The Roadmap to In-Orbit Refuelling for Telecom Satellites

Tiago Amaral
Mission and GNC Senior Engineer
Orbit Fab Limited
Oxfordshire, United Kingdom
tiago.amaral@orbitfab.com

Tejaswi Tiruvuru
Business Development Manager-UK & Europe
Orbit Fab Limited
Oxfordshire, United Kingdom
jas.tiruvuru@orbitfab.com

Shreya Ramteke
Graduate Mission Engineer
Orbit Fab Limited
Oxfordshire, United Kingdom
shreya.ramteke@orbitfab.com

Orla Menzies
Graduate Systems Engineer
Orbit Fab Limited
Oxfordshire, United Kingdom
orla.menzies@orbitfab.com

Sebastian Hill
Head of Engineering- UK & Europe
Orbit Fab Limited
Oxfordshire, United Kingdom
Sebastian.Hill@orbitfab.com

Orbit Fab is developing an orbital infrastructure designed to provide a ubiquitous supply of propellant for all in-orbit assets, both governmental and commercial, extending their lifespan and providing the possibility of less frequent deorbiting and replacement. This vision will end the single-use paradigm for spacecraft and enable the next generation of missions based on extended lifetimes and higher flexibility for manoeuvring and retasking of assets. Orbit Fab Limited (OFL) is a wholly owned subsidiary of Orbit Fab Inc with the vision to independently leverage the UK and European space ecosystem to contribute to the global effort to make efficient in space refuelling a reality.

This paper presents Orbit Fab's progress in developing a scalable refuelling architecture targeting both LEO and GEO environments. Through RADICAL, a collaborative initiative with GEO telecommunications operators and satellite platform providers, OFL has conducted a structured analysis of the operational, business, and technical requirements necessary to enable commercial satellite refuelling. This engagement drove the definition of mission use-cases and scenarios of interest, which in turn informed the design of a refuelling architecture centered on the most likely early adopters in the GEO telecommunications sector. The paper presents the key business developments arising from RADICAL, describes the resulting GEO and LEO refuelling architectures, and discusses their scalability for servicing future clients across both orbital regimes.

Central to this architecture is OFL's RAFTI interface, which has been qualified and is currently being integrated across multiple missions, demonstrating its readiness for adoption by other integrators and operators. The paper also outlines planned remaining interface development, identifying the qualification gaps that may need to be covered for specific missions.

Keywords—refuelling, telecoms refuelling, RAFTI, GRASP, SatCom, shuttle, depots

I. INTRODUCTION

A. *The case for in-space refuelling*

The space industry remains constrained by the limitations of single-use satellites, creating both economic inefficiencies and sustainability challenges. Satellites are typically launched with a fixed amount of propellant, which limits their operational lifetime, mobility, and ability to adapt to evolving mission requirements. Once propellant is depleted or a spacecraft suffers an orbital insertion anomaly [1], the asset often becomes unusable, leading to costly replacement cycles and contributing to orbital congestion and space debris accumulation.

Refuelling and broader in-orbit servicing can mitigate such risks by extending satellite lifetimes, reducing dependence on large CAPEX cycles, and even repurposing impaired assets as depots or support platforms. Unspent fuel on a satellite can be transferred to service other satellites, fostering a circular economy in space.

In parallel, the rapid growth of satellite deployments in both LEO and GEO is increasing the demand for more flexible and sustainable space infrastructure. Current operational paradigms rely heavily on expendable systems, despite the high cost of manufacturing and launching spacecraft and the growing need for orbital servicing, mobility, and debris mitigation capabilities [2].

By enabling spacecraft servicing and sustained orbital operations, in-space refuelling changes the paradigm from expendable satellite architectures toward a more serviceable and sustainable space ecosystem [3]. In summary, the key benefits of satellite refuelling include:

- **Extended mission lifetime and increased revenue potential:** Allowing longer operational periods by refuelling satellites, extending the lifetime of the spacecraft, reducing replacement frequency and increasing revenue generation from existing assets.
- **Enhancing mobility:** Repositioning assets, negating the mission life reduction caused by collision avoidance manoeuvres, enabling on-demand re-tasking and correcting orbital inaccuracies.
- **Improved launch mass allocation:** Reducing the amount of propellant required at launch allows either mass and launch cost savings or greater fraction of spacecraft mass to be allocated to payloads.
- **Enabling new operations & business models:** Performing secondary missions, offering unique capability by supporting a variety of operations such as inspection, repair and debris removal, enabling

access to novel manoeuvres, orbits, spacecraft designs and constellation architectures.

- **Enhanced exploration opportunities:** Facilitating deep space exploration by reducing launch weight requirements or refuelling in cis-lunar space and beyond.
- **Supporting space sustainability and debris mitigation:** Reducing space debris by prolonging the life of satellites and enabling their controlled decommissioning. Refuelling is also critical for Active Debris Removal servicers to perform multiple removal services.

B. *OFL UK - Background and Vision*

OFL (Orbit Fab Ltd) is the UK subsidiary of a US based parent company operating within the UK and broader European space ecosystem. OFL is focused on UK and European operations, supply chain positioning, and service delivery architecture.

The OFL in orbit refuelling architecture is built around a system of systems approach designed to efficiently deliver propellant to spacecraft operating across a wide range of orbits. It relies on standardised interfaces that enable cooperative docking and safe propellant transfer between spacecraft that are pre-configured for refuelling operations.

The two sides of the interface, which are developed in-house in the UK are RAFTI, the passive interface mounted on the client satellite, and GRASP, the active interface mounted on the servicer. RAFTI is a passive externally mounted fill and drain valve designed as a drop-in replacement for conventional spacecraft propulsion interfaces. It incorporates mechanical grapple features that allow it to function as a docking interface, while also supporting ground servicing operations and in-orbit refuelling. A single RAFTI interface enables bidirectional transfer of two independent fluids, that can typically be propellant and pressurant.

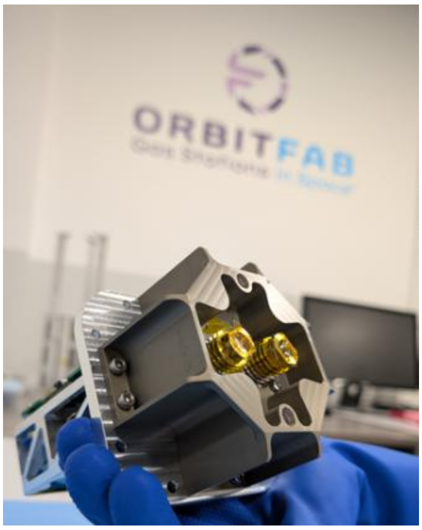

Fig. 1. RAFTI High Pressure Variant

GRASP is the active counterpart used on servicing vehicles. It is an electromechanical docking and fluid transfer mechanism that engages RAFTI grapple features, establishes mechanical coupling, and enables controlled opening of the fluid transfer path. It is designed for both low and high pressure operational variants. A comparable system, GRIP, is being developed by the US based parent company but is currently limited to low pressure qualification. GRASP is fully developed in the UK, without ITAR constraints, supporting broader deployment flexibility across international missions.

Together, RAFTI and GRASP form a cooperative docking system. Client spacecraft are equipped with RAFTI and visual fiducials to support rendezvous and proximity operations. This standardisation enables servicing vehicles to interact with a wide range of spacecraft without bespoke mechanical adaptation.

The broader OFL servicing architecture consists of three interacting elements: clients, fuel shuttles, and fuel depots [4]. Clients are end users of the refuelling service and carry RAFTI to enable docking and propellant transfer. Fuel shuttles are highly manoeuverable servicing vehicles equipped with GRASP and full RPO capability, responsible for rendezvous, docking, and transferring propellant between depots and clients. Fuel depots provide long duration in-orbit storage of propellant and act as supply nodes that enable repeated reuse of shuttle assets. Fuel depots are designed for simplicity, reliability and high propellant mass fraction.

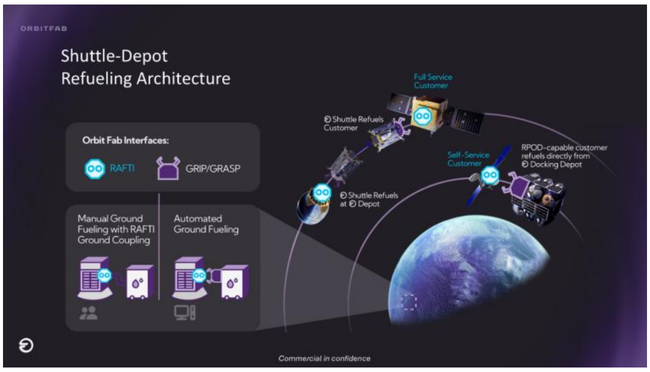

Fig. 2. Orbit Fab Service Architecture Overview

A typical refuelling operation follows a structured sequence. The fuel shuttle performs rendezvous and proximity operations with a prepared client spacecraft. Once within capture range, GRASP engages RAFTI to establish a soft dock, providing a compliant mechanical connection that dampens relative motion. This is followed by a transition to hard dock, which rigidises the interface and ensures precise alignment of fluid transfer ports. After mechanical stability is confirmed, the fluidic connection is established, leak checked, and validated prior to propellant transfer. Undocking is performed as a controlled reversal of this sequence.

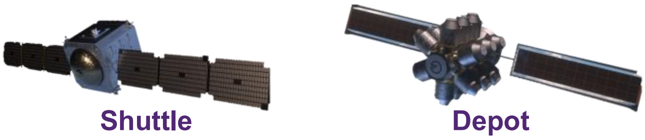

Fig. 3. Orbit Fab's fuel shuttles and depots roles in a refuelling architecture

C. *Paper outline*

This paper is structured as follows. Section 2 presents the RADICAL project, including its objectives, stakeholder engagement activities, and the development roadmap toward a first commercial refuelling service for the telecom market. Section 3 introduces the GEO and LEO refuelling use-cases identified through the RADICAL engagement process and quantifies their representative propellant requirements. Section 4 presents the resulting GEO and LEO refuelling architectures, including their operational concepts and scalability. Finally, Section 5 summarises the key outcomes of the RADICAL project and presents the main conclusions of this work.

II. PROJECT RADICAL

A. *Radical Overview and Objectives*

Telecoms spacecraft are typically high-value, long-life assets, operating across both LEO and GEO. In GEO, demand is driven by the need for stable, always-on coverage over fixed regions, while in LEO it is driven by large-scale constellations providing global, low-latency connectivity. In both orbital regimes, satellites are constrained by the amount of propellant carried at launch.

The RADICAL (Refuelling Architecture Development for In-Orbit Communications and Logistics) project is an ESA and UK Space Agency (UKSA)-supported initiative under the ESA ARTES programme, aimed at developing and de-risking the technical and service requirements for spacecraft refuelling, with an initial focus on telecom (satcom) satellite operator platforms.

In collaboration with satellite manufacturers and operators, Orbit Fab is developing a SatCom Refuelling Roadmap. This roadmap will assess how the open-licence RAFTI can be integrated into satellite platforms and mission concepts of operations (CONOPS), enabling in-orbit refuelling as a standard capability and extending spacecraft operational life. Orbit Fab will use and further develop its Universal Mission Planner to Investigate Refuelling Effectiveness (UMPIRE) tool to evaluate and optimise in-orbit refuelling strategies for SatCom users. The objectives of RADICAL are to:

- Define and de-risk the technical and service requirements for a minimum viable spacecraft refuelling offering, focused initially on SatCom operators.
- Develop a SatCom Refuelling Roadmap in collaboration with manufacturers and operators, identifying how refuelling can be integrated into future satellite platforms and mission CONOPS.
- Assess and enable integration of the RAFTI refuelling interface into spacecraft designs, including identification of required platform modifications to support refuelling capability.
- Address the “why” and “how much” of refuelling, by tailoring strategies to specific SatCom operational concepts and identifying the most valuable use cases across GEO and LEO markets.
- Use the UMPIRE tool to evaluate the effectiveness of refuelling strategies, including operational benefits, cost implications, and mission-level value.
- Support the development of scalable business models for in-orbit refuelling that can adapt to evolving telecom market structures, including GEO-heavy systems and emerging multi-orbit architectures.

B. *Stakeholders – Operators and Platform Providers*

RADICAL focuses on collaborative requirements capture with GEO and LEO telecom stakeholders. GEO and LEO satellite operators, alongside spacecraft platform providers, were onboarded into the RADICAL project to ensure that both major orbital regimes are represented in the definition of future refuelling services.

As part of the engagement process, an operator refuelling questionnaire was developed and circulated to collect data on mission requirements, operational constraints and future interest in refuelling. The questions were designed to determine the scale of operations and understand operator fleet characteristics, in order to identify how an optimum refuelling service could be designed if adopted. The questionnaire also considered potential constraints on a refuelling service, particularly where Quality of Service (QoS) requirements must be maintained for end customers.

The requirements capture methodology combines the outcomes of the questionnaire and workshops with structured stakeholder discussions and mission CONOPS analysis, enabling a systematic assessment of refuelling from three perspectives:

- Operational requirements, including how refuelling would be integrated into mission operations such as station-keeping, constellation management, orbital repositioning, and lifetime extension strategies.
- Business requirements, including the economic value of refuelling in terms of extended asset utilisation, revenue protection, and improved service continuity across different orbital markets.
- Technical requirements, including spacecraft design modifications required to enable refuelling, such as integration of refuelling interfaces (e.g. RAFTI), propulsion system compatibility, docking considerations, and updates to mission CONOPS.

The outcome of this activity is a consolidated definition of the key steps required to make telecom satellites refuellable, derived from aligning operator needs with platform design feasibility. This directly informs the SatCom refuelling roadmap and supports the definition of a refuelling service offering within the RADICAL project.

C. *Roadmap for Commercial Service for Telecom Market*

Figure 4 presents the development roadmap adopted within the RADICAL project to define and mature a commercial refuelling service for the telecom sector. The roadmap combines customer engagement, technology development, and ground and in-orbit validation activities to ensure alignment between operational needs and technical implementation.

RADICAL defined three parallel workstreams to address the demand for lifetime extension on both GEO and GEO telecom market. The first focuses on customer engagement, where telecom customers are onboarded, complete a refuelling questionnaire, and take part in business and requirements workshops. This captures mission needs, operational constraints, and helps identify suitable reference missions. This engagement runs throughout the project to ensure the service is aligned with real customer needs.

In parallel, Orbit Fab is progressing technical development, including maturing both the GRASP refuelling system and the RAFTI interface to TRL 7. These technologies will be integrated into a fuel shuttle spacecraft, which will then be launched to enable on-orbit operations.

A third workstream focuses on validation activities, including ground testing, system simulations, and in-orbit demonstrations. This is critical to reduce risk and demonstrate that the refuelling system works in a real operational environment.

The outputs of these activities are consolidated into a common set of operational, technical, and business requirements, which are then used to define the SatCom refuelling roadmap. This roadmap establishes how refuelling capability can be incorporated into future spacecraft platforms and mission concepts of operations.

The resulting objective is a scalable refuelling service architecture for GEO and LEO spacecraft, supported by validated technologies, operationally representative mission concepts, and direct engagement with prospective customers.

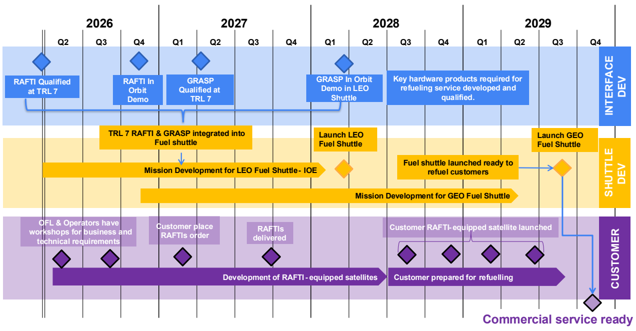

Fig. 4. Roadmap for Telecoms refuelling services

III. REFUELLING SCENARIOS AND USE-CASES

The use-cases and mission scenarios presented in this section were derived directly from the RADICAL engagement process described in Section 2. They form the design basis for the refuelling architecture of Section 4 and represent the most commercially relevant early-adoption opportunities. Three GEO scenarios and one LEO scenario were defined:

1. **GEO – Life Extension:** Refuelling a satellite near end-of-life to extend its operational service beyond its original design lifetime, maximising the value of an existing asset, and reducing the cost of replacement
2. **GEO – Relocation Support:** Refuelling to compensate for propellant expended during orbital relocation, preserving mission lifetime while enabling strategic repositioning to higher-value orbital slots. Note: can be combined with a life extension refuelling as well.
3. **GEO – Early life refuelling for mass savings:** Launching satellites with reduced onboard propellant and relying on early life once in GEO, enabling lighter and smaller spacecraft and more flexible, cost-efficient mission architectures.
4. **LEO – Life extension of a LEO constellation:** Refuelling satellites of a LEO constellation to extend their operational lifetime beyond the originally planned service period, reducing the need for replacement launches and maximising the value of an existing asset.

To illustrate the quantitative benefits of each scenario in a consistent and comparable manner, a common reference satellite has been used throughout this section. The reference platform is a representative mid-sized GEO telecoms satellite, and its main parameters are depicted in Table 1.

TABLE I. REFERENCE SATELLITE PARAMETERS

Parameter	Value	Note/Reasoning
GEO satellite Dry mass	3250 kg	Mid-sized GEO telecom satellite
GEO satellite Wet mass	4250 kg	1000 kg of fuel carried at launch
Propellant used	Xenon	Typical propellant used in electric propulsion and the one used by operators involved in RADICAL
Isp	1500 s	Typical value of Isp for EP propulsion system using Xenon.

A. *Primary GEO Refuelling Scenarios*

1) *Life Extension*

Life extension is the most direct and immediately actionable application of in-space refuelling for GEO satellites. The use-case is straightforward: a satellite approaching end of life is refuelled with sufficient propellant to continue station-keeping operations for an additional 5 years beyond its originally planned service life.

The biggest benefit to the client is revenue extension, with the client being able to operate beyond its nominal lifetime, and decreasing the replacement costs of GEO assets over time. A key assumption is that onboard hardware remains sufficiently operational at the point of refuelling to justify the service investment.

The propellant required for life extension depends on the spacecraft mass and station-keeping requirements. The graph of Figure 5 demonstrates roughly how much fuel a satellite requires to extend its operational life by 5 years, depending on it mass. The results were computed based on a GEO satellite nearing end-of-life, assuming that onboard propellant is largely depleted, with only reserves remaining for disposal manoeuvres and operational margins. Using a typical station-keeping requirement of approximately 50 m/s per year and an effective specific impulse of 1500 s, the required refuelling mass is estimated as a function of the satellite's mass.

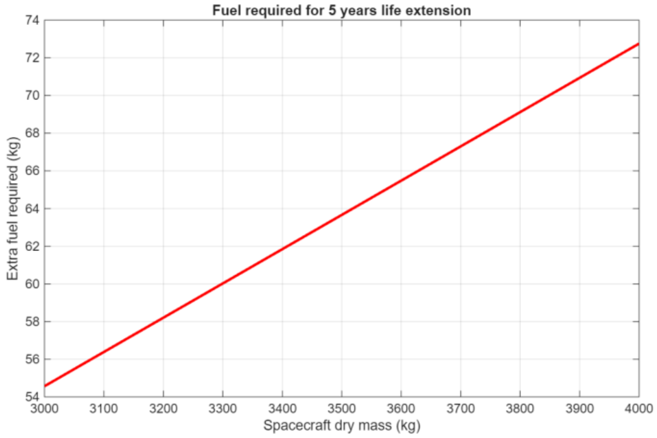

Fig. 5. Minimum fuel required by a GEO satellite for 5 years of station keeping capability. Assuming that GEO satellite has 1500 of Isp and consumes 50 m/s for station keeping.

2) *Relocation Support*

The second use-case addresses a common and commercially significant need in GEO operations, which is the need to relocate to a different orbital longitude. Such relocations are often unavoidable due to evolving market conditions and customer demand, which are difficult to predict over 15+ years of mission lifetime.

Without refuelling, relocation imposes a direct impact on mission lifetime and revenue because propellant used during the manoeuvre is taken from the station-keeping budget, reducing the satellite's remaining operational life and future revenue. With refuelling, this propellant can be replenished, restoring the satellite to its full remaining station-keeping capacity.

This provides two key benefits. First, it avoids revenue loss when a relocation is needed. Secondly, it also introduces operational flexibility by allowing operators to relocate assets to higher-value orbital slots or markets without long-term penalties. Importantly, this relocation use-case can also be combined with additional fuel for life extension.

Analysis: GEO telecom revenue loss when performing a longitude relocation

The loss of revenue when relocating satellites happens for two reasons. First, during the drift phase, the satellite is typically unable to provide its intended telecoms service, resulting in direct revenue loss due to downtime. Second, the propellant used to perform the relocation manoeuvre reduces the amount available for station-keeping, leading to a reduction in future operational lifetime and therefore an indirect loss of revenue.

These two effects introduce the need to optimise a relocation strategy. The satellite can either relocate quickly, which reduces downtime but increases propellant consumption, or relocate slowly, which minimises fuel consumption, but increases service interruption.

An analysis was performed to quantify the combined impact on revenue from travel downtime and propellant expenditure by evaluating a range of relocation strategies with different drift rates and dV consumption. The results, presented in Figure 6, show that even when selecting the optimal relocation strategy, a 180° longitude relocation leads to a minimum equivalent revenue loss of approximately six months, which represents a significant financial impact for telecom satellites generating tens of millions in annual revenue.

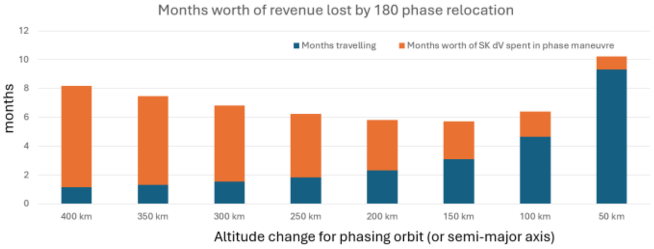

Fig. 6. Trade-off analysis for optimal longitude relocation

However, when a satellite can manoeuvre "without regret", relocation time becomes the only direct impact on down-time. In this case, the operator can prioritise rapid relocation to minimise downtime, with the additional fuel consumption compensated through refuelling. The results in Figure 7 show the required propellant as a function of the desired relocation time. In the analysis, to compute the mass at the time of relocation, it was assumed that the reference satellite still had 25% of the tank full.

For example, completing a 180° longitude relocation in one month reduces the effective revenue loss from approximately six months to one month of interrupted service, at a cost of around 16 kg of xenon for the relocation manoeuvre. When combined with a life-extension service, the total refuelling requirement increases to approximately 75 kg (16 kg for relocation plus 59 kg for station-keeping extension).

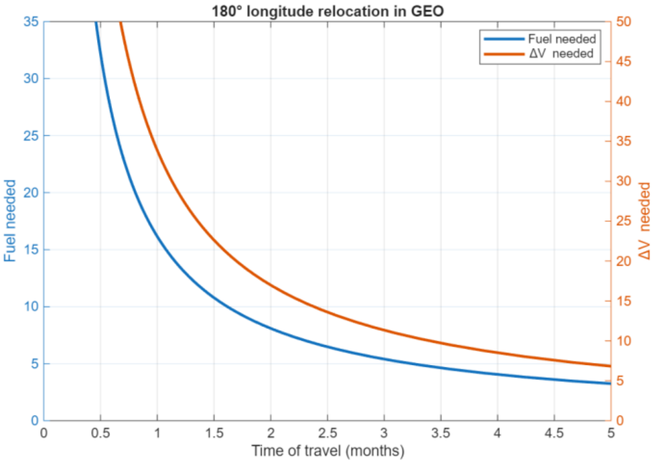

Fig. 7. Fuel and dV needed for 180° longitude relocation in GEO

3) *Early Life Refuel*

The third GEO use-case represents a more design transformative opportunity, with the greatest long-term impact on satellite architecture. Unlike the previous use-cases, it enables a significant reduction in launch mass, allowing operators/manufacturers either to reduce launch costs or increase payload capacity within the same launch envelope.

In this concept, a satellite is launched with only the propellant required to transfer from GTO to GEO and begin operations, and the propellant needed for long-term station-keeping is instead delivered in GEO via an early-life refuelling. The commercial rationale is driven by the strong dependence of launch cost on spacecraft mass. In GEO missions, propellant can represent more than 30% of the total launch mass. By deferring this propellant to orbit significantly reduces launch mass through three complementary efficiency gains:

- **Propellant delivery in-orbit:** The propellant required for long-term station-keeping does not need to be launched with the spacecraft. Instead, it is supplied once the satellite is operational in GEO, eliminating a large portion of the initial wet mass.
- **More efficient fuel spent in transfer due to lower mass:** A lighter satellite, without needing to bring the station-keeping fuel as "dead-weight", requires also less fuel to perform the GTO to GEO orbit raising. This creates a compounding effect.
- **Reduced dry mass savings:** Since the satellite will have less fuel needs at launch, the fuel tanks and the platform can be designed to be smaller and lighter, providing further dry mass savings.

Together, these effects significantly reduce launch mass and enable more efficient satellite designs. This can translate into lower mission costs, increased payload capacity, or new launch strategies such as co-manifesting multiple satellites. However, a key assumption which needs to be studied further is that launch cost savings and reduced procurement cost (in the medium-long term) exceed the refuelling service.

An analysis was performed to quantify the mass savings enabled by early-life refuelling, assuming a GEO satellite is launched into GTO carrying only the propellant required for orbit raising, with a 5% fuel margin. The comparison focused on the differences in propellant needs at launch, potential dry mass reductions driven by smaller tankage, and resulting total mass differences.

The results, which are illustrated in Table 2, show that an early-life refuelling can reduce launch mass by approximately 445 kg for the reference satellite, driven by a direct fuel savings at launch of 410 kg (41% fuel need reduction at launch) and secondary dry mass savings. This reduction is enabled by delivering approximately 170 kg of propellant on-orbit. These results highlight the strong leverage of refuelling on launch mass and demonstrate the feasibility of the concept within the proposed GEO refuelling architecture presented in Section 4.

TABLE II. USE-CASE 3 BENEFITS SUMMARY

Parameter	Value	Note/Reasoning
Nominal Satellite Dry Mass (kg)	3250 kg	Original dry mass
Nominal Satellite Wet Mass (kg)	4250 kg	Original wet mass without refuelling
Satellite Dry Mass with refuel (kg)	3215 kg	A conservative dry mass saving of 35 kg is assumed, based solely on propellant tank mass reduction derived from internal tank catalogue. Larger additional savings may be achievable through further optimisation of the spacecraft bus enabled by smaller tank sizing.
Satellite Wet Mass with refuel (kg)	~3805 kg	Assuming 410 kg in fuel savings at launch and 35 kg in dry mass savings.
Fuel savings at launch	~410.4 kg	Amount of fuel saved at launch (~41%)
Expected total mass savings at launch	~445.4 kg	Total savings of dry mass and fuel savings at launch.
Refuelling amount needed in GEO (for 15 years of nominal station-keeping)	~170.5 kg	Assuming dV consumption of 50 m/s per year for station-keeping

B. LEO Scenarios

The primary LEO use-case identified by OFL is the on-orbit refuelling of constellation satellites to extend their service life and reduce or eliminate the need for early replacement. Rather than deorbiting and replacing satellites as they approach end of propellant life, operators could instead receive a refuelling service that extends each satellite's useful life, maintaining constellation density and capability at lower cost.

To illustrate the scale and feasibility of constellation refuelling, a representative LEO constellation scenario was defined. As the specific constellation analysed within the RADICAL project cannot be disclosed, an example based on the telecoms Iridium satellite constellation is used for this study. The selected case reflects a typical medium-sized LEO constellation used for telecom services, capturing the key orbital and operational characteristics relevant to refuelling analysis. The reference constellation consists of:

- 66 satellites, each with a mass ~700 kg
- 6 planes, each separated by 30° RAAN
- 11 satellites per plane, evenly distributed in true anomaly
- Circular orbits at~780 km altitude and 86.4° inclination

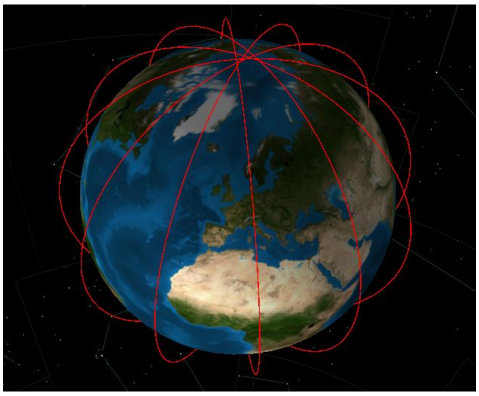

Fig. 8. Visualisation of the LEO constellation

For this scenario, a representative refuelling quantity of approximately 15 kg per satellite is assumed, (990 kg across full constellation) corresponding to a 4-year life extension beyond a nominal 8-year mission lifetime.

C. *Summary of Use-Cases Refuelling Requirements*

Table 3 summarises the representative refuelling needs associated with each use-case. The values presented are based on the reference scenario described in this section and are intended to provide only an order-of-magnitude comparison of propellant demand, as these values are mission and client-specific

TABLE III. USE-CASES REFUELLING REQUIREMENTS

Use-case	Objective	Representative refuelling amount
GEO Life extension	Extend operation life (~5 years)	~ 59 kg
GEO Relocation support	Enable longitude relocation without lifetime impact	~ 16 kg Note: can range for ~ [5 to 35] kg depending on how aggressive the operator wants to perform transfer. See Figure 7
GEO Relocation + life extension	Enable longitude relocation + life extension	~ 75 kg
GEO Early-life refuelling for mass savings	Reduce launch mass / increase payload flexibility	~ 170 kg
LEO constellation life extension	Extend satellite life (~4 years)	~15 kg per satellite ~990 kg across LEO constellation

IV. REFUELLING ARCHITECUTRE DESIGN

A. *Architecture Design Philosophy and Drivers*

This section presents the refuelling architectures, which were derived directly from the use-cases identified through stakeholder engagement in RADICAL. The use-cases helped Orbit Fab to compute roughly how much fuel each satellite needs, and this ensured alignment with real mission needs in both GEO and LEO. The design of the architecture was driven by a small set of core principles:

- **Client-driven approach:** Architecture design based on operational requirements and interest use-cases from clients
- **Financial feasibility and cost effectiveness:** What is the best architecture deployment for efficient refuelling and cost minimisation?
- **Reusability and scalability:** Allow the use of the same OFL's shuttles and depots to serve additional clients and growing demand

While GEO and LEO architectures differ in implementation, both follow this common philosophy, enabling a transition from mission-specific servicing to a scalable, reusable refuelling infrastructure.

B. *GEO Refuelling Architecture*

The deployment of servicing infrastructure to GEO is heavily constrained by the high cost of manufacturing and launch. Therefore, the GEO refuelling architecture is designed to minimise upfront cost while enabling early operational capability.

This is achieved with an incremental approach design, with the goal of starting with a minimal asset configuration and scaling only when demand materialises. This is possible with a single shuttle and a single depot, because as it will be seen, even this minimal configuration is capable of delivering refuelling services to any satellite in GEO, while still minimising the initial capital expenditure.

1) *Role of Location of Depot in GEO Operations*

The depot serves as a central logistics hub within the GEO architecture, almost like a reset point. It enables the shuttle to operate in a cyclic manner, performing repeated servicing missions between the depot and client satellites.

In this concept of operations, the shuttle departs from the depot, performs rendezvous and refuelling with a client satellite or more, and then returns to the depot for replenishment. In this way, the depot also provides a stable loitering location, allowing the shuttle to await subsequent servicing opportunities.

The selection of the depot orbit is therefore a key characteristic of the GEO architecture, with implications for both operational efficiency and propellant consumption. Two primary depot placement options were considered: within the GEO ring, or in an orbit with an altitude offset relative to the GEO ring. While placing the depot in the GEO ring simplifies access to client satellites (as only true anomaly phasing is needed), it requires strict station-keeping to maintain its assigned longitude, and complying with stricter safety standards, which results in increased operational burden and propellant consumption.

In contrast, placing the depot in a slightly lower or higher orbit introduces a controlled differential in orbital period, resulting in a natural longitude drift relative to the GEO belt. This behaviour is illustrated in Figure 9, which shows the relationship between altitude offset, longitude drift rate, required dV for orbit transitions, and the time required for a full 360° drift relative to GEO. The results show that an offset of approximately 300 km below GEO provides a particularly attractive balance: it limits transfer dV between the depot and GEO to a relatively small value (on the order of ~10 m/s), while inducing a natural drift period of approximately 3 months for a full revolution around the GEO ring. This effectively allows the depot to sequentially "visit" all longitudes every 3 months without active longitudinal station-keeping. Based on this trade-off, the architecture adopts a depot located 300 km below GEO.

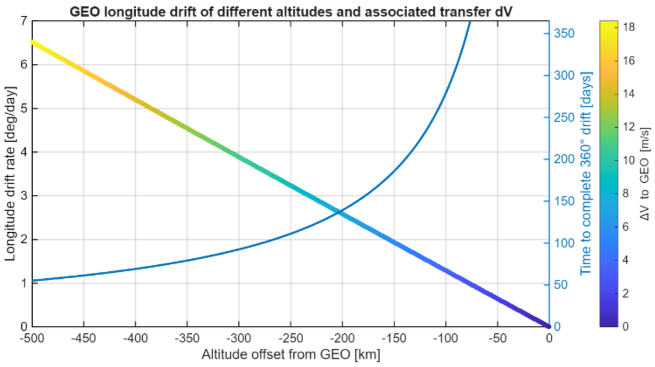

Fig. 9. GEO longitude drift behaviour of different altitude

2) Early Operations And Minimisation of Upfront Deployment Cost

The architecture and the sizing of the shuttle are designed to support early missions without requiring a fully deployed infrastructure. The shuttle can perform an initial number of refuelling operations using its launch-loaded propellant, enabling early revenue generation.

The deployment of a depot is therefore aligned with the materialisation of additional servicing demand, rather than being a prerequisite for initial operations. This approach reduces initial investment risk and allows the architecture to scale in response to confirmed market needs.

3) Reference Mission Concept of Operations

A representative mission sequence as seen in Figure 10 illustrates the operation of the GEO refuelling architecture. The shuttle is launched into GTO and performs orbit raising to reach GEO. Upon arrival, it can begin its servicing operations using the propellant carried at launch, enabling an initial set of refuelling missions without reliance on a pre-deployed depot.

Once the onboard propellant of the shuttle is depleted, or not enough for the subsequent service, the shuttle transfers to the depot to replenish its tanks. It then resumes servicing operations, repeating a cyclic mission profile of depot-to-client transfers, refuelling operations, and return to the depot until a replenish is needed again. This cycle is repeated until the shuttle reaches its maximum lifetime and performs a end-of-life manoeuvre.

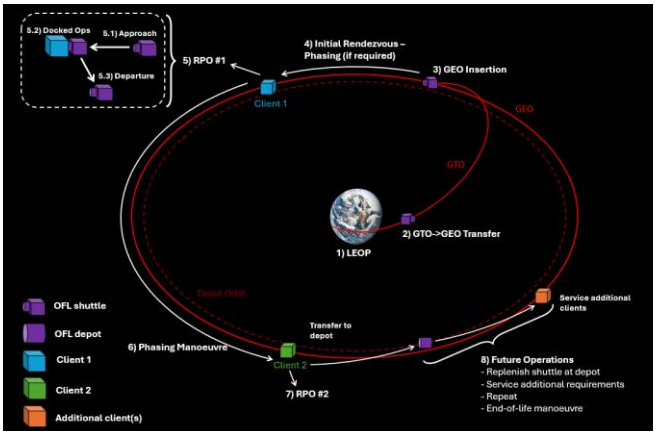

Fig. 10. Illustration of GEO refuelling CONOPS

4) Reference Results for GEO Refuelling Service

A GEO fuel delivery analysis was carried using Orbit Fab's in-house mission analysis tool, UMPIRE (Universal Mission Planner to Investigate Refuelling Effectiveness). Analyses were conducted to assess the feasibility of early GEO refuelling missions using a minimal asset configuration. The results indicate that a servicer with a dry mass on the order of 400 kg can perform two refuellings in the order of 65kg each without reliance on a depot. The analysis shows that the required xenon propellant at launch is below 200 kg, which is compatible with existing propellant tank solutions and represents a manageable launch configuration.

These results reinforce the proposed incremental deployment strategy for the minimisation of OFL's upfront cost. A shuttle can be launched and begin operations immediately, delivering an initial set of refuelling services using onboard propellant. This enables early revenue generation without requiring pre-deployed infrastructure, with the deployment of a depot happening only when additional servicing demand materialises.

From a commercial perspective, the analysis indicates that two refuelling missions may be sufficient to offset the initial cost of a single shuttle, subject to mission-specific cost and revenue assumptions. While a detailed financial assessment is outside the scope of this paper, these results provide an initial indication of the economic viability of early GEO refuelling operations.

C. GEO Scalability and Reuse

The GEO refuelling architecture is inherently scalable and largely independent of the specific client use-case. As outlined in Section 3, life extension, relocation, and early-life refuelling can all be supported using the same core architecture. The primary variable across these use-cases is not the servicing approach, but the quantity of propellant delivered.

As a result, the same GEO architecture can be extended beyond GEO telecom satellites to service any spacecraft in GEO equipped with RAFTI. This includes governmental, scientific, and emerging servicing platforms.

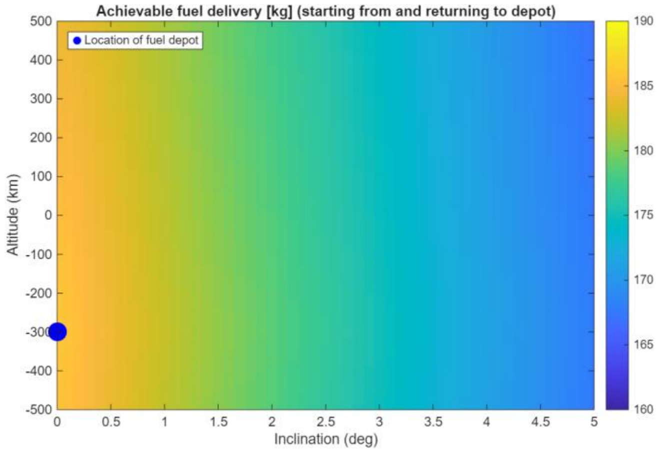

Fig. 11. GEO fuel delivery capability heatmap

Figure 11 illustrates the fuel delivery capability of the architecture for a representative round-trip mission between a depot and a client satellite. The analysis is based on the same shuttle parameters presented before (dry mass of 400kg and 200kg propellant capacity). Additionally, it accounts for the propellant required for transfer manoeuvres to and from the client (using Xenon with an Isp of 1500 s), as well as rendezvous and proximity operations with both the client and the depot (using Hydrazine with an Isp of 230 s). The analyses also accounted that the shuttle has a remaining fuel safety margin of 10 kg after returning to the depot.

The results show how the deliverable propellant varies as a function of the client's relative location with respect to the depot. This highlights the impact of orbital geometry on servicing efficiency and demonstrates that a single shuttle and single depot can support refuelling operations across a wide range of GEO longitudes. Overall, the analysis confirms that the architecture can provide meaningful propellant delivery across the GEO belt while maintaining efficient shuttle utilisation.

D. *LEO Refuelling Architecture*

Refuelling in LEO is driven by the need to service large constellations of satellites distributed across multiple orbital planes. Therefore, LEO refuelling requires coordinated operations across many spacecraft within a defined campaign period.

Shuttles are always required and deployed to service satellites sequentially across the constellation, following optimised routes that account for orbital geometry and phasing opportunities. Depots, on the other hand, when included act as intermediate refuelling resets, enabling shuttles to replenish propellant and extend their operations without having to carry excessive fuel at launch.

A nominal sequence for a single shuttle is as follows:

1. Shuttle insertion into LEO constellation orbit
2. Refuel all satellites in one plane
    2.1. True Anomaly phasing with a satellite
    2.2. RPO & Docking with a client satellite
    2.3. Propellant Transfer
    2.4. Undocking and departure
    2.5. Repeat this sequence for all the satellites within the orbital plane
3. Optimal RAAN transfer to next constellation plane (if shuttle is servicing more than one plane)
4. Replenish shuttle at a depot (if there is a depot visit planned in this plane)
5. Repeat steps 2 and 3 and 4 until all planes are serviced by a shuttle.
6. End-of-life manoeuvre once all refuelling are complete by a shuttle

The case where 2 shuttles and 2 depots is illustrated in Figure 12. As for the shuttle's propulsion, the shuttle used Xenon for any orbital transfer and uses hydrazine for 6DoF control during RPO.

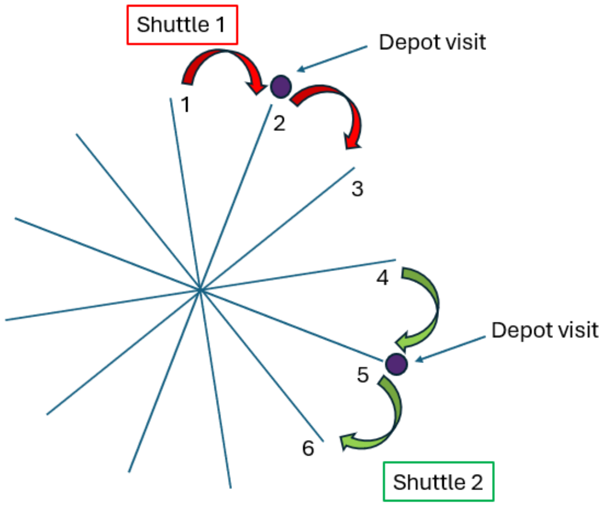

Fig. 12. Illustration of OFL's shuttle operations in LEO constellation, for the case of 2 shuttles and 2 depots being used.

1) *Architecture Definition and trade space*

A wide range of architectural options can be considered to service a LEO constellation, and it is not straightforward to understand what is the optimal configuration of number of shuttles and depots. To pick the optimal configuration, which depends on many factors, a system-level analysis is required.

To address this, as part of the RADICAL work, OFL developed a novel architecture optimisation capability within its mission planning tool, UMPIRE, to design refuelling strategies for LEO constellations.

UMPIRE explores this design trade by evaluating multiple architecture options, varying the number of shuttles and depots and adapting the shuttles operations automatically. For each candidate architecture, the tool simulates a complete refuelling campaign, generating the sequence of operations required for each shuttle to service its assigned satellites. Based on this, UMPIRE computes:

- The amount of fuel required at launch for each shuttle.
- The amount of fuel required for replenishment at depots (if applicable)
- The ability to complete the full servicing campaign under the constraints set by the user.

The optimisation is driven by key mission and system parameters, including campaign duration, servicing time per satellite, propellant demand per client, RPO dV and initial orbital conditions

Candidate architectures that do not meet mission constraints (e.g. too many cycles, or too much fuel required at launch by a shuttle) are filtered out. The remaining feasible solutions can then be assessed using cost and performance metrics like total propellant requirements (at launch and taken from a depot) and refuelling efficiency.

This approach supports the selection of configurations that balance operational feasibility, efficiency, and infrastructure cost. In doing so, it allows OFL to optimise refuelling strategies for any LEO constellations while also providing insight to operators on how future constellation designs and deployment strategies can be adapted with refuelling.

2) *LEO Results*

An exhaustive presentation of the results is beyond the scope of this paper, as it would require a detailed description of the optimisation frameworks and analysis methodologies employed. Therefore, only a representative subset of the results is presented, with the aim of illustrating the proposed approach and demonstrating the viability of on-orbit refuelling for LEO satellite constellations.

The results of this analysis, which considered the use of a shuttle with a dry mass of 200kg (based on previous OFL designs [5]), are presented in Table 4. The table summarises the amount of propellant a shuttle needs to carry at launch for the different combinations of shuttles and depots considered. The results show that increasing the number of shuttles reduces the propellant required per shuttle at launch, while the inclusion of depots further improves efficiency by delaying the propellant demand from launch to replenishments at depots. This, in turn, enables a reduction in the number of shuttles required to complete the servicing campaign.

The analysis demonstrates that LEO constellation refuelling can be achieved with multiple architecture options. A key observation is that it may be possible to service the fuel constellation without depots, but at a cost of a higher number of shuttles, which is unwanted due to the higher cost of a shuttle than a depot.

For the example studied here, results indicate that configurations combining a limited number of shuttles and depots offer an effective balance between operational efficiency and infrastructure deployment. In particular, a configuration composed of two shuttles and two depots was shown to successfully service the full constellation while requiring approximately 180 kg of propellant at launch per shuttle. This requirement is compatible with the propellant capacities considered in previous OFL shuttle studies and servicing vehicle concepts [5].

While these results are indicative and should be complemented by detailed cost modelling, which is outside the scope of this paper, they highlight the potential for efficient, scalable servicing architectures. Overall, these results serve to support the viability of a LEO constellation refuelling and provide a quantitative basis for selecting configurations aligned with specific constellation characteristics and business objectives. When combined with cost modelling of shuttles and depots, this framework enables OFL to identify and deploy an optimal refuelling architecture.

TABLE IV. AMOUNT OF FUEL NEEDED BY EACH SHUTTLE AT LAUNCH TO SERVICE LEO CONSTELLATION

Amount of fuel needed by each shuttle at launch			
# of shuttles	**# of depots per shuttle**		
	0	**1**	**2**
1	Total: 1425 kg Xenon: 1169 kg Hyd.: 256 kg	Total: 608 kg Xenon: 535 kg Hyd.: 73 kg	Total: 385 kg Xenon: 346 kg Hyd.: 39 kg
2	Total: 586 kg Xenon: 514 kg Hyd.: 72 kg	Total: 183 kg Xenon:168 kg Hyd.: 15 kg	Total: 180 kg Xenon: 166 kg Hyd.: 14 kg
3	Total: 376 kg Xenon: 338 kg Hyd.: 38 kg	Total: 181 kg Xenon: 167 kg Hyd.: 14 kg	
6	Total: 182 kg Xenon: 167 kg Hyd.: 15 kg		

E. *LEO Scalability and Reuse*

In LEO, scalability is driven by the ability to service a large number of satellites efficiently within a distributed orbital environment. The architecture defined for constellation refuelling, based on a combination of shuttles and depots, can be readily extended to additional clients operating within similar orbital regimes.

As discussed in the previous section, a relatively small number of shuttles and depots can service an entire constellation, operating across multiple orbital planes. Once deployed, this infrastructure is not limited to a single client because:

- The shuttles operating within a given altitude and inclination band can service any compatible satellite within that region.
- Depots act as a “reset point” for a shuttle, enabling the shuttle to, if needed, replenish its fuel and start a new delivery to a client.
- The architecture for the LEO constellation naturally covers all RAAN planes, only proper scheduling is required with additional clients.

A coverage analysis with a heatmap of Figure 13 illustrates the accessible region from a given depot location, coming from the LEO constellation analysed before, showing the delivery capability across nearby orbital planes and altitudes. The results indicate that more than 140 kg of propellant can be delivered to satellites across a broad range of LEO regimes, spanning altitudes from approximately 400 km to 1600 km and inclinations within a ±5° band relative to the reference constellation orbit. This highlights the ability of a LEO constellation architecture deployment to support multiple clients.

By deploying an architecture around a primary constellation ensures frequent use of OFL’s assets, achieving high utilisation of both shuttles and depots. This, in turn, enables the marginal cost of servicing additional satellites in the same region to be significantly reduced.

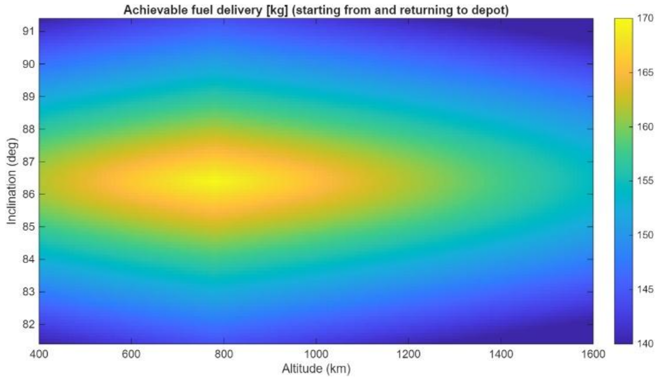

Fig. 13. Amount of fuel capable to be delivered by a shuttle in the vicinity of the LEO constellation

V. CONCLUSIONS

This paper presented Orbit Fab's ongoing development of a scalable in-space refuelling architecture for both GEO and LEO telecom missions, combining customer-driven requirements capture with technical architecture development and mission analysis activities performed within the RADICAL project.

The work identified and analysed a set of commercially relevant refuelling use-cases for telecom satellites, including GEO life extension, relocation support, early-life refuelling for launch mass reduction, and LEO constellation life extension. The analyses demonstrated that relatively modest refuelling quantities can provide significant operational and commercial benefits, including extended mission lifetime, improved mobility, reduced replacement cadence, and substantial launch mass savings.

Based on these use-cases, scalable refuelling architectures for GEO and LEO were developed. For GEO, the results showed that an incremental architecture based on reusable shuttles and depots can support servicing across the GEO belt while minimising upfront deployment cost. Preliminary analyses indicate that early servicing missions can be performed without pre-deployed infrastructure, enabling a progressive deployment strategy. For LEO constellations, optimisation analyses demonstrated that coordinated shuttle and depot architectures can efficiently service distributed constellations with a relatively small number of servicing assets.

A. RADICAL Outcomes

The RADICAL project has enabled direct engagement with GEO and LEO satellite operators and platform providers to define the operational, technical, and business requirements associated with future refuelling services. The project demonstrated strong market interest in refuelling, particularly within the GEO telecom sector, where operators identified life extension and early-life refuelling as key applications.

A consistent theme across discussions is that RAFTI offers high potential value with low upfront commitment. As highlighted by one operator, "why would we not incorporate RAFTI, it opens the optionality for refuelling". This reflects a broader shift in mindset, where refuelling is seen not as a niche capability, but as a low-risk design choice that preserves future flexibility.

From the supply side, a platform provider engaged in RADICAL is actively working to define the delta-design work required to make their platform refuellable. There is also interest in extending this work beyond the current project, including the development of a full breadboard model incorporating refuelling capability, which would represent a significant step toward hardware readiness.

More broadly, RADICAL has helped bridge the gap between customer needs, mission operations, and servicing architecture development. By combining stakeholder engagement, mission analysis, and technology maturation, the project has established a clearer pathway toward commercially viable refuelling services and the deployment of a scalable orbital fuel supply infrastructure.

Strong interest from operators, manufacturers, and servicing stakeholders has created momentum for continued and expanded activities beyond the current scope of the project. This positions Orbit Fab to move from early adoption into a scalable commercial offering within the broader refuelling market.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of ESA through the RADICAL project, an UKSA-funded activity. The authors also acknowledge the valuable contributions of the stakeholders involved, whose technical input and constructive discussions have helped shape the development of the refuelling concepts presented in this work.

REFERENCES

[1] J. Rainbow, "ViaSat-3 failure investigation to conclude next week," *SpaceNews*, Nov. 8, 2023, [Online]. Accessed: May 7, 2026.

[2] I. Levchenko, K. Alexander, C. R. et al., "On-orbit servicing as a future accelerator for small satellites," *npj Space Exploration*, vol. 2, art. no. 14, 2026, doi: 10.1038/s44453-025-00024-7.]

[3] Novaspace, Fueling the Future: The Missing Link to Space Superiority — In-Orbit Refueling, White Paper, Jan. 2026.

[4] C. Geiman, et. Al., "A Shuttle and Depot Architecture for Reliable and Cost-Effective Refueling Operations in All Orbit" presented at the 2022 International Astronautics Congress, Paris, France, Sept. 18-22 2022.

[5] S. Hill, A. Kolhatkar, T. Amaral, J. Allen, J. Geer, and M. Sharf, "RAFTEA: A mission concept to support space sustainability through refuelling services in LEO," in *Proc. 75th Int. Astronautical Congr. (IAC)*, Milan, Italy, Oct. 14–18, 2024, Paper IAC-24-D2,8,6,x90035.