbit servicing.

5.3 Additional Policy Considerations

While the recommendations above are paramount, the working group identified several other policy and regulatory areas that are vital for the long-term health and expansion of the GEO refueling ecosystem.

5.3.1 Domestic Policy Considerations

5.3.1.1 Refine Orbital Debris & Space Traffic Management Rules

The operational profile of a refueling servicer, which involves multiple RPO maneuvers and docking events, differs significantly from that of a traditional satellite. It is important to update the U.S. Orbital Debris Mitigation Standard Practices (ODMSP) and domestic Space Traffic Management (STM) rules to explicitly account for the unique characteristics of active servicing missions to ensure they can operate safely without creating undue debris risks.

5.3.1.2 Incentivize "Design-for-Refuelability"

To maximize the market for on-orbit refueling, new satellites must be prepared to be refueled. The U.S. government can accelerate this adoption by creating domestic policies—such as tax incentives, grants, or procurement requirements—that incentivize or mandate the inclusion of standardized refueling interfaces on relevant new U.S. government and commercial GEO satellites.

5.3.2 Foreign Policy Considerations

5.3.2.1 Promote International Norms for RPO & SSA

Safe refueling operations depend on transparency and predictability. The U.S. should lead the development and integration of international norms of behavior and "rules of the road" for RPO in GEO, including ISO-24330 [7]. This includes championing robust information sharing and Space Situational Awareness (SSA) protocols to ensure that all operators in GEO have a clear understanding of planned servicing activities, reducing the risk of miscalculation and collision.

5.3.2.2 Secure International Spectrum Allocations

On-orbit servicing missions require reliable communication links for command, control, and data transmission. The U.S. should advocate at the international level, through bodies like the International Telecommunication Union (ITU), to secure dedicated and internationally recognized spectrum allocations for these critical functions, ensuring that refueling operations are not subject to harmful interference.

5.3.2.3 Establish International Hardware Norms & Standards

The proliferation of proprietary, incompatible refueling interfaces would fragment the market and hinder interoperability. The U.S. should actively champion and lead the international adoption of recognized, industry-driven, non-proprietary or widely licensable standards for refueling hardware, including docking mechanisms, fuel ports, and electrical/data interfaces. This will foster a more competitive and resilient global supply chain for on-orbit servicing.

5.4 Implementation Framework

Effectively addressing these complex policy recommendations requires a coordinated, whole-of-government approach. A single agency or a dedicated task force must be empowered to drive this effort forward.

5.4.1 Recommended Lead Organization: An Interagency Task Force

Given the cross-cutting nature of the required policy changes—spanning commerce, transportation, foreign policy, and national security—we recommend the establishment of a National ISAM Policy Task Force that includes commercial involvement to the extent possible.

5.4.2 Recommended Framework for Action

The Task Force should adopt a phased approach to develop and implement the necessary policy and regulatory changes:

5.4.2.1 Phase 1: Foundational Scoping

The immediate priority is to convene the Task Force, formally map the existing regulatory landscape as it applies to GEO refueling, and identify specific statutory or regulatory gaps. This phase must include structured engagement with industry and international partners to ensure the resulting framework is practical and globally competitive.

5.4.2.2 Phase 2: Domestic Policy Development & Rulemaking

The Task Force will draft the necessary regulations for the unified mission authorization framework and the clarification of liability. This will involve initiating formal Notice of Proposed Rulemaking (NPRM) processes where required. Concurrently, the Task Force will develop unified U.S. government positions on all foreign policy recommendations in preparation for international engagement.

5.4.2.3 Phase 3: International Engagement & Harmonization (Ongoing)

Using the newly established domestic policies as a foundation, the U.S. Department of State, in coordination with the Task Force, will lead a concerted diplomatic effort. The goal is to establish bilateral and multilateral agreements and to champion U.S.-led standards and norms at international forums such as the UN Committee on the Peaceful Uses of Outer Space (COPUOS) and the ITU.

5.4.2.4 Phase 4: Implementation and Continuous Review (Month 18+)

As new domestic regulations are finalized, the lead agency will implement the new authorization and liability frameworks. The Task Force should remain as a standing body to monitor the effectiveness of these policies, adapt to new technologies and market developments, and ensure U.S. leadership in the evolving space economy.

6. Integrated Assessment

6.1 Current State

Although the U.S. is expected to demonstrate GEO refueling technologies by 2026, and some international demonstrations have already occurred, significant work remains to make GEO refueling reliable and routine. While upcoming U.S. missions will advance the TRL of essential technologies for refueling, single demonstration missions do not fully address the necessary infrastructure or regulatory changes required for a robust commercial refueling ecosystem.

Section 3 identified critical technology areas and existing or developing technologies necessary for implementing the GEO refueling use case. The most mature technologies are related to RPOD, which have been used since the Gemini missions in the 1960s. However, technologies specific to refueling, such as fluid couplers, flow measurement and leak detection sensors, are less developed and need further maturation and in-space demonstration.

The primary gaps in demonstration infrastructure include the capability to consistently and rapidly perform in-space testing of fluid transfer and storage, as well as end-to-end systems for RPOD. Traditional approaches involve launching one-off technology demonstration missions to mitigate specific risks. However, the infrastructure required to thoroughly and cost-effectively demonstrate these technologies in relevant environments is lacking. A persistent orbital testbed is seen as the most promising solution to bridge these gaps, minimize risk, reduce costs, and support a broader range of technological innovations in space servicing and refueling. Such a testbed could repeatedly demonstrate RPOD reliability, refueling interfaces, CONOPS, algorithms, and components.

Addressing the policy challenges is equally important. Establishing a clear, streamlined, and timely domestic licensing and mission authorization framework, managed by a single lead agency, will reduce administrative uncertainties, enhance regulatory clarity, and support innovation.

Refueling in GEO is crucial because of the number of different client spacecraft that could benefit from common infrastructure. In other Earth orbits, servicing spacecraft requires significantly more fuel to transfer between clients at varying altitudes and inclinations. An in-space refueling ecosystem is likely to start in GEO, but technologies and capabilities demonstrated there can also be adapted for other domains, depending on the business case.

6.2 Opportunities for Investment

Based on the Technology Taxonomy prioritization effort and the COSMIC Technology Inventory, there is a strong alignment between stakeholder priorities and current technology development. Many technologies exist between TRL 3 and 6, but few have reached TRL 8 or 9. Investment is crucial to elevate these technologies to operational readiness and establish a pathway for continual demonstration of new advancements in space.

The categories of Robotic Manipulation and Autonomous Rendezvous and Docking are essential for the refueling use case and well-represented in the COSMIC Technology Inventory. These technologies are ready for implementation and integration into future missions or demonstration activities. Fluid transfer technologies represent the most significant technological gap. Investment in these categories should focus on research and development to create new technologies, techniques, and approaches to address identified gaps.

The authors recommend the development of an uncrewed, "persistent platform" in orbit to serve as a multi-purpose testbed for rendezvous, docking, robotics, refueling, and other ISAM capabilities. Such a testbed could support a wide range of experiments by multiple government, commercial, and academic entities. It could also provide embedded capabilities (power, robotics, computing, and communications) that reduce the per-mission cost and risk by avoiding the need for dedicated missions for each technology demonstration. The persistent platform could potentially be deployed in less commercially valuable orbits (e.g., graveyard orbits) to mitigate risks to operational spacecraft.

7. Conclusions

The advancement of GEO refueling capabilities is crucial for the future of space exploration and utilization. As the demand for more ambitious and complex missions grows, the limitations of pre-integrated spacecraft become increasingly apparent.

The analysis of demonstration infrastructure reveals critical gaps that must be addressed to enable effective testing and validation of GEO refueling technologies. The proposal for a persistent in-space testbed platform offers a viable solution to these challenges, providing a cost-effective and versatile environment for demonstrating and refining these and other ISAM capabilities.

Furthermore, the establishment of a robust policy and regulatory framework is essential to support the growth and sustainability of the GEO refueling ecosystem. The proposed recommendations for domestic and foreign policy actions aim to create a clear and enabling regulatory landscape that fosters innovation, ensures safety, and promotes international collaboration.

This use case demonstrates the practical benefits of on-orbit refueling, such as extending the operational lifespan of satellites, enhancing national security through dynamic operations, and enabling more efficient mission planning. The comprehensive assessment of the current state of technology and the identification of gaps underscores the necessity for continued investment and development to bring these technologies and capability to maturity.

Appendix A. GEO Satellite Refueling CONOPS

Mission Activities	Considerations
RPOD Ingress: • Request from client for servicing spacecraft to provide fluid • Servicing spacecraft performs long range rendezvous with client spacecraft • Servicing spacecraft performs ingress to docking • Client spacecraft configures itself for combined stack operation	• Lighting conditions and requirements • Identifying fiducials • Abort conditions
Docked – Initial Checkout: • Docking confirmation feedback between servicing spacecraft and client spacecraft • Collect state knowledge – docking, alignment, fuel capacity	• Responsibility for ADCS control of combined stack • CONOPS to keep both vehicles positively powered • Communications between vehicles and ground
Docked – Refueling: • Mate fluid interface (if separate from mechanical docking) • Perform interface leak check, evacuate, and prime interface • Vent ullage gas of client tank(s) (if required) • Servicing spacecraft performs transfer of fluid(s) to client spacecraft • Depressurize interface and de-mate fluid interface	• Vehicle overpressure fault detection • Method of fluid transfer (e.g., pump, blow down) • Measurement technique for total fluid transferred (center of gravity measurements, flow sensors, system pressure)
Docked – Final Checkout: • Perform system checks (leak, over pressure, contamination)	• Remedies for off-nominal conditions (leaks, over pressures, contamination)
Egress and Return to Parking Orbit: • Servicing spacecraft egress to safe state • Re-engage configured systems on client spacecraft • Perform independent system checks (spacecraft systems, leak, over pressure, contamination) • Perform center of gravity measurements to update propellant estimates • Servicing spacecraft return to parking orbit	• Re-engagement timing for comms and ADCS systems Inspection methods (self-inspection, servicing spacecraft inspection of client spacecraft) • Client return to parking orbit or dispatched to next client

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