In-Orbit Servicing - Refuelling Assessment Report

Executive Summary and Final report

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Contents

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V1.0	New Doc	Issued	22nd Nov 2022	Marie Tilbee	All

Reference Documents

Reference Document Number	Document Title
[RD-01]	AS-IOSRefuel-035-TCD Astroscale In-Orbit Servicing - Refuelling Final Assessment Report (IOSAR)
[RD-02]	AS-IOSRefuel-023-SPC Astroscale IOR-R Ex(ample)Sat Technical Parameters

Acronyms:

The following Acronyms and Abbreviations are used throughout this document:

Acronym	Definition
CAMs	Collision Avoidance Manoeuvres
ConOps	Concept of operations
CP	Chemical Propulsion
DDV	Design, Development & Verification
DSV	Dual Solenoid Valves
EDT	Express Delivery Tanker
ELSA-M	End-of-Life Service, Astroscale – Multi-client
EP	Electric Propulsion
FDIR	Fault Detection Isolation and Recovery
FOS	Flight Operations System
FSM	Full-Service Mission
GNC	Guidance Navigation and Control
IOS	In-Orbit Servicing
IOS-R	In-Orbit Servicing – Refuelling
IOSAR	In-Orbit Servicing Assessment Report
LEO	Low Earth Orbit
LEOP	Launch and Early Operations
MEOP	Maximum expected operating pressure
N2H4	Monopropellant hydrazine
PST	Propellant Supply Tank
RANN	Right ascension of the ascending node
RPO	Rendezvous & Proximity Operations
SSO	Sun-Synchronous Orbit
TRL	Technology Readiness Level
TV	Test & Validation

1 EXECUTIVE SUMMARY

Astroscale Ltd. (ASUK) have led the completion of a Phase 0 study to mature plans to provide a unique refuelling service in Low Earth Orbit (LEO). The study consortium brings together an outstanding team of industry leaders with extensive flight heritage in relevant IOS systems, and world leading experience in space propulsion and robotics.

During the Phase 0 maturation study, ASUK, with the support of Thales Alenia Space (TAS), Nammo, MDA and GMV, have performed a programmatic, business and technical assessment of a future LEO refuelling mission. The mission proposes developing and demonstrating core technologies in a preliminary service offering to enable a commercial in-orbit refuelling service. Such a service will swiftly redefine how satellites are designed and operated, launching a dynamic and sustainable in-orbit ecosystem with significant potential.

The maturation study concludes at Mission Definition Review and represents a critical first step to realising the future of commercial and sustainable LEO In-Orbit Services (IOS).

ASUK recognises that providing a reliable, cost effective, and commercially sustainable service is critical to the viability of the future refuelling market. Throughout this study the overall solution has been designed with commercial sustainability in mind.

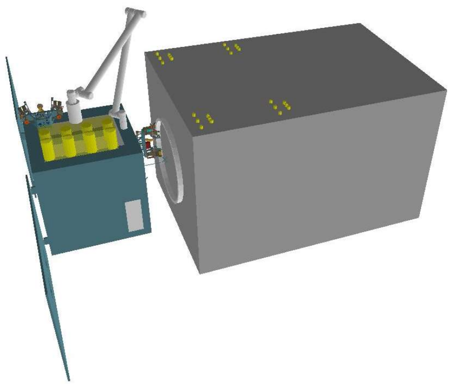
The solution proposed by ASUK is a variant of their ELSA-M LEO Servicer (built upon the flight heritage of Astroscale's pioneering ELSA-d mission), to refuel client satellites, granting additional on-orbit lifetime for satellites and providing significant value to satellite operators.

This variant of the ELSA-M Servicer leverages ASUK's flight heritage, rendezvous capabilities, and European supply chain, to offer a cost-effective and low risk proposition which allows the refuelling of satellites to be offered at a commercially viable price within a competitive timeframe.

ASUK aim to develop a preliminary refuelling service offering by 2028, full commercial servicing by late 2020s or early 2030s. ASUK was specifically created to realise commercial IOS provision, and so the barriers and solutions to IOS commercialisation are already very well understood, including a mature understanding of regulation and policy for IOS technology and missions.

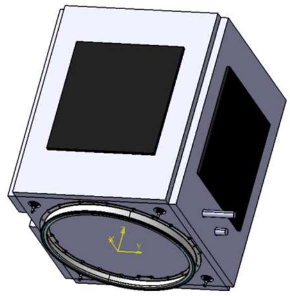
The studied in-orbit refuelling service requires two key space segment elements:

Refuelling Servicer: a modified ELSA-M platform updated to accommodate a revised capture and refuelling system. The capture system consists of a "gripper" mechanism mounted on a 6 DOF robotic arm and a docking and capture mechanism. An upscaling of some ELSA-M subsystems will be necessary; structure, chemical propulsion tanks, power subsystems, and Attitude and Orbit Control System (ACOS) actuators.



Propellant Supply Tanks (PST): a simple spacecraft that provides a fuel source. A mixture of PST sizes are likely for final commercial service infrastructure including:

- Large tanks to support multiple refuelling missions
- Smaller tanks for targeted refuelling



The IOS Refuelling (IOS-R) Servicer, using Astroscale's advanced Rendezvous and Proximity Operation (RPO) capabilities will dock with a PST, collect fuel and then transfer the fuel to an end customer (i.e. spacecraft on-orbit). It is envisaged that the service could refuel LEO assets, which may include unprepared satellites already in space, and assets yet to launch that can be prepared to take advantage of simpler, lower cost services. Initially, the system would refuel client satellites with monopropellant hydrazine using one or more propellant supply tanks to replenish the Servicer.

This Final Assessment Summary Report details the developments made by the consortium during the IOS Refuelling maturation study and summaries key findings. Several key areas of technology development have been identified to build the capability needed to offer a full commercial refuelling service. Recommendations on activities to increase technical readiness levels in these key areas are provided and a high-level mission schedule is summarised which takes these developments into account. Full details of the analysis undertaken in this study can be found in main technical report [RD-01]

2 CUSTOMER LANDSCAPE & SERVICE EVOLUTION

Astroscale's service offering would enable satellites to be refuelled in orbit, extend their satellite operations, and maximise the value of their assets in orbit.

We consider the refuelling market in LEO to be comprised of the following segments:

1. Refuelling unprepared satellites that are already in orbit that have fuel constraints but are otherwise operational.
2. Refuelling satellites prepared for in-orbit refuelling that have yet to launch that are designed to be refuelled, reducing the complexity and cost of such servicing. By including refuelling as part of satellite operations, operators can launch with significantly less fuel, providing more mass to revenue/value generating payloads.
3. Refuelling other prepared in-orbit servicing vehicles to reduce their mission costs and increase the value of their services. In-orbit servicing vehicles are those which manoeuvre regularly between different orbits as part of their normal CONOPS to deliver services to other systems.

The initial addressable market is existing unprepared satellites. Potential target customers in this market segment are high-mass, high value satellites >800kg in mass. These are primarily government (both civil and military) Earth observation satellites. JAXA have been used as a benchmark customer for this study and have expressed interest in being a future customer of refuelling services. Throughout this study, JAXA have participated in a number discussions with Astroscale in relation to refuelling services and JAXA in-space assets and future assets have been discussed as potential candidates for refuelling.

To allow a technical assessment of a future mission to refuel a high mass unprepared client, the consortium synthesized key technical parameters representative of a potential client satellite, JAXA ALOS-2 (*Figure 1*). Noting that any viable commercial service would need to be able to service a range of clients to be successful, the consortium also derived an estimated parameter range which would allow the proposed refuelling system to be designed to refuel a range of client satellites within the specified envelope. The example satellite design parameters are provided in [RD-02]

Figure 1: Illustration of representative client satellite, JAXA ALOS-2

During the course of the study, Astroscale have engaged several different end customer prospects and markets simultaneously to validate user requirements and evaluate customer interest over a longer timeframe.

Despite initial positive engagement, the large LEO market has not yet demonstrated a need for an unprepared refuelling service. Whilst there may still be interested customers (e.g. NOAA), it is unlikely that there will be a sizeable market for unprepared refuelling. However, a rapid adoption of refuelling interfaces and internal studies show that a prepared LEO refuelling market is closer than initially thought and shows considerable promise. A refuelling system to service prepared clients fitted with fluidic refuelling interfaces would be less complex than a system designed to refuel unprepared clients. Since the preliminary design work in this study has been undertaken with interoperability in mind, the refuelling system proposed in this Phase 0 study can be easily pivoted in future phases to target prepared satellites fitted with fluid coupling interfaces. It is envisaged that the initial design would be pivoted in future phases of the programme to capture this nascent but potentially sizeable market. Further details on this recommended next step are provided in Section 11.

3 MISSION OVERVIEW

The proposed refuelling service consists of a Servicer spacecraft and one or more Propellant Supply Tanks (PST), that may be launched with the Servicer or independently. An “Express Delivery” system is assumed where the Servicer would be the primary re-usable system that remains in orbit, and the PST would be a disposable one-use system that is “express delivered” close to the Servicer orbit. This essentially is a rapid on demand launch of the PST. The PST in the mission is assumed to facilitate the delivery of hydrazine propellant to orbit for use by the refuelling Servicer and its potential refuelling clients.

A nominal CONcept of OPerationS (CONOPS) for the proposed service is provided below broadly showing the following steps:

- Both the ELSA-M variant “Refuelling Servicer” and PST are launched (either independently or together)
- The Refuelling Servicer docks with a PST.
- Fuel is transferred from the PST to the Refuelling Servicer
- Refuelling Servicer rendezvous with client satellite.
- The Refuelling Servicer provides fuel to the end customer client. For ‘unprepared clients’ this would be achieved by accessing client Fill and Drain Valves (FDVs) and for ‘prepared clients’ through a fluidic refuelling interface.
- The Refuelling Servicer can then return to a PST to take on more fuel for client delivery and repeat as required for efficient multiple service operations.
- Refuelling Servicer and PST shall re-enter at the end of mission.

The overall mission concept phases are illustrated in *Figure 2* Commercial service development is divided into two key missions. A mission to develop and demonstrate core technologies in a preliminary service offering trialled on a fuel tank in space (Phase 1 – Phase 6). This would lead towards an end customer fuel delivery and follow-on commercial service missions (Phase 8 -13).

In the CONOPs shown operations will be greatly de-risked by an existing GMV robotics simulation testbed, as well as aided by their experience. The system shall be supported by re-using ASUK's existing Ground Segment, providing a flight *heritage commercial solution*

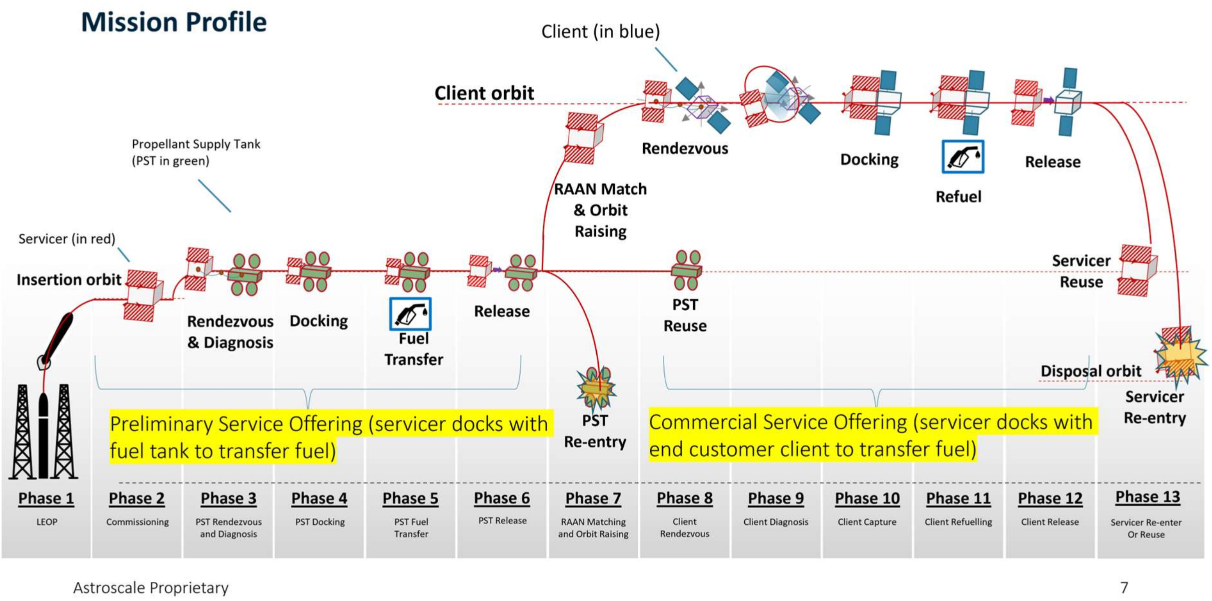


Figure 2 Nominal CONOPS

4 SYSTEM DESCRIPTION

The overall system comprises of an Express PST with 135kg fuel capacity alongside the Servicer with a fuel capacity of 150kg, and this provides 285kg of fuel in total. The Servicer is also equipped with robotic arm for client manipulation and tooling for accessing FDVs and FDV actuations along with the necessary fluidic couplings. Further details are provided in the subsequent sections.

4.1 Refuelling Servicer

The Refuelling Servicer concept is based on the Astroscale ELSA-M vehicle with modifications to allow the specific requirements of the refuelling mission to be met. This approach takes advantage of elements that already have (or will have by the time of a refuelling mission CDR) a high level of technology readiness and minimising the overall level of development risk. The ELSA-M mission is already in development and is currently working towards a CDR in 2023 and a launch in 2025.

As with ELSA-M the Servicer would be equipped with both Electric propulsion (for efficient orbit raising and lowering) and Chemical propulsion for rendezvous and close proximity operations, where high thrust and fast response is needed. The platform Power, Thermal, Communications and Guidance, Navigation & Control (GNC) sub systems are the same as for ELSA-M whilst the Command & Data Handling (C&DH) hardware is expected to include some architectural changes to incorporate lessons learned from the ELSA-M development.

Those elements that are additional to the baseline ELSA-M design consist of a mechanical robotic capture system provided by MDA, propulsion refuelling hardware from Nammo, modifications to the Payload GNC sensors required to support the capture system and upscaled larger chemical propulsion tanks. It is envisaged that chemical propellant tank would be enlarged from its current 45 kg maximum capacity to 150 kg.

The structure design is expected to be similar to that of ELSA-M, but, as a result of the need to accommodate the Capture system payloads, some redesign and a delta structural qualification campaign are envisaged.

Finally, a refuelling coupling interface may be integrated to facilitate fuelling of prepared clients. This would be evaluated further in a future Phase A/B study. An illustration of the proposed refuelling spacecraft is shown in *Figure 3*

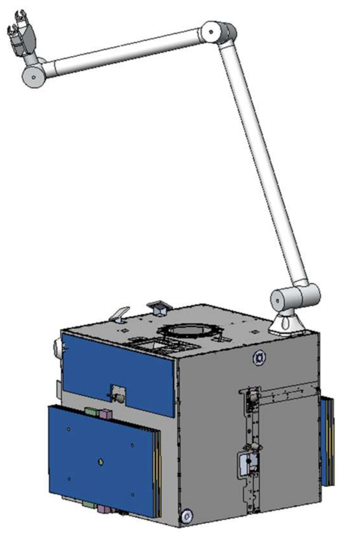


Figure 3: Illustration of the proposed Refuelling Servicer

Figure 4 below shows the Servicer's fluidic architecture. The heritage ELSA-M chemical propulsion system is in black, with dedicated refuelling hardware in red. The Servicer takes propellant in via coupling FTC-A and passes it to the client via the client interface.

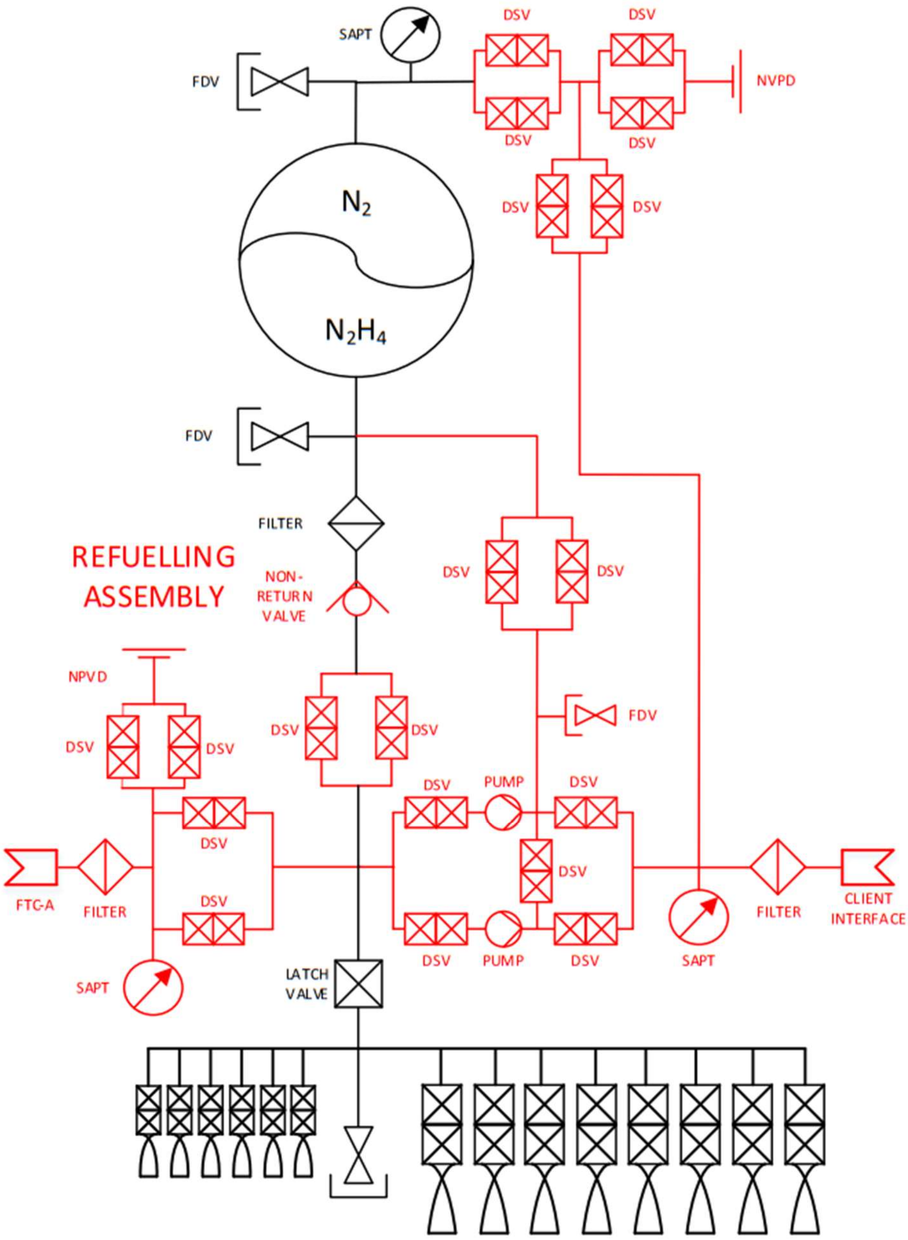


Figure 4: Servicer Chemical Propellant Fluidic Architecture (Presuming Blowdown Transfer)

4.2 Propellant Supply Tanks

In this study we have undertaken initial trade-off studies to understand the relative merits of a large tanker with ample propellant capacity (currently 750 kg) for all the refuelling that the Servicer may need to do during its lifetime, and a smaller “Express Delivery” PST, designed and developed by TAS, with a maximum of 135 kg of embarkable propellant, that could be launched into the vicinity of client orbits once the Servicer is ready to be replenished. With the smaller PST the Servicer would be the primary re-usable system that remains in orbit, and the PST would be a disposable one-use system that is “express delivered” close to the Servicer orbit.

During this study it has been demonstrated that the concept of operations for both the “Express Delivery” PST and the larger tanker is feasible from a fluidic point of view. For the larger tanker the pressure evolution and mass transfer evolution analysis has shown that a significant amount of Servicers can be supplied with fuel, however at a decreasing amount with each subsequent refuel. Therefore, the envelope of clients will decrease with each cycle, to a cut-off point where it is unpractical to continue operations. A pump however would allow operations to be prolonged.

The performance maps of the “Express Delivery” PST highlight that a large range of client sizes could be serviced and therefore the concept is versatile. Launching a smaller PST on demand near the Servicer also avoids the Servicer needing to carry extra fuel for missions, besides those of the immediate client(s) that require servicing. Given the flexibility afforded by the “Express Delivery” PST the smaller, simpler tank is currently the preferred solution for a preliminary service offering. The “Express Delivery” PST would be based on low-cost CubeSat bus with CubeSat electronics for the platform functionality, onboard-processing, communications and power handling of the PST. The CubeSat bus would be equipped with a tank with a fuel capacity of 135kg. The PST tank currently envisaged is a PTD-177 tank, which is not demisable and a controlled re-entry will be necessary. The Express Delivery Tanker (EDT) is shown in *Figure 5* below.

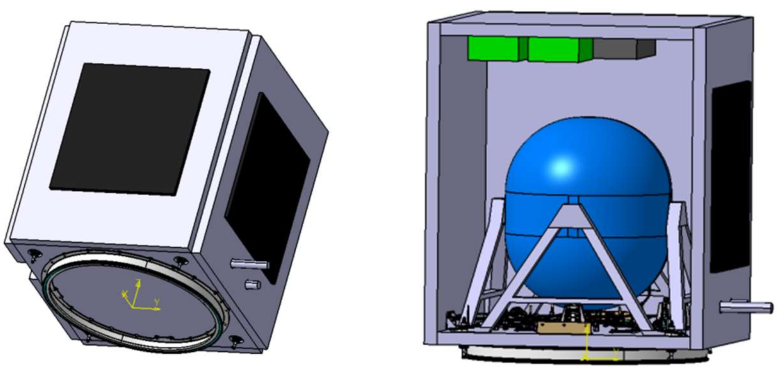


Figure 5 : Express Delivery Tanker, with Internal (left) and External (right) Views

Figure 6 below shows the tanker's envisaged fluidic architecture, employing blowdown propellant transfer. This architecture is chosen whatever the tanker size as a simpler architecture compared to the employment of pumps as in the Servicer architecture. The number of thrusters in the tanker architecture, however, may vary and is still subject to design evolution the design matures.

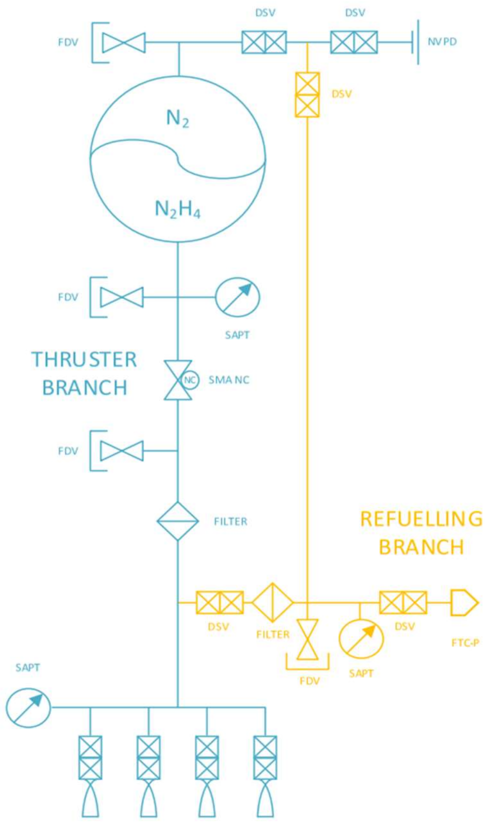


Figure 6: Tanker fluidic PST architecture, presuming blowdown transfer

Common to the tankers is the need to provide collision avoidance maneuvers, the need for thermal control of the propellant, command and telemetry capability, and a coarse attitude control. The concept of a very simple tank has evolved into becoming a limited-capability spacecraft which is absolutely necessary if the tank is able to have any maneuverability capability of its own and demonstrate full compliance with space debris mitigation guidelines. The end of life and de-orbiting plan for the PST is an open trade-off which would need to be further evaluated in Phase A. Given the evolving complexity of the tank, an alternative solution to developing new PST infrastructure could be to seek to refuel the Servicer through a fuel sale agreement with an existing fuel service provider, such as OrbitFab. This would negate the need for bespoke tank development and leverage the expertise of companies with existing fuel tank design experience. The relative merits of both options would be explored further in a future Phase A study.

4.1 Fuel Transfer Method

Transferring propellant between two tanks in orbit is significantly more complicated than fuelling on the ground. There were several methods that were considered in how the transfer of fuel could be undertaken, these were blowdown, gas-assisted and pumped. Each method was assessed against 9 factors which had individual weightings. The outputs of the study, show that gas assisted blowdown is a viable business model for a future mission. It offers the simplest architecture for the system both in terms of fluidics, but also on-board processing and power distribution.

4.2 Capture System

The capture system design adopted for the IOS Refuelling mission consists of a low cost 6 degree of freedom (6DOF) robotic arm equipped with a grapple mechanism and a pair of structured light projectors/sensors. The grapple is designed to capture the proposed clients using their Launch Attachment Ring (LAR) fixing (*Figure 7*). Capturing a spacecraft using the LAR has many benefits, most notably a rigid hard point close to the combined centre of mass and with low moment of inertia. It is also safe to capture operational satellites at this point without risking damage to operational surfaces or appendages, creating future applications for this technology and most importantly, minimising the risk of accidentally creating a further debris hazard through damage to the client resulting from an unsuccessful capture attempt.

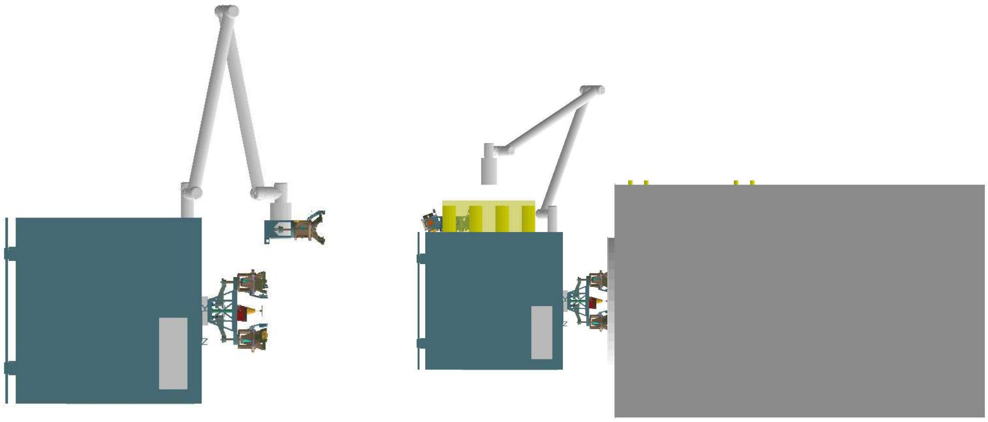


Figure 7 Robotic arm in capture configuration (left) and showing tool caddy volume and location (right)

The major downside of LAR capture is its small capture envelope, which requires the grapple to be positioned more precisely than other approaches. To address this challenge the robotic manipulator is equipped with end effector and mounted fine approach sensor (Structured Light Sensors) which are used to provide control and position knowledge respectively.

A single robotic arm has been baselined that can perform capture and refuelling, with a docking clamp to retain the Client, as this will be more mass and volume efficient than two robotic arms. If Servicer control authority proves to be a challenge, the arm length could be reduced, but this will limit the range of FDV worksites that can be accessed.

The servicing tools needed for the robotic arm are driven by the nature of the worksites and the valves to be serviced. The following tools are expected to be sufficient across a wide range of FDV types:

- Blanket cutting tool
- Blanket Handling tool
- Lock-wire cutting tool
- Cap tool
- Refueling tool

It should be noted that when thermal blankets are removed, the thermal condition of the FDV changes, which could lead to challenges for refuelling. It may be necessary to install a temporary cover, or to heat (or shade) the exposed FDV during the operation. The thermal conditions needed for safe transfer of fuel through the exposed Client FDV, and the means by which they can be achieved after thermal blanketing is removed, should be investigated in the next phase of the project if unprepared clients were to be considered as potential customers.

4.3 Refuelling Interfaces

The refuelling tool contains a primary refuelling coupling, that has to be mated to either a Client FDV directly, or to a leave-behind interface valve that the robotic system attaches to the FDV first. As the refuelling tool can be picked up or put down by the robotic arm, it also requires a fluidic coupling to the fuel hose that runs along the arm and terminates at its end effector. Nammo has proposed an implementation of the leave-behind interface valve, as well as a refuelling coupling based on the design of the Nammo ground half coupling. Further development is required in the next phase of the project, to refine the interfaces between the Nammo proposed concept and the robotic refuelling tool into which Nammo hardware will have to be integrated. The method of transporting the leave-behind FDV interface valve to the worksite and installing it on the FDV requires further investigation, as the means of retaining it in the refueling tool that also allows for it to be installed on the FDV by the tool is yet to be determined. Nammo's RIDER prepared fluid coupling is being considered as the fluidic connection between the fuel hose running up the arm and the refuelling tool, as this is a prepared interface.

5 GROUND SEGMENT

The ground segment has been developed in-house by Astroscale and first proven on the ELSA-d mission. It is intended that it will be further proven and demonstrated on ELSA-M, ADRAS-J and other Astroscale missions before the scheduled launch of IOS-R. It consists of a global spread set of participating earth stations, a terrestrial communications network tying them together, and a control center based in the Satellite Applications Catapult at the Harwell Campus *(Figure 8).*

Figure 8 The In-Orbit Servicing Control Centre (IOSCC) Operations Centre

6 OPERATIONS

Most of the intended operations of the proposed system are routine and have been already performed many times by others. However, operations of the robotics and refuelling are not yet routine. *Figure 9* below, shows a depiction of a refuelling activity flow, considering the differences between unprepared clients and those possibly prepared for refuelling with refuelling fluid interface. Further details on each operational phase of the mission concept are provided in ***Table 1***.

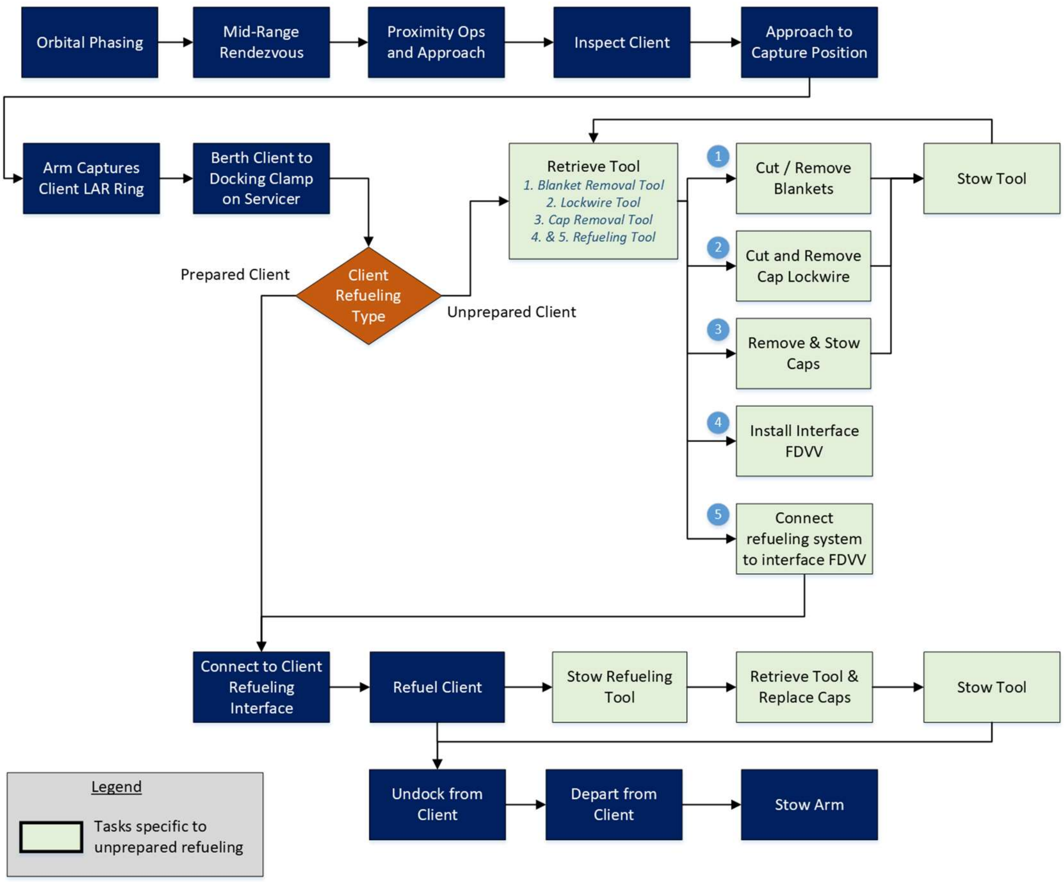


Figure 9: Fuel Refuelling Activity Flow

Phase 1	Launch and Early Operations (LEOP) including the initial automated sequence to power on the spacecraft, as well as in-orbit commissioning of the spacecraft following contact with the ground segment.
Phase 2	Is where the Servicer is commissioned, and orbit raising and orbital alignment with the PST
Phase 3	Is where the Servicer rendezvous with and diagnose the PST
Phase 4	Servicer will dock to the PST
Phase 5	the PST will transfer the propellant to the Servicer. Mating and coupling, leak check venting, line priming, fuel transfer, vent. De-mating
Phase 6	is where the Servicer undocks from the PST. the Servicer commands the capture system to extend to a release configuration, to achieve the maximum possible separation between the Servicer and the client
Phase 7	the Servicer will perform Orbit Raising and RAAN Matching. The Servicer will use its EP thrusters to raise the orbit keeping, RANN Matching performed passively
Phase 8	is where the Servicer rendezvous with the Client, which. The Servicer will adopt a direct approach trajectory until about 10 km away for GO/NOGO. The Servicer will perform a direct insertion on the Client orbit (~800m away) for GO/NOGO
Phase 9	the Servicer will perform a full diagnosis of the Client. The Servicer will go to home position, then point A (~20m), from which diagnosis of the Client can be done, for GO/NOGO
Phase 10	the Servicer will capture the Client. The capture system is in extended position and mechanical clamp of the grappling point (e.g. Launcher Adapter Ring) will be performed.
Phase 11	the Servicer will transfer the propellant to the Client. In the assumption that the refuelling port is a FDV (unprepared), the Servicer shall: Cut and remove thermal blankets (if any), Cut and remove Cap Lockwire (if any), Remove and Stow Cap. Mate to the FDV on the client. For prepared clients the Servicer shall dock via the fluidic interface. The propellant is transferred from the PST to the Servicer with a TBD method (could be similar to that of Phase 5).
Phase 12	the Servicer undocks from the Client. Prior to release, the Servicer commands the capture system to extend to a release configuration, to achieve the maximum possible separation between the Servicer and the client. The capture system is retracted to stowed position
Phase 13	The Servicer could in general refuel several Clients, therefore there could be two options upon completion of Phase 12.n:The Servicer lowers its orbit to Rendezvous with the PST. The cycle Phase 3.n to Phase 12.n is repeated for the Client n+1. Finally, PST and Servicer re-enter the atmosphere.

Table 1: Mission concept phases

7 CONSORTIUM ORGANISATION

The maturation study has been undertaken by a core team of a highly credible industry leaders with extensive flight heritage in providing IOS systems and technologies. The consortium completing the Phase 0 study consisted of:

Astroscale UK

- Overall Program Management
- Leading mission & systems engineering,
- CONOPS development and Requirements development
- Ground Segment and Operations
- Mission Cost and Commercial Analysis
- Regulatory, Legal and licensing aspects

Thales Alenia Space (TAS-UK)

- Propellant Supply Tank
- Refuelling subsystem

Nammo

- Refuelling Interfaces
- Subsystem components

MDA UK

- Capture robotics analysis
- Support mission requirements,
- CONOPS definition and operations planning.

GMV

- Test bed development & GSE

Progressing to Phase A the existing core consortium may seek to bring onboard new specialist skills to mitigate development risks that have been identified during the initial study phase. In particular, ASUK is interested in exploring the implications of utilising the RAFTI interface with Orbit Fab who have recently established a UK office. Orbit Fab are a company aiming to specialise in refuelling and offer existing fuel tank design experience. Orbit Fab may also support end customer sales and provide access to LEO customers with RAFTI couplings. A possible Phase A/B consortium structure is shown in

Figure 10. As the programme develops, the consortium will grow with geographical return flexibility across ESA Member States, leverage the mature supply chain relationships already developed under the ELSA-M and COSMIC programmes. ASUK is also currently seeking German support for commercial LIDAR development in collaboration with Jena Optronik.

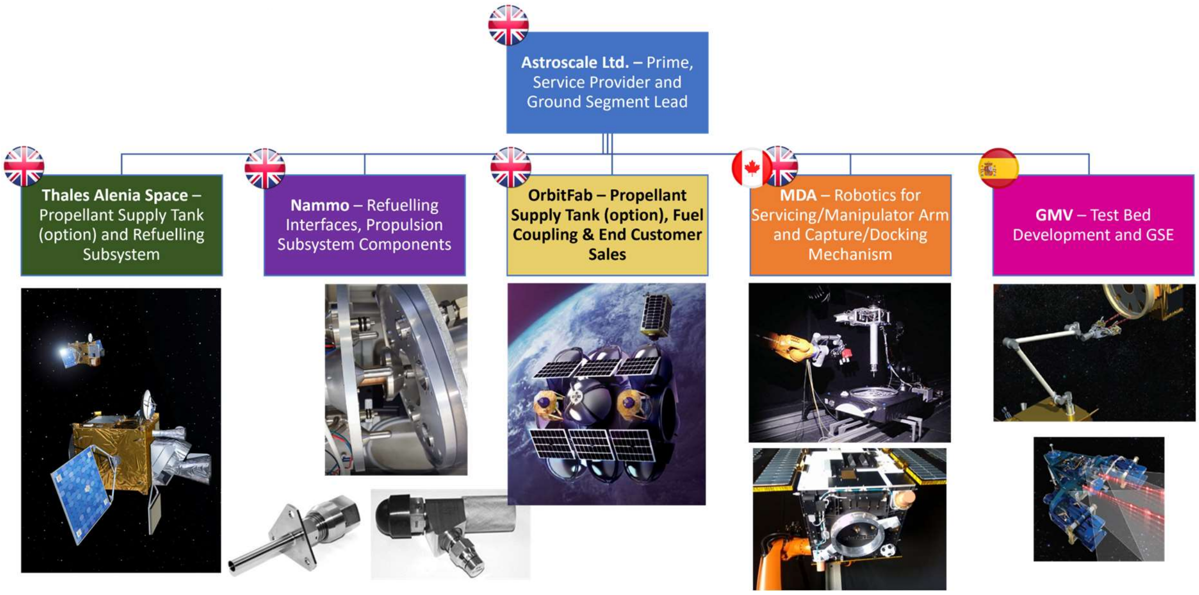


Figure 10: Industrial Organisation

8 MISSION TIMELINE & MILESTONES

Customer and market analysis has demonstrated that refuelling in LEO is a nascent and rapidly evolving market. First mover competitive advantage is likely to be key to realising a successful commercial service. Following completion of the Phase 0 study, a follow-on Phase A/B programme is proposed as the next step to position Europe a future leader in the Low Earth Orbit refuelling services. A Phase A/B Programme would provide the next step towards a preliminary service offering trialled on a fuel tank in space. The preliminary service offering, envisaged to launch on the European Vega C launcher, would lead towards an end customer fuel delivery and commercial refuelling services which would be provided in the late 2020s or early 2030s-time horizon.

The rollout of the commercial servicing development programme is shown in the roadmap below. Key development milestones are shown in the top-level mission timeline shown in Figure 11. The timeline drives towards an early market entry to secure the greatest market share and commercial value. Following discussions with both ESA and UKSA the proposed timeline in Figure represents a credible schedule would be commensurate with likely budget availability for follow on IOS activities. The schedule allows for the necessary equipment procurement timescales, design activities, development roadmaps and Assembly, Integration & Test (AIT) with a proposed mission launch date of late 2020s.

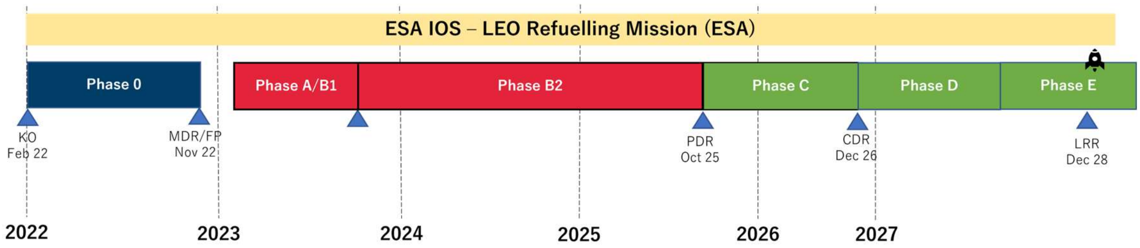


Figure 11: Top-level mission timeline for Prepared Refuelling Development (Budget Cognisant)

It is recognised that the LEO fuelling market is a nascent market and the earlier a mission can be launched the greater the chances of maximising market share. An alternative timeline is outlined below (*Figure 12*) which presents a more aggressive schedule with launch scheduled for 2028, if securing first mover advantage is considered high priority.

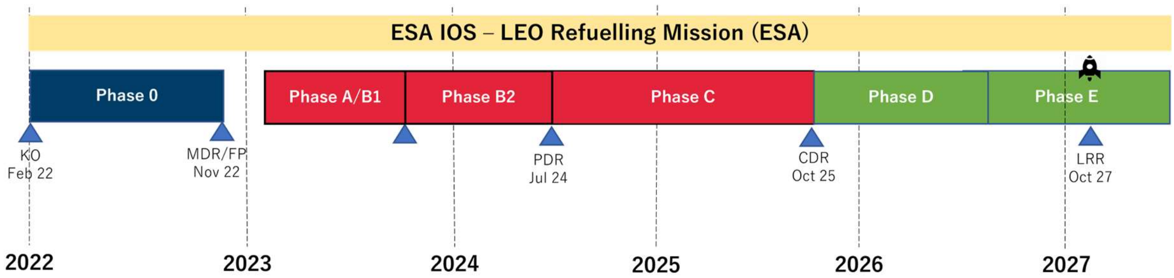


Figure 12: Top-level mission timeline for Prepared Refuelling Development Prepared Refuelling (Rapid)

9 RISK MANAGEMENT

Several risks have been identified during the Phase 0 study and a summary of the most significant programme level risks together with current planned strategy for mitigation is shown below.

	Risk Description	Risk Effect	Likelihood	Impact	Planned Mitigation
1	Tooling compatibility with FDV is not established	Project is delayed	High	High	Perform detailed tooling and FDV design activity (section 2.5.5).
2	Cannot access Client FDV after launch	Mission Failure	Low	High	Need details of client mechanical FVD positioning. Pivot to refuelling prepared clients
3	FDV and adapter design/configuration does not work	Project is delayed	Med	High	Re visit mechanical operation of mechanical arm and tooling MDA are proposing – close collaboration between Nammo & MDA essential.

4	Necessary developments are delayed	Project is delayed	Low	High	Early KO of all identified developments
5	Incorporation of Nammo refueling coupling and FDV interface into robotic tooling leads to a complex and heavy solution	Project is delayed	Med	High	MDA and Nammo to work closely to refine interfaces and requirements between Nammo supplied components and the robotic tooling required to deliver those components and install them at worksites. Build and test a proof of concept breadboard. Start with the MDA TRL 4 breadboard refueling tool concept, and update to incorporate Nammo supplied components.
6	Thermal regulation of the fuel line, including the hose running up the arm, through the refuelling coupling within the refuelling tool, the interface valve, and the exposed Client FDV	Dangerous conditions of fuel transfer making fuel transfer impossible due to excessive risk. Mission Failure	High	High	Thermal analysis and thermal control system investigation. Need to investigate the thermal condition of the exposed Client FDV in particular.
7	Additional fluidic couplings not yet considered in the Refuelling Subsystem concept (e.g. fuel hose to refuelling coupling in the refuelling tool, refuelling coupling to the FDV interface valve, FDV interface valve to Client FDV) lead to operational and/or design complexities in the transfer and metering of fuel, leak detection strategies, and purging operations prior to disconnecting from the Client.	Project is delayed	High	High	TAS/Nammo/MDA update fluid transfer path schematics to include all planned fluidic couplings, and work through the conops and design issues associated with them.
8	Feedback required by operators to safely monitor and execute refuelling operations from the ground may be insufficient.	Difficult execution of fuel transfer. Excessive time spent during refuelling process may lead to excessive consumption of Servicer fuel, thereby limit Servicer life and ultimately business profitability.	Med	High	Establish the video architecture and camera placements for viewing the execution of Client servicing tasks. Ensure there is sufficient telemetry from the system to confirm completion of each operational step.

9	Early take up of standard refuelling interfaces than envisaged by Satellite manufacturers. This implies new satellites being launched are "prepared clients".	The marketplace may not be lucrative for unprepared clients by the time we have developed complicated systems to cater for unprepared clients. Unnecessary developments may have taken place which could potentially harm the business case.	Med	Med	Focus the business case towards prepared clients

10 COMMERICAL ANALYSIS & MISSSION COSTS

Currently, satellites are launched into orbit with all the fuel they will need for their entire operations. Such a single-use culture leads to an increasingly congested environment and inefficient use of assets. In-orbit refuelling unlocks a dynamic in-space ecosystem that brings flexibility, sustainability, and resiliency to space. Astroscale's refuelling service would enable satellites to be refuelled in orbit, extend their satellite operations, and maximise the value of their assets in orbit.

Considered market analysis has identified that it is unlikely there will be a sizeable market for unprepared refuelling, however the prepared refuelling market shows promise with an initial need for the re-supply of Hydrazine propellant. This initial service offering should pivot to a prepared refuelling concept which can be positioned to expand into wider refuelling services covering different orbits, propellant types, and different types of pre-prepared clients.

Overall, in-orbit refuelling presents a compelling way to extend satellite operations to maximise the use of assets, escape from the constraints placed of satellite design during launch, and reduce overall costs for satellite service provision. Refuelling in LEO is a critical component to unlocking the In-Orbit Services and a driver of the IOS economy is a key technology to future growth (Figure 13).

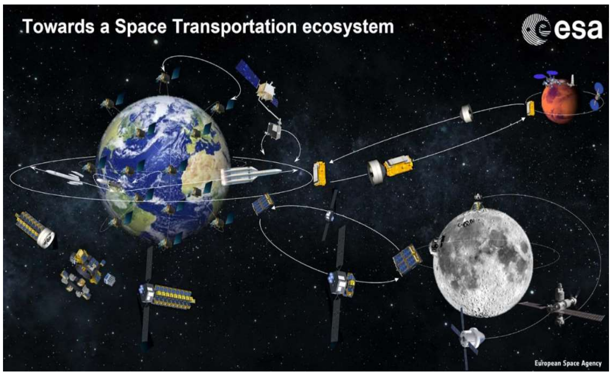


Figure 13: Illustration of future space transportation

The cumulative number of satellites available for refuelling is shown in *Figure 14* demonstrating an addressable market for prepared clients establishing from ~2027 onwards. The serviceable obtainable market is shown in Figure 15.

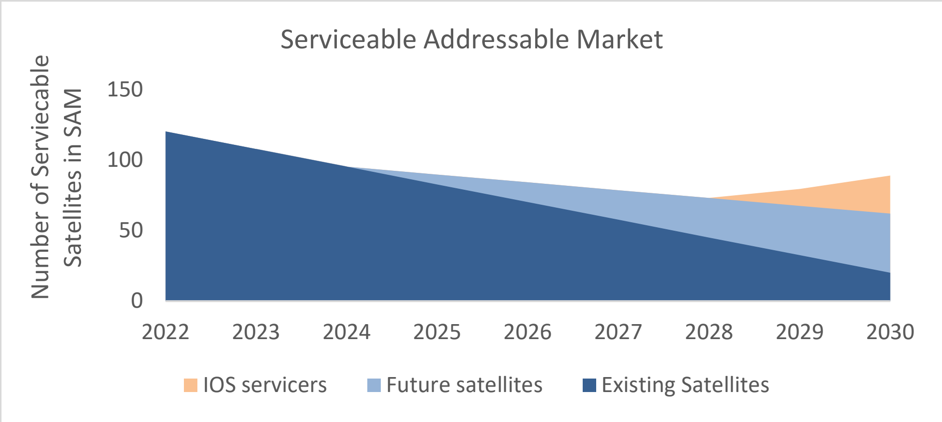


Figure 14: Serviceable Addressable Market

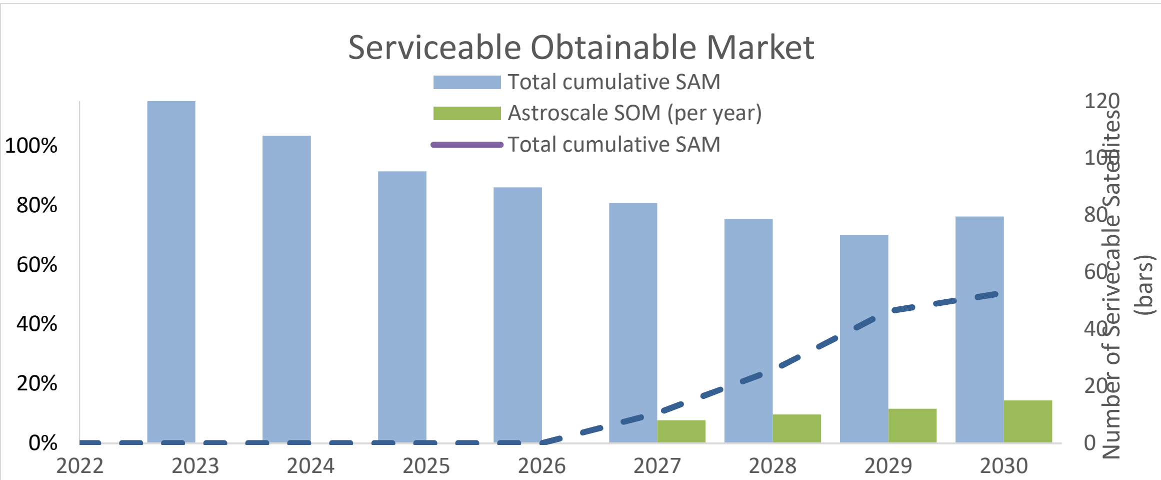


Figure 15: Serviceable Obtainable Market

During this Phase 0 study the market opportunities and broader applications of the refuelling service have been examined. Initial mission costs have been evaluated. As discussed in Section 2 of the report the next step in the development of a commercial refuelling service would be a preliminary service offering trialled on a fuel tank in space. This would lead towards an end customer fuel delivery and follow-on commercial service missions. Leveraging existing cost analysis of the ELSA-M baseline and design deltas within the refuelling servicer, design, we arrived at an estimated figure of ~40M € total price for a preliminary service offering excluding launch costs. A further breakdown of the of the preliminary price, cost and preliminary geo-return split is provided in Section 11.

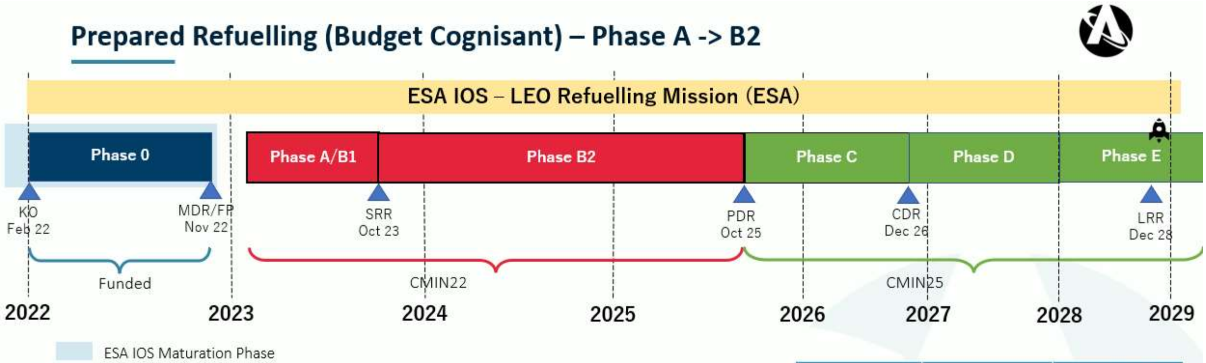
11 NEXT STEPS AND RECOMMENDATIONS

As already noted, an observed rapid adoption of refuelling interfaces and internal studies show that a prepared LEO refuelling market is closer than initially thought and shows considerable promise. Following discussions with ESA and UKSA, Astroscale have decided to pivot their recommended follow-on mission towards a reframed concept for a prepared LEO refuelling service, with greater commercial promise.

In the full report, prices have been provided for three programme scenarios:

1. **Unprepared Refuelling** – Delivery of the concept originally proposed for an unprepared LEO mission. This is no longer recommended by Astroscale, but included for completeness.
2. **Prepared Refuelling (Rapid)** – Delivery of the reframed concept, if unconstrained by budgets, to reach market in the shortest possible time, and thus secure the greatest market share. This would be recommended but, following national delegate feedback, is understood to not be realistic given the available funding.
3. **Prepared Refuelling (Budget Cognisant)** – Deliver reframed concept at a slower pace. This still would get us to market first and but believed to more realistic to achieve with available funding. As such, this is the scenario which Astroscale recommends for further development.

A preliminary price, cost and preliminary geo-return split has been provided below for this Prepared Refuelling (Budget Cognisant) scenario. A first order bar schedule is also provided. This is in-line with budgetary requests that have been submitted for ministerial consideratio



- Astroscale are still likely able to realise a faster schedule than competitors, leveraging ELSA-M experience
- May have an impact on market share with global competitors
- Price assumes 20% co-funding during Phase B2
- Geo-return is somewhat flexible between these countries.
- Also seeking German support for commercial LIDAR development

Geo-Return	Price (€M)	Cost (€M)
UK	4.9	5.8
Canada	1.5	1.7
Spain	0.7	0.8
Total	7.1	8.3