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Designing a Commercial Mission Operations Center for RPOD Missions

Commented [ZB1]: @Ethan Spessert Should we change the title to say ISAM since we talk about a bit more than just RPOD? Happy either way.

Commented [ZB2R1]: If we keep we should change every instance of RPO and POD-U to RPOD to be consistent probably.

Commented [ES3R1]: If we are allowed to change that sounds like a good idea

Commented [ES4R1]: I don't totally follow you on the RPO/PODU thing though

Commented [ZB5R1]: I mean I guess it isn't necessary but it feels annoying to have all three

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Abstract

Orbit Fab is developing a dedicated Mission Operations Center (MOC) in Colorado, USA in order to support the next generation of Refueling and Satellite Servicing Missions for commercial and government customers and service providers. Mission Operations Centers have historically been designed around individual Earth Observation (EO) or Communications spacecraft operations; recently, these systems have been modified for operating large constellations. Further modifications to traditional MOCs will be needed to support the growing in-orbit servicing ecosystem and enable the next generation of missions which are designed around the utilization of these services. While In-space Servicing Assembly and Manufacturing (ISAM) MOCs can benefit from the advances in automation that have come from constellation operations, new challenges also arise. ISAM missions differ from most commercial missions in their risk, operational cadence, and reliance on onboard automated control. In planning the four main components of satellite operations: the team, their procedures, software tools, and ground station communications, Orbit Fab has found that current methods bias heavily towards the EO and Comms use cases. This paper will explore key areas where Mission Operations needs to be designed uniquely for spacecraft expected to participate in ISAM, especially those whose primary mission involves repeated Proximity Operations and Docking-Undocking (POD-U). These areas include data sharing and collaboration with the client vehicle operations center, negotiating use of Ground Stations as a Service for close-to-continuous comms during POD-U while operating under other system constraints, dispersing the information necessary for other operators to steer clear of POD-U operations without requiring additional tools or analysis on their end, and developing operator views and tools that allow them to analyze and react to events at a rate commensurate with the dynamics of autonomous docking.

Orbit Fab will seek out the best solutions to overcome these challenges in the process of developing their MOC to fly the Podracer-1 mission and their future fleet of depots and shuttles. Podracer-1 will launch in early 2024 and will serve as an orbital testbed for Orbit Fab's POD-U hardware, software, and operations.

Keywords: Operations, ISAM, Servicing, RPO

Acronyms/Abbreviations

CDM	Conjunction Data Message
CORE	Common Orbital Refueling Elements
EO	Earth Observation
GRIP	Grappling and Resupply Interface for Products
GSaaS	Ground Station as a Service
ISAM	In-Space Servicing Assembly and Manufacturing
MOC	Mission Operations Center
NIST	National Institute of Standards and Technology
OD	Orbit Determination
OTV	Orbital Transfer Vehicle
POD-U	Proximity Operations, Docking, and Undocking
RAFTI	Rapidly Attachable Fluid Transfer Interface
RPO	Rendezvous and Proximity Operations
SDA	Space Domain Awareness
SPARK	Smart Prox Ops and Rendezvous Kit
TCM	Trajectory Correction Maneuver

1. Introduction

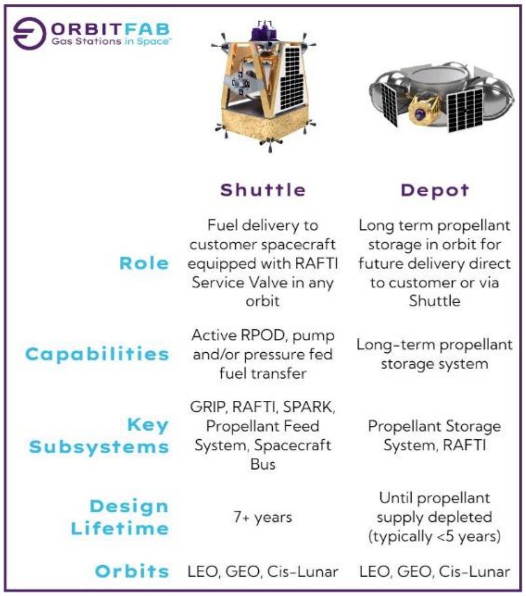
The space industry is entering a new paradigm and the way we approach space operations must adapt to support it. New technologies and business models for in-space servicing, assembly, and manufacturing (IASM) and in-space refueling will lead to the emergence of a new, bustling in-space economy. This in-space economy is distinct from the current situation because it will feature commodities and services being provided in space for space applications rather than for terrestrial applications. All of this will rely on reliable and safe execution of operations which have previously been regarded as high risk, including rendezvous and proximity operations (RPO), docking, and robotic manipulation of spacecraft components for assembly or servicing. Where previously entire missions would be planned solely around these high-risk activities, in the future in-space economy these will be commonplace mission phases which exist to support broader, ongoing mission objectives. To ensure that the in-space economy is developed in a sustainable and safe manner, it is critical that the industry quickly establishes safe best practices for operations within this new paradigm.

This paper captures some significant considerations for space operations in the new in-space economy. The remainder of Section 1 provides an overview of Orbit Fab, Orbit Fab's architecture for in-space refueling, and the emerging changes in the industry that will drive new approaches to space operations. Section 2 provides an overview of changes from the traditional operations approach needed to support the next generation of missions involving ISAM and RPOD. Section 3 highlights some ways that Orbit Fab is building these capabilities in its own operational ecosystem.

1.1 Orbit Fab Overview

Orbit Fab is building the in-space propellant supply chain to support the development of a bustling in-space economy. The in-space economy of the future will feature dynamic operations characterized by frequent maneuvers, multi-spacecraft activities and flexible mission plans. All of this depends on the availability of plentiful supplies of propellants which will remove the significant constraints placed on current space operations by limited delta-V budgets, enabling life extension, reuse, dynamic retasking of assets, and new mission concepts and business models. Including refueling in mission plans has also been shown to reduce total implementation costs for a variety of mission scenarios [1] [2]. Widespread availability of fuel in space is critical for scaling up and enabling the next generation of space activities in a sustainable and scalable manner.

To form the infrastructure backbone of this in-space propellant supply chain, Orbit Fab is developing fuel shuttles and fuel depots. A fuel shuttle is a highly maneuverable spacecraft capable of active rendezvous, proximity operations, and docking (RPOD) that can deliver fuel to a customer spacecraft. A fuel depot is designed to store large quantities of fuel in orbit to resupply shuttles and other vehicles capable of RPOD. Fuel shuttles and depots are both built on Orbit Fab's common orbital refueling elements (CORE) architecture which includes the Rapidly Attachable Fluid Transfer Interface (RAFTI) which is Orbit Fab's interface for both docking and fuel transfer. CORE also incorporates the refueling fluid feed system as well as all necessary electronics to drive the refueling operation. In addition to CORE, fuel shuttles also include Orbit Fab's Grappling and Resupply Interface for Products (GRIP) which is the active side of the docking and refueling interface. Figure 1 provides an overview of fuel shuttles and depots while Figure 2 shows RAFTI [3].



ORBITFAB Gas Stations in Space™

	Shuttle	Depot
Role	Fuel delivery to customer spacecraft equipped with RAFTI Service Valve in any orbit	Long term propellant storage in orbit for future delivery direct to customer or via Shuttle
Capabilities	Active RPOD, pump and/or pressure fed fuel transfer	Long-term propellant storage system
Key Subsystems	GRIP, RAFTI, SPARK, Propellant Feed System, Spacecraft Bus	Propellant Storage System, RAFTI
Design Lifetime	7+ years	Until propellant supply depleted (typically <5 years)
Orbits	LEO, GEO, Cis-Lunar	LEO, GEO, Cis-Lunar

Figure 1: Orbit Fab Fuel Shuttles and Depots

RAFTI

- **R**apidly **A**ttachable **F**luid **T**ransfer **I**nterface
- Passive RAFTI Valve Cores
- Passive Grapple Fixture
- Used on Clients, Depots & Fuel Shuttles

GRIP

- **G**rappling & **R**esupply **I**nterface for **P**roducts
- Active RAFTI Valve Cores
- Active Grappling Mechanism
- Used on Fuel Shuttles (& Docking Depots)

Figure 2: Orbit Fab's RAFTI and GRIP

1.2 Motivation

In addition to refueling and associated infrastructure, the bustling in-space economy will rely on a variety of organizations providing services in space. This is the focus of the growing ISAM sector of the space industry. ISAM missions include refueling, missions which provide services/repairs to other spacecraft in orbit, inspection missions, reusable orbital transfer vehicles (OTVs), active debris removal, in-space assembly, and other similar mission concepts. ISAM activities have a huge potential to revolutionize the way the space industry operates but carry significant new risks and operational challenges that must be addressed for them to be implemented in a safe and sustainable manner. These differences are primarily driven by the need to operate vehicles in close proximity without introducing a chance of collision, complex robotic operations, and tight timelines for execution of critical maneuvers. All ISAM missions must deal with one or more of these considerations which have not been common for traditional space missions.

Importantly, these factors will drive new risks and operational considerations for the customers of ISAM missions as well as the missions themselves. Because of this, there is a need to educate operators across the industry of what will be required of them to receive ISAM services and what upgrades to systems and procedures will be needed for the future of the industry in the new bustling in-space economy.

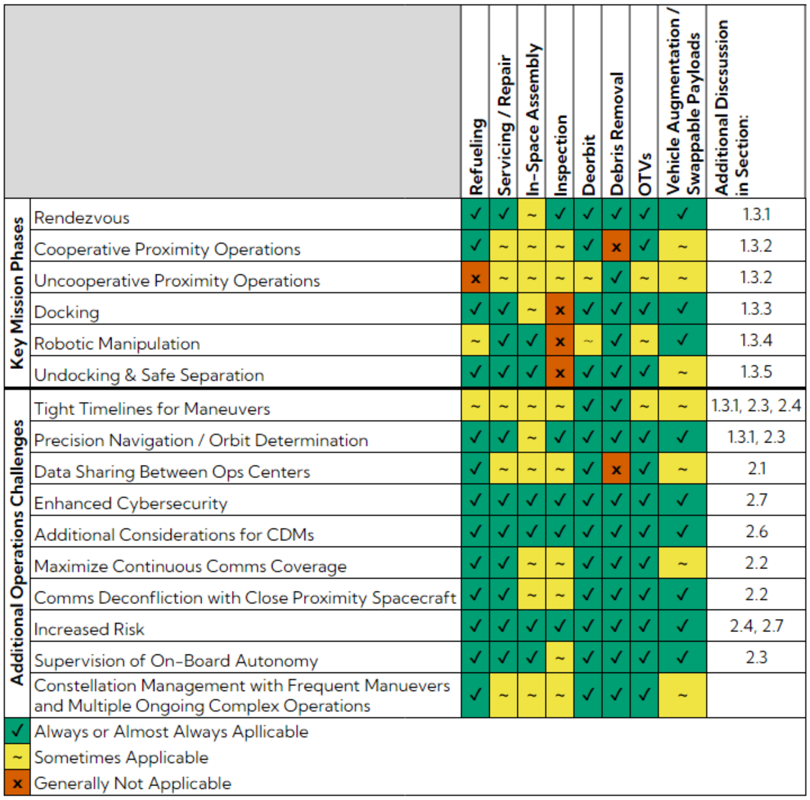
1.2.1 Traditional Ops Approach

The majority of value in the commercial space industry has historically been in the Earth observation (EO) and telecommunications segments [4]. Unsurprisingly, this means that the operations approaches of most commercial spacecraft operators have been driven by these operations needs and best practices and assumptions based on the heritage of the generation of space missions. These methods are geared towards missions with lower risk, lower operational cadence, and less reliance on onboard autonomous decision making. EO and comms missions typically only need to plan maneuvers for initial commissioning, station-keeping and end of life disposal. These maneuvers are often somewhat flexible on timing, needing to be planned and executed over the course of days rather than hours. It is also generally possible of operators of such missions to take a fairly siloed approach, only interacting with other operators as needed for dealing with conjunction events.

1.2.2 Why it needs to change for ISAM

ISAM missions have an entirely different set of operational needs and requirements from the traditional EO and comms missions. Rendezvous and proximity operations (RPO) activities are critical to the successful implementation of ISAM concepts as two spacecraft must be brought close to one another to interact. RPO requires maneuvers to be implemented on much faster timetables for planning and execution along with higher precision and speed in orbit determination to ensure safe relative motion. Operators will also need to be able to react quickly to any anomalies that arise; while in a traditional mission an anomaly might result in loss of revenue, ISAM missions add an additional risk of damaging collisions which can destroy expensive assets and produce debris. This necessitates response on a much faster timetable to restore safety. RPO and robotic manipulation needs also drive requirements for additional data sharing between spacecraft/operators, either by way of the ground or through an intersatellite link. Additionally, ISAM missions may be at higher risk from cybersecurity threats due to the additional data interfaces presenting more vulnerabilities and the high consequences of failure presenting a target for bad actors. Table 1: New Aspects of Operations Required by Mission TypeTable 1 outlines the key mission phases and operations needs that are driving the need for new operations approaches for ISAM missions and indicates where in the paper readers can find more detailed discussion on each topic.

Table 1: New Aspects of Operations Required by Mission Type



		Refueling	Servicing / Repair	In-Space Assembly	Inspection	Deorbit	Debris Removal	OTVs	Vehicle Augmentation / Swappable Payloads	Additional Discsussion in Section:
Key Mission Phases	Rendezvous	✓	✓	~	✓	✓	✓	✓	✓	1.3.1
	Cooperative Proximity Operations	✓	~	~	~	✓	x	✓	~	1.3.2
	Uncooperative Proximity Operations	x	~	~	~	~	✓	~	~	1.3.2
	Docking	✓	✓	~	x	✓	✓	✓	✓	1.3.3
	Robotic Manipulation	~	✓	✓	x	~	✓	~	✓	1.3.4
	Undocking & Safe Separation	✓	✓	✓	x	✓	✓	✓	~	1.3.5
Additional Operations Challenges	Tight Timelines for Maneuvers	~	~	~	~	✓	✓	~	~	1.3.1, 2.3, 2.4
	Precision Navigation / Orbit Determination	✓	✓	~	✓	✓	✓	✓	✓	1.3.1, 2.3
	Data Sharing Between Ops Centers	✓	~	~	~	✓	x	✓	~	2.1
	Enhanced Cybersecurity	✓	✓	✓	✓	✓	✓	✓	✓	2.7
	Additional Considerations for CDMs	✓	✓	✓	✓	✓	✓	✓	✓	2.6
	Maximize Continuous Comms Coverage	✓	✓	~	~	✓	✓	✓	~	2.2
	Comms Deconfliction with Close Proximity Spacecraft	✓	✓	~	~	✓	✓	✓	✓	2.2
	Increased Risk	✓	✓	✓	✓	✓	✓	✓	✓	2.4, 2.7
	Supervision of On-Board Autonomy	✓	✓	✓	~	✓	✓	✓	✓	2.3
	Constellation Management with Frequent Manuevers and Multiple Ongoing Complex Operations	✓	~	~	~	✓	✓	✓	~	

✓ Always or Almost Always Apllicable
~ Sometimes Applicable
x Generally Not Applicable

1.3 *Typical ISAM Mission Phases*

ISAM missions and missions receiving services from ISAM providers frequently include new phases that are not typical for current operators. Each of these phases drives new operational requirements and procedure considerations with implications for how to set up and use an MOC. Several of the most significant of these will be highlighted in Section 2. The following subsections provide the definitions of each of the phases shown in Table 1 and outline some of the most critical operating requirements and considerations for each. Generally, the considerations in these phases differ between a vehicle which is actively performing the primary activities of a phase (maneuvering, actively manipulating robotics, etc.) and one which is passively participating. The former is referred to as the chaser vehicle or, in the case of Orbit Fab's architecture, a shuttle, while the latter is referred to as the client spacecraft. Figure

3 provides an example of how each of these phases come together in the context of Orbit Fab's fuel shuttle delivery concept of operations.

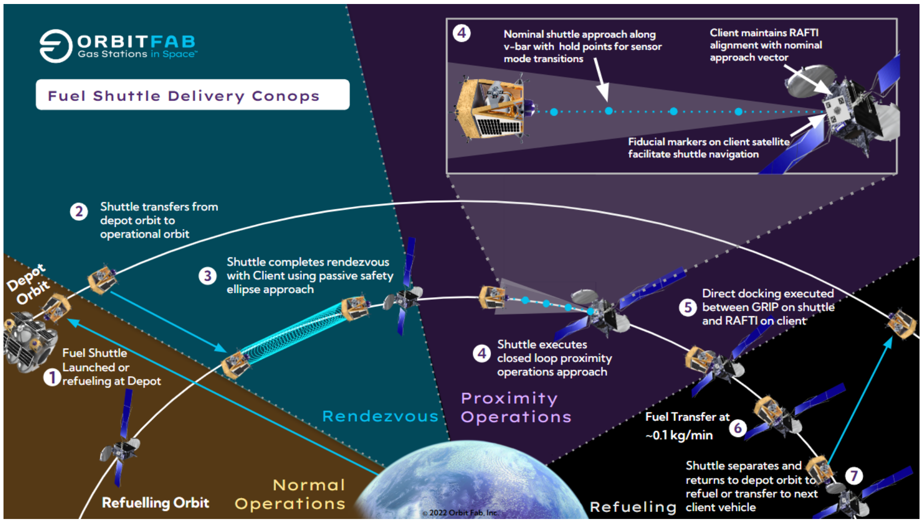


Figure 3: High Level Overview of Orbit Fab's Fuel Shuttle Delivery Concept of Operations

1.3.1 Rendezvous

The term rendezvous is used to refer to maneuvers used to place to vehicles in proximity with one another. Precises ranges for the beginning and end of rendezvous will depend on orbital altitude and the particular requirements of a given mission scenario, but in general is defined for purposes of this paper as a period where the chaser spacecraft is in a roughly matched orbit with the client and must perform maneuvers to reduce the range between the two vehicles at a cadence which is fast compared to normal space operations for common EO use cases but is slow enough for maneuvers to be planned and commanded from the ground rather than relying on on-board closed-loop control. Rendezvous can be completed with a variety of approaches, but for ideal safety between the two vehicles it is best practice to use passively safe trajectories wherever possible *[5]*. An example of a passively safe rendezvous approach for LEO is given in Figure 4 *[6]*.

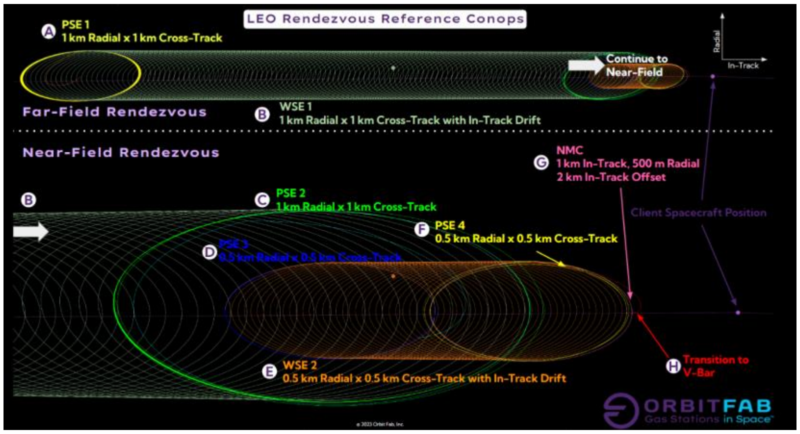


Figure 4: Orbit Fab's Example LEO Rendezvous Reference Concept of Operations

Rendezvous generally imposes few new operational needs on a passive client spacecraft aside from sharing information on their orbital state knowledge periodically with the operators of the chaser if possible. Chaser spacecraft operations, however, will need to account for several challenges presented by the maneuver cadence involved with a rendezvous plan such as that shown in Figure 4. For example, the transfer from PSE 2 (C) to PSE 3 (D) requires two maneuvers to be executed within half an orbit of one another. Operators will need to quickly be able to process data from each maneuver to determine whether it has been accomplished with the specified precision and either replan the second maneuver or add a trajectory correction maneuver (TCM) accordingly. Additionally, operators must be able to verify that the state uncertainty between the two vehicles is greater than their separation in each direction at each point in the rendezvous. Both of these factors drive a need for new tools which allow for rapid processing of new maneuver plans and relative orbit determination (OD) to enable operators to make the correct decisions quickly.

1.3.2 Cooperative/Uncooperative Proximity Operations

Proximity operations is defined as the phase where the chaser vehicle approaches the client using closed loop control to calculate the necessary thrusts and torques needed to bring the two vehicles into a desired relative state based on onboard relative navigation solutions. While proximity operations will be enabled by onboard autonomy, it is expected that the current generation of ISAM missions will need operators to supervise this autonomy closely until it is proven to be reliably safe. Operators of both vehicles must carefully monitor telemetry to ensure that it is safe to continue with the proximity operations approach. Key factors to consider include verification that both spacecraft remain in the correct control mode and momentum state, verification that chaser relative navigation solutions are sufficiently accurate to proceed, and verification of the power state of both spacecraft.

1.3.3 Grappling/Docking

In the grappling/docking phase, two vehicles equipped with a docking or berthing interface are physically connected. This is generally the shortest of the ISAM mission phases by time, but one of the most safety critical. Unexpected behaviors on contact could damage one or both vehicles and operators have limited time to respond to any anomalies. Therefore, the most important operations needs driven by this phase are to verify the safe state of the system before beginning contact and to ensure the behavior of both spacecraft in the mode they will be in at contact is extensively verified both before flight and during flight before docking. Particular attention must be given to avoiding a 'force fight' situation where actuators on one or both vehicles attempt to counter the expected docking contact dynamics. Because of the time sensitive nature of the grappling activities, this phase is generally expected to be executed with full or near full on-board autonomy.

1.3.4 Robotic Manipulation

The robotic manipulation category covers operations performed by ISAM missions using robotic manipulators to complete servicing, assembly, or other activities. Due to the wide variation in possible activities in this phase, particular operations requirements are highly use case dependent. In general, operators will have more time to make decisions and send commands from the ground than during the time-critical docking phase. However, time efficient servicing may be a driver for commercial business model viability in some cases. Attitude control while docked is also a significant factor for operators to consider when planning for any docked operations. It is once again essential to avoid a potential 'force fight' between the two systems while ensuring sufficient control authority over the combined stack, especially in the presence of torques generated by the robotic manipulation sequence.

1.3.5 Undocking/Separation

Separation refers to the breaking of the physical connection between the two spacecraft, while departure refers to the trajectory followed after separation resulting in the vehicles being in safe relative orbits and ready to continue with their respective missions. The exact operational needs of this phase depend most on the particulars of the separation mechanism. If the disconnection imparts a separation impulse between the two vehicles, it may be possible for this phase to happen relatively passively; the combined stack can slew to an attitude such that the separation impulse produces a safe departure trajectory. In such cases, it may be sufficient for operators to monitor the relative departure trajectory for safety as they return to normal operations. Attention should also be given to the distance from separation impulse to the center of gravity of each vehicle to ensure the vehicles are not put into a dangerous relative spin state. If no separation impulse is imparted by the mechanism or the separation impulse is insufficient, additional requirements will be placed on operators to plan a propulsive separation maneuver. It should be ensured that this maneuver does not cause dangerous thruster plume impingement on either vehicle and the impact of such maneuvers on the total mission delta-V budget must be assessed.

2. Mission Operations for ISAM

2.1 Data Sharing and Collaboration

Safe RPOD requires collaboration between the operators of the two spacecraft. While initial missions may test two spacecraft from the same operator, the end goal is to perform a service to a customer whose client spacecraft will be operated elsewhere to the chaser. A Mission Operations Center must be designed ready to share data and operate alongside a second MOC. For ISAM missions that do not have inter-satellite links all data will need to be transmitted between MOCs in real time. Even if an inter-satellite link is used, operators will need to maintain constant communication in order to be aligned on decision making about how to proceed if anything goes wrong.

To limit the delay and number of interfaces, Orbit Fab will grant the client vehicle operations team access to the same ground software that we use to view real time telemetry, with limited permissions. Full access will not be possible, one reason being potential hosted payloads. Both parties will want to run their own analytics on each other’s telemetry to verify it is safe to continue. Clients will query APIs to access Orbit Fab shuttle telemetry for their analytics.

Additionally, a MOC for ISAM missions should be equipped with systems to quickly share data with the international space industry as a whole. Firstly, sharing when RPO activities will happen publicly is important to help avoid misunderstandings about whether there are possible collision situations developing and to reduce the risk of third-parties accidentally approaching and interfering in RPO operations. Orbit Fab supports the creation of an international standard for such public disclosures to foster transparency and safe RPO, which will be a risk reduction in space traffic management globally [7]. Data sharing interfaces built for these purposes could also be used to share other information on ISAM activities and other mission parameters in the future, helping to increase the sustainability and efficiency of the industry in the context of the space donut model [8].

2.2 Ground Station as a Service

It is clear that ISAM missions need to use Ground Stations as a Service (GSaaS) rather than building dedicated antennas. ISAM vehicles need the flexibility to operate in multiple different orbit regimes that may not be known at the time of launch, which also creates a licensing challenge. Lighting conditions and revenue-generating operations of the client vehicle will determine when and over what ground track POD-U can be performed. The spread of GSaaS antennas across the globe, from numerous different providers will make this possible.

For the foreseeable future Orbit Fab will seek near continuous contact with our shuttles during Proximity Operations and Docking for human supervised on-board closed loop control. Achieving 30-40 minutes of near continuous contact for Prox Ops and Docking will likely require the use of multiple GSaaS providers. Failure to book one of the 5-7 passes required could result in a delay of the docking. Each GSaaS provider has different processes and timelines for booking passes, increasing the difficulty of getting all the required passes for POD-U. Orbit Fab will work with partners to create a scheduling tool that finds and books these series of passes.

A client operator will inevitably select their Ground Station antennas based on what is best for their mission and finances. The best ground station choices for this application are unlikely to also be the most suitable for the near continuous contact needed during proximity operations and docking. Mission planners must ensure both vehicles are licensed and capable of working with a set of ground stations that will support RPOD. The use of software defined radios by both the ISAM vehicle and the client will increase the likelihood of finding suitable ground stations. Many customers want to use a single GSaaS provider in order to benefit from discounts on per minute pricing the more minutes used. With current ground stations each provider has up and running, no one provider can support the swath of contact necessary for proximity operations and docking. Orbit Fab intends to use a combination of providers to achieve 40-45 minute long near continuous communication passes.

Table 2 shows that no single GSaaS provider achieves more than 70% of the potential for continuous comms available by combining all providers. This data was determined using publicly available ground station antenna location data from commercial GSaaS providers and placing a 5° mask.

Table 2: Continuous contact available from different GSaaS providers

Provider	Continuous Contact Duration (minutes)
Provider 1	30.6
Provider 2	29.8
Provider 3	13.9
Provider 4	19.3
Combined	44.5

2.3 New Operators Views and Tools

Advanced data analysis tools can remove the onus on analysts to understand the interactions and interrelationships of telemetry values and subsystems [9]. The dynamics of RPOD require fast decision making from both software and operators. Understanding why, in relation to the system at large, one is seeing anomalous telemetry takes time. Time to think through the possible scenarios and track down data to validate hypotheses. This operator driven process would take too long during RPOD. Software that can expose these dependencies and connections between seemingly unrelated data brings the time of this process to an acceptable speed. Additionally, requiring analysts to bring this understanding to the table accepts that an individual's unique experiences will impact what connections they will see. Data driven software that can find outlier data in a multivariate dataset [10] can effectively share a high level of understanding of the system with the entire team, from the newest members to experienced leads. Now that these interactions have been identified by the ground software, the remaining challenge is presenting them to analysts in a rapidly digestible form. Node based diagrams have been shown to help communicate interrelationships of thermal telemetry to operators [11].

Commented [ZB6]: @Ethan Spessert Mention fast processing for maneuver plans and OD somewhere here if you aren't planning to already

Commented [ES7R6]: Will do. Kind of like what we discussed the other day with maneuvers half an orbit apart during Rendezvous?

Commented [ZB8R6]: Yes

Again, driven by the dynamics of RPOD, ground processing of orbit determination and maneuver planning must occur in less than half an orbit (~48 minutes in LEO) for paired rendezvous maneuvers [6]. After the first of a pair of rendezvous ellipse sizing maneuvers, the MOC needs measurements from post maneuver to characterize actual effect of the maneuver on the orbit, due to errors in timing, duration, thruster performance, and attitude control. A ground station pass to downlink GPS data, or an opportunity for ground-based measurements is required shortly after the maneuver. The time between reception of that data and the last contact before the next maneuver determines the amount of time that orbit determination and maneuver planning have to run. Increasing access to ground station antennas and ground-based measurements should increase the amount of time these processes have to run.

2.4 Digital Twins

Digital twins are precise virtual copies of systems. They differ from traditional simulations by having integrated models of each aspect of a system as well as a direct link to actual telemetry coming from the operational system [12]. Numerous studies have shown the benefits of digital twin approaches for space applications, including for ISAM [13]. The integrated nature of a digital twin model makes it a powerful tool for ensuring the correctness of spacecraft commands, greatly reducing risk by ensuring that unexpected interactions between subsystems are captured before commands are implemented on the spacecraft. The digital twin approach has also been demonstrated to increase the accuracy and consequently the speed of operator responses in off nominal scenarios when FDIR procedures are being executed by enabling easier identification of the affected subsystems and their interactions [14]. These characteristics of digital twins make them ideal tools for use with ISAM missions. They can help operators deal with the rapid cadence of commands and maneuvers needed, quickly analyze causes and impacts of off-nominal conditions, and accelerate the implementation of correct responses to such conditions in high-risk scenarios. Digital twins offer benefits that help address many of the ISAM mission challenges discussed in Table 1, especially challenges around risk and timing constraints. Perhaps most valuably, digital twins allow for easy testing of commands and procedures to be executed on the spacecraft that were unexpected at the design stage. ISAM and refueling will push missions to engage in many activities which were not preplanned before launch due to the added flexibility enabled [2], so needs of this kind will become increasingly common and are enabled by a digital twin approach.

2.5 SDA Integration

While Orbit Fab and other operators within the ISAM sector are working on reliable and robustly safe RPO systems, unexpected anomalies or failures are always possible in any space activity. In the event of such an anomaly occurring, it may not be possible for operators to trust the onboard relative navigation solutions coming from the spacecraft to be accurate for safe abort trajectory planning. Therefore, it is desirable for data from third party space domain awareness platforms and sensor networks (e.g. COMSPOC, LEOLabs, etc.) to be integrated into the operations data ecosystem for spacecraft that will be passive or active participants in RPO activities. By timing critical RPO phases to align with passes over SDA sensors, this data interface can enable verification of the safety of the system based on an independent data source.

2.6 Conjunction Handling

Automated collision avoidance maneuver planning has progressed significantly in recent years. However, conjunctions during an RPO phase of an ISAM mission require different approaches. If a conjunction occurs with a third-party object during RPO, both vehicles must coordinate their maneuvers in order to avoid accidentally colliding with one another while avoiding the third-party object or maneuvering in different directions that significantly increase the delta-V needed for RPO following the conjunction event [7]. Additionally, RPO requires frequent maneuvers, and current automated avoidance planning approaches are not compatible with a frequently changing orbit because they are based on predictions from days in advance [15]. To mitigate this problems, ISAM missions should pursue the following for dealing with conjunction events with third parties:

1. Communicate expected RPO operations to the global space community as discussed in Section 2.1 so that operators of other spacecraft can plan to avoid any close conjunctions proactively if possible.
2. Screen expected rendezvous trajectory for potential conjunctions before beginning RPO and consider delaying if a conjunction is likely.
3. Develop dedicated automated planning features in the chaser operations ecosystem to automatically plan avoidance maneuvers for both vehicles that maintain them in a safe relative state without inflating the delta-V needed for RPO.
4. Integrate SDA data and OD solutions from both spacecraft directly into the conjunction avoidance process to ensure planning is based on the most up to date data possible.

2.7 Additional Cybersecurity Requirements

Orbit Fab is working with Rebel Space Technologies to define a robust cybersecurity strategy that will allow ISAM operators to engage in secure mission operations. A well-executed and resilient ISAM cybersecurity strategy enables collaboration, authentication, threat response, and positive control of autonomous capabilities across a disparate collection of platforms and systems, such as space stations, satellite vehicles, rendezvous vehicles, orbital manufacturing, etc. To successfully conduct in-space servicing, which requires both object approach and object acquisition, operators and the autonomous decision-making protocols must trust the data, communications, and autonomous functions of all platforms and space vehicles involved. ISAM systems require the ability to securely interoperate, establish the identity of interacting systems, maintain positive control of systems, and ensure the security of networks and communications. Recognizing the importance of cybersecurity to space operations, the National Institute of Standards and Technology (NIST) has developed NISTIR 8270 [16], a draft publication that addresses Cybersecurity for Commercial Satellite Operations, and NISTIR 8401 [17] for the Satellite Ground Segment; however, these publications do not specifically address the issues associated with ISAM or RPOD. As a result, further analysis is required to identify the specific risks and develop capabilities to ensure the safe execution of ISAM and RPROD.

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The potential cybersecurity threats for satellite communications also apply to on-orbit servicing, shown below in Table 3.

Table 3: Cybersecurity threats and impacts to ISAM

	Cybersecurity Potential Threats (from NISTIR 8270)	**Business Impact to ISAM / RPOD**
1	Intentional jamming and spoofing of sensor data	Disabling, Disruption, and/or Mission Failure
2	Interception and theft of sensor data	Disruption, Loss of Data Integrity, Loss of Controlled Information
3	Intentional corruption of sensor systems	Disabling, Disruption, Loss of Data Integrity and/or Mission Failure
4	Denial-of-service attack of sensor	Disabling, Disruption and/or Mission Failure
5	Intentional jamming and spoofing of guidance control	Disabling, Disruption, Malicious Control and/or Mission Failure
6	Hijacking and unauthorized commands to guidance control	Disabling, Disruption, Malicious Control and/or Mission Failure
7	Malicious code injection	Disabling, Disruption, Malicious Control, Loss of Data Integrity, Loss of Controlled Data and/or Mission Failure
8	Denial-of-service attack of guidance	Disabling, Disruption and/or Mission Failure

According to the Aerospace Corporation, example attacks include :

- Subversion of ground system capabilities by utilizing the ground system to maliciously interact with a satellite
- Communications hacking on TT&C systems via command link injection, replay attacks, or electronic attacks like jamming and spoofing
- Malicious features embedded during hardware development, including hardware-based trojans
- Design vulnerability exploitation, where designed-in features of the system are used for malicious purposes, i.e., direct memory writes to a satellite
- Software-defined radio compromise
- Software weaknesses and vulnerabilities exploitation
- Insider threats

Commented [ES10]: @Zach Burkhardt at "trojansDesign" (end of first line) it looks like "Design" should be the first word of the next bullet. Can you confirm with what Carrie sent you and correct if so?

NIST 8270 recommends a risk management process to address these threats that includes the capability to identify, protect, detect, respond and recover from cybersecurity threats. With the increased use of software-defined radios for communications, as mentioned above, and high performance edge computing, more advanced techniques and intelligent software for autonomous threat detection and response to meet these requirements are possible and necessary.

Finally, with the increased reliance on autonomy for ISAM operations, the autonomous space system protocols also need to trust the data and communications have not been corrupted.

Rebel Space Technologies, Inc. is developing cybersecurity software for trusted communications and NISTIR 8270 compliance that protects the space system, and its data, from communications spoofing, interception, corruption, tampering, and denial of service during an on-orbit servicing operation. With this software, the confidentiality, integrity, and availability of space systems communications are assured through the application of a robust cybersecurity risk management process on the space system that uses zero-trust principles to validate the identity of all potential communication links and implements autonomous vulnerability detection and response onboard the spacecraft.

3. Orbit Fab MOC development

3.1 MOC Status

Orbit Fab is developing a Mission Operations Center (MOC) based on the needs and principles outlined here for safe and effective operations for our missions, all of which will execute RPOD numerous times. While software development is still in progress, basic infrastructure in the physical location is being prepared. Redundant access to the internet and uninterruptable power supplies are being installed. Mission rehearsals for Podracer in Q4 2023 will mark the first formal use of the Orbit Fab MOC.

3.2 Training facility for RPO

Over the first missions, Orbit Fab will develop digital twins of each spacecraft. These digital twins will be used to test new RPO approaches, as well as train Orbit Fab operators. Digital Twins will more accurately capture the nuances of a spacecraft's flight software's interactions with its implementation of RPO. Digital twins model interactions across multiple subsystems, enabling operators to develop a holistic understanding of possible system behaviors during training and rehearsals. These rehearsals will also be able to incorporate operationally realistic data, including for rehearsing off-nominal scenarios. This, combined with the benefits of digital twins outlined in Section 2.4 points to clear benefits of integrating a digital twin ecosystem with a MOC for ISAM missions [18].

The in-space economy will benefit greatly from an increase in the number of organizations capable of RPOD operations. RPOD capable vehicles unlock entirely new space applications, allowing significantly more robust space-to-space markets that can better serve space-to-earth ones. These include space debris removal, keeping operators in-orbit safe; in-space servicing, extending the life and value proposition of assets; in-space manufacturing, making higher quality materials in-space to serve ground customers; and more. Organizations who may need to execute RPOD a single time during their mission, and not as a primary mission objective will benefit from acquiring practices and lessons learned from a company such as Orbit Fab who will have spent years refining RPOD operations. Orbit Fab can take them through planning far field rendezvous with walking safety ellipses that minimize collision risk in the case of missed maneuvers or spacecraft faults. Based on the availability of ground stations for a mission, necessary operational cadence, thruster performance, level of automation, and risk posture we will decide on hold points and Go/No-Go conditions for the planned mission. Assuming the training organization is preparing to be the active vehicle in RPOD, Orbit Fab will play the client vehicle. Telemetry exchange between the two parties will be agreed upon in mission planning. Given both parties will be using the same MOC software for these exercises, selecting what data at what points to exchange will be the crux of the operation rather than transfer itself.

During the training exercise Orbit Fab and the training organization can start fully integrated in the same room with completely open lines of communication and access to each other's information. Subsequent exercises will separate the teams to mimic a real life RPOD mission with operations teams in different geographic locations.

Owens and Crocker describe operators' interaction with the spacecraft as control loop [19]. For a complex system on a tight schedule every procedure cannot be rehearsed, and every possible scenario will not have a procedure written for it. Introducing anomalies from each block of a generic control loop over the course of mission rehearsals will give operators an understanding of how to approach anomaly resolution regardless of its source. The control loop includes the following, and examples of RPOD anomaly scenarios to rehearse under each block are given:

- Control Input Issues
  - An operator commands the servicer to begin proximity operations before the agreed upon conditions are met with the client.
- Controller Issues
  - The impact of differential drag on in track drift rate is larger than the flight dynamics system predicted.
- Actuator Issues
  - Active docking mechanism is stuck in the closed configuration.
- Controlled Process Input Issues
  - Attitude dynamics of the docked stack do not perform as expected due to the provided moment of inertia of the client vehicle being incorrect.
- Disturbances to the Controlled Process
  - Upon contact with the client vehicle, an electro static discharge from the client vehicle affects the servicer C&DH subsystem.
- Observer/Sensor Issues
  - Operator indicator of hard dock does not turn on after hard dock command is sent, and spacecraft C&DH system received the command.

3.3 The Podracer Mission

Orbit Fab expects to first demonstrate these operational capabilities in the execution of the Podracer mission that Orbit Fab is currently developing with Apex. Podracer will be an orbital testbed for RPO capabilities, equipped with Orbit Fab's SPARK POD-U, and a propulsion system from Stellar Exploration, Inc. enabling six degree of freedom control. The inclusion of these systems will enable extensive testing of both the onboard hardware and software of the SPARK system and RPO operations. The large amount of delta-V available from the propulsion system will allow for repeated approaches with variable operational strategies. This will result in quantitative data that will enable direct comparison of different alternatives which can verify the safety and efficiency of operations options for future missions.

Podracer will launch on Space X's Transporter-10 mission in January 2024. After deployment and commissioning, the Podracer spacecraft will execute several simulated rendezvous phases where it will maneuver relative to a selected 'virtual' target point in space to demonstrate successful execution of the rendezvous conops before attempting with a real client vehicle. Similarly, after completing this empty-space rendezvous, the SPARK proximity operations system will be activated and supplied with simulated navigation data to enable testing of proximity operations with respect to an empty point in space. These empty-space tests will serve as critical risk reduction, proving the functionality of the spacecraft and validating key operations procedures before proceeding with RPOD with an actual client where the consequences of failure would be much higher. Next, the spacecraft will complete several flybys of the selected client object which will be another spacecraft launched on Transporter-10 equipped with fiducials to aid relative navigation and Orbit Fab's RAFTI, making it optically representative of a client vehicle for a refueling operation. These flybys will enable calibration of the SPARK sensors and verification of the data and communication interfaces between the Podracer operators and client operators. Having completed these risk reduction steps, Podracer will then be ready to complete a robustly safe RPO with the client spacecraft.

4. Conclusion

In-space refueling and ISAM missions will fundamentally change the paradigm in the space industry and drive a shift to a new in-space economy of services and commodities. The approach taken to operations must shift as this new reality comes online to ensure continued safe and sustainable space activity. The inclusion of either active or passive participation in RPOD operations drives significant additional operational challenges, especially in the domains of flight dynamics, communications, cybersecurity and constellation management. Operations capabilities that are not typical to current generation missions will need to be integrated to address these new requirements. This includes the integration of new flexible commercial services in the areas of space domain awareness and ground stations as a service, as well as setting up new data interfaces and processing methods to provide operators with the information that they need to make quick decisions in RPOD operations where response time and safety are highly correlated.

Orbit Fab is taking several key steps towards implementing a robust operations framework for future missions participating in RPOD activities in support of in-space refueling. Firstly, Orbit Fab will soon publish a Refueling Operations Guide which will be available on the Orbit Fab website and provide an overview of the major steps operators must take and requirements they must observe to safely receive fuel in an in-space refueling operation. In January 2024, Orbit Fab and Apex will launch the Podracer-1 mission as an orbital testbed for Orbit Fab's RPOD ecosystem. The Podracer mission will safely, reliably, and repeatedly complete RPOD operations by addressing the needs, requirements, and principles outlined in this paper. The future of space operations in a bustling in-space economy depends on a wide range of missions being able to participate in RPOD safely and efficiently. The community of spacecraft operators should begin planning and taking steps now to be ready for this shift.

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