

OMAR Mission Architecture Study Executive Summary Report

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Table of Contents

| | | |
|----------|--|-----------|
| 1 | INTRODUCTION | 5 |
| 1.1 | Study Scope..... | 5 |
| 1.2 | Study Objectives | 6 |
| 1.3 | Abbreviations & Nomenclature | 6 |
| 2 | OVERVIEW IN-ORBIT SATELLITE LANDSCAPE AND MARKET | 7 |
| 3 | MISSION SCENARIOS..... | 14 |
| 3.1 | Medium-size Telecommunication Constellation Manufacture and Assembly | 16 |
| 3.2 | Refurbishment Facility in Dawn-Dusk SSO | 18 |
| 3.3 | GNSS Constellation Refurbishment / Upgrade | 21 |
| 4 | CONCLUSIONS AND OUTLOOK | 24 |

List of Tables

| | |
|--|----|
| Table 2–1: Overview of Satellite Purposes and Tasks | 8 |
| Table 3-1: Comparison of Number of IOAM stations | 16 |
| Table 3-2: LEO4 IOAM station mass budget | 18 |
| Table 3-3: Number of Launches per Cluster | 19 |
| Table 3-4: LEO5 IOR station mass budget | 20 |
| Table 3-5: Total Number of Launches | 21 |
| Table 3-6: MEO1 IOR station mass budget | 23 |
| Table 3-7: Comparison IOR vs From Ground Replacement | 23 |

List of Figures

| | |
|---|----|
| Figure 2–1: Civilian Satellites in Earth Orbit (>100kg) (February 2020) | 9 |
| Figure 2–2: Satellite Purposes in Earth Orbit (February 2020)..... | 9 |
| Figure 2–3: Preliminary On-Orbit Service Tree | 13 |
| Figure 3–1: Scenario Selection..... | 15 |
| Figure 3-2: Operational Phase Mission Profile and Timeline – Case 1 | 17 |
| Figure 3-3: OSS operational phase sequences | 17 |
| Figure 3-4: Operational Phase Mission Profile and Timeline | 19 |
| Figure 3–5: LEO5 IOR operations on client satellite CONOPS | 20 |
| Figure 3-6: Operational Phase Mission Profile and Timeline | 21 |
| Figure 3-7: Focus on the refurbishment operations for MEO1 | 22 |

1 INTRODUCTION

This document presents the final report of the OMAR Design for Recycling - Mission Architectures to Manufacture, Refurbish and Recycle Satellites On-Orbit study led by OHB. It describes the activities performed and the main results achieved. An overview of the study results elaborated by the OHB / TAS-F / TAS-I industrial team is provided for each main task of the activity.

1.1 Study Scope

To contribute to space sustainability, some Agencies and Governments have established or adopted policies to mitigate space debris. Through its Clean Space (CS) initiative, ESA has been devoting an increasing amount of attention to the environmental impact of its activities, including its own operations as well as operations performed by European industry in the frame of ESA programmes. In ESA Technology Strategy, the Agency has identified as one of the four technology development targets inverting Europe's contribution to space debris by 2030. The OMAR activity is intended to support achieving the target as part of the Discovery Preparation and Technology Development (DPTD) activities. The Discovery & Preparation undertakings interface in different ways with all of ESA's programmes, carrying out preparatory analysis and laying the groundwork for the Agency's future activities.

The concept of On-orbit manufacturing and recycling has received increasing attention in the past years and a number of isolated technology developments have been initiated. The production and reuse of spacecraft in orbit provides the potential to turn problems into valuable assets. This requires the understanding of the implications at mission and system level as well as a clear view of the use cases benefiting from this approach. To address this complex issue, a comprehensive systems approach involving a multidisciplinary team and exploring synergies among the different possible scenarios and building blocks is necessary. With this aim, ESA introduced the OMAR (On-orbit Manufacture, Assembly & Recycle) initiative. OMAR is a system approach aiming to give an overview of the most interesting applications, map the state-of-the-art and derive a roadmap for the development of the critical technologies. The proposed approach follows 3 steps:

Step 1: Preparatory small CDF study screening the relevant mission scenarios, assess feasibility and derive systems architecture. This step was completed in 2019.

Step 2: Industrial studies addressing main system segments based on established architectures. Three industrial activities will be carried out in parallel. These studies aim at understanding the possible strategies, system level impacts and potential benefits, while exploring the trade-space.

One of these studies is the OMAR Mission Architecture Study. Multiple mission architectures are possible for the implementation of services in orbit. This activity shall focus on the trade-off of the mission architectures for an on-orbit manufacturing and refurbishment mission performed by an On-orbit Servicing Station.

Step 3: Future full CDF study - preliminary system and subsystem design of all elements based on industrial inputs, consolidation of the mission scenario and concept of operations, definition of system interfaces between the different segments, evaluation of industrial and economic impacts of the proposed approach, definition of technology development roadmap.

1.2 Study Objectives

The main objective of the OMAR Mission Architecture study is to identify and trade-off different mission architectures, to provide different services on-orbit. For each of the relevant scenarios, this objective shall be achieved by the definition of the associated system functional analysis and by trading-off of different architectures and concepts of operations. Further the impact of aspects such as: operational orbit, type of serviced satellites, services provided, different levels of autonomy, and any other relevant factors is to be assessed. In order to achieve the main objective the following three main tasks are defined:

The objective of Task 1 is to map and classify all possible mission scenarios and to perform a mission level functional analysis for each of the identified services.

The objective of Task 2 is to establish the domains of application and driving criteria for different mission profile, concept of operations and functional breakdown, by assessing each of the identified mission scenarios.

The objective of Task 3 is to define a comprehensive mission architecture for selected mission profiles, i.e. the architecture, mission profile and concept of operations shall be detailed. Furthermore an initial assessment of commercial considerations shall be carried out.

1.3 Abbreviations & Nomenclature

| Abbreviation | Meaning |
|--------------|---|
| AIT | Assembly, Integration and Test |
| CSG | Guiana Space Centre |
| ELL | Elliptical Orbit |
| EPS | Electrical Power System |
| GEO | Geostationary Orbit |
| GTO | Geostationary Transfer Orbit |
| IOAM | In-Orbit Assembly and Manufacturing |
| IOR | In-Orbit Refurbishment |
| LEO | Low-Earth Orbit |
| MAIT | Manufacture, Assembly, Integration and Test |
| MEO | Medium-Earth Orbit |
| OMAR | On-orbit Manufacture, Assembly and Recycle |
| OOS | On-orbit Servicing Station |
| ORU | Orbital Replacement Unit |
| RAAN | Right Ascension of the Ascending Node |
| SA | Solar Array |
| SSO | Sun-Synchronous Orbit |

2 OVERVIEW IN-ORBIT SATELLITE LANDSCAPE AND MARKET

In order to identify the key parameters and factors leading to the definition of mission scenarios and architectures for on-orbit servicing a comprehensive review of the past, current and future developments of the satellite landscape in Earth orbit was conducted. Further past and current studies representative of key aspects of on-orbit services, e.g. robotic and manufacturing processes were also included in the review.

The results of the review were analysed, condensed and categorized to identify potential clients across the orbit regimes of low (LEO), medium (MEO) and geosynchronous earth orbits (GEO). A high level assessment of the on-orbit service market evolution was performed. An on-orbit service tree was established and enabling factors to provide services as manufacturing, refurbishing and recycling to individual satellites as well as satellite constellations were compiled.

The literature review is focused on civilian satellites with a launch mass higher than 100 kg. Although in very high value and representing considerable market share, satellites for military purposes are explicitly excluded as clients as they are subject to extensive non-disclosure regulations and are most likely not accessible to civil or commercial service providers.

Also excluded from the analysis are small satellites (mass < 100kg) launched from Earth, e.g. Nanosatellites, Microsatellites and CubeSat as there are not deemed eligible client satellites for on-orbit servicing as refurbishment due to their low overall cost and life times. However the on-orbit manufacturing of these satellite as service is not excluded.

The literature review and the analysis is mainly based on the evaluation of data collected from various source and database freely accessible via internet:

- Spacecraft and satellite databases
- Archives and reports of established space related internet news outlets
- Websites of space agencies and space related institutions
- Summary of market reports
- Research and white papers and presentations
- Company Websites

In general, the most populated orbit regimes are LEO and GEO, as shown in Figure 2–1, whereas the highest number of satellites is located in LEO. Both orbit regimes are occupied by operational and retired satellites. About 60 % of satellites in LEO are currently operational whereas 40 % are retired satellites. In GEO regime about half of the satellites are operational while the other half is retired in graveyard orbits.

The number of LEO satellites is currently increasing rapidly due the launch of new communication mega constellations comprising thousands satellites as for instance Starlink. Communication mega constellations will dominated LEO in the coming years. Aside from communication satellites, other purposes of LEO satellites, as listed in, are earth observation, science and meteorology as well as satellites for experimental and technology development proposes..

Satellites are categorized according to their dedicated purpose and tasks. The top level categories are summarized in Table 2–1 also providing a brief description of the task for each category. It is to be noted that meteorological satellites are technically Earth observation

satellites, however a dedicated category was introduced to set them apart because meteorological satellites are usually deemed higher value and have longer life times.

Table 2–1: Overview of Satellite Purposes and Tasks

| | Tasks |
|--------------------------|---|
| Communication | Satellites for telecommunication: <ul style="list-style-type: none"> • TV Broadcasting • Radio Broadcasting • Telephone Services • Internet Access • Data Relay |
| Earth Observation | Satellites using optical, radar, infrared, multispectral or hyperspectral imaging for: <ul style="list-style-type: none"> • Earth imaging and mapping • Earth science (relying on imaging) • Environmental monitoring • Disaster monitoring |
| Science | Satellites that are used to investigate scientific topics in e.g.: <ul style="list-style-type: none"> • Space science • Astronomy • Life science • Earth science not utilizing imaging |
| Meteorology | Satellites that used predominantly for: <ul style="list-style-type: none"> • Weather Forecasting • Weather Observation • Meteorological Modelling |
| Technology | Experimental satellites for technology demonstration and development |
| Navigation | Satellites used for: <ul style="list-style-type: none"> • Global Positioning • Regional Positioning • Navigation and Navigation Enhancement |
| Other | Miscellaneous Satellites for <ul style="list-style-type: none"> • Educational Purposes • Amateur Radio • Experimental Satellites |

The GEO space is dominated by large communication satellites as shown in Figure 2–2. The communication satellites currently comprise about 86% of the satellites in GEO. The communication satellites are mostly owned and operated by commercial telecommunication

network providers as Intelsat and SES. In addition various civilian navigation (augmentation), meteorology and earth observation satellites are also located in GEO.

Global navigation satellite systems (GNSS), like Galileo, are predominantly located in higher MEO. Whereas the lower MEO space is also utilized by a small communication constellation.

Elliptical orbits (ELL) are mainly utilized for a comparably small number of mainly individual scientific satellites. Due to the uniqueness of the science objectives the elliptical orbits of each satellite tends to be very different from the other. Satellites in elliptical orbits are therefore not further considered in the study.

Based on the current and developing satellites landscape it is safe to assume that LEO and GEO will remain be the most populated orbit regime for the next decades. Although the MEO regime will likely see also an increase in satellites in the next decade mainly regarding the communication satellites, its number of satellites will remain low compared to LEO and GEO.

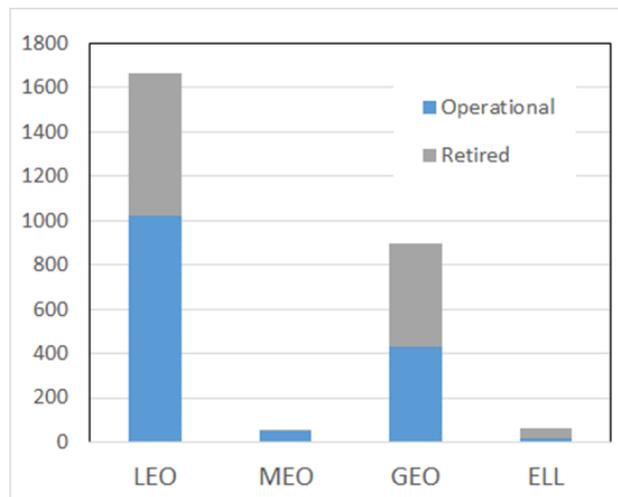


Figure 2-1: Civilian Satellites in Earth Orbit (>100kg) (February 2020)

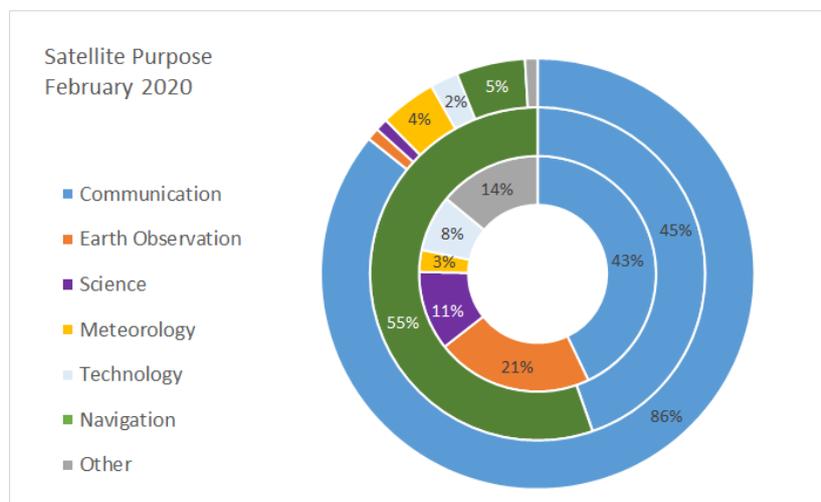


Figure 2-2: Satellite Purposes in Earth Orbit (February 2020)
 LEO-inner, MEO- middle, GEO-outer circle

In order to determine potential markets, customers and client satellites for on-orbit servicing scenarios, the results of the orbit regime analysis are evaluated and assessed in regard to preliminary metrics. On top level the metrics are differentiated in orbit, customer and development related metrics. These metrics were chosen to address the most relevant question regarding potential markets:

- Where will the client satellites be located?
- What kind of client satellites will there be?
- How many client satellites will there be?
- How will the market develop over time?

At this point the metrics are mostly of qualitative nature. Several metrics are interrelated while others are independent. A specific ranking of the metrics is not performed at the present time.

The market assessment was performed for each orbit regime, the focus was however on identified high value orbits as sun-synchronous and polar orbits in LEO as well as the geostationary ring in GEO. The market assessment takes near term, medium term and far term timeframes into consideration. Hereby, the timeframes are defined as follows:

- Near term – from 2030 onwards (2030+)
- Medium term – from 2040 onwards (2040+)
- Far term – from 2060 onwards (2060+)

As it is difficult to predict the future involving innumerable factors and variables, it is to be remarked that especially medium and far term assessments contain considerable uncertainties. Also considering that market predictions and forecast periods of professional market research institutes are usually only in the order of five to ten years ahead.

The on-orbit service market strongly depends on the development of the satellite market. Currently, two general trends become apparent throughout market reports and development predictions. The market for LEO satellites is increasing while the market for GEO satellites is stagnating or declining. Especially the communication satellite market may see a paradigm shift from GEO to LEO in the coming years with the emerging mega constellations. This however depends heavily on the long term success and viability of the mega constellations, which at this point is difficult to assess.

Aside from a few occasions, there was no wide-spread intrinsic need for on-orbit servicing in the past, although interest in on-orbit service has been expressed by companies. In the past and still currently the development of the OOS market faces and has to overcome the “hen-egg” problem. Overcoming the problem might be considerably accelerated by the fact the valuable earth orbits become more and more populated elevating OOS from “nice to have” towards “must have”.

It is widely reported by numerous market research institutes that the LEO market is continue to increase in the coming years. The LEO market consists of two main commercial segments communication and earth observation satellites. In addition there are also non-commercial satellites of higher value as meteorology and science satellites. Earth observation satellites have a wide range of applications from agriculture and environment monitoring to mining industries as well as business intelligence and insurance sectors. The demand for satellite-based earth observation data is constantly growing producing annual revenues in the order of

several US\$100 million. This is also reflected by the launches of larger Earth observation satellites in the past decade. Earth observation satellites are located several clusters in sun-synchronous orbits. Therefore one on-orbit service station is able to access up to 15 to 20 client satellites without performing costly plane change manoeuvres. Using drift orbits the number of client satellites can be increased to up to 100. The satellites population on the other hand is very diverse involving numerous parties and designs as they mostly individual satellites. The satellite diversity is an impeding factor for on-orbit servicing, therefore a common standardizations and agreements have to be established between all involved parties to enable on-orbit services for a viable number of client satellites. In general earth observation satellites are assessed to be viable client satellites if prerequisites are established for future satellites. Over the OOS market has a prospective to evolve from limited service to full service as new enabling technologies are developed.

Small communication constellation in LEO produce a large share in revenues of commercial space markets by providing telephony and internet services as well as internet of things applications and M2M communication. They also provide services for ship tracking via AIS and other maritime applications. The constellations are also widely used in disaster response and emergency communications. The Iridium Next constellation for example was recently also certified for use in the Global Maritime Distress and Safety System. It is assumed that small communication constellations will prevail in the near and medium term future also due to their established application in disaster response communication. The next generation of satellites is therefore also considered as potential client satellites. The number of client satellites ranges from 30 to 80 depending on constellation. The satellites are distributed over four to six orbital planes each accommodating up to 14 satellites. As the planes have the same inclination one service station could in theory access the entire constellation utilizing drift orbits to change RAAN. As constellation satellites, they are already subjected to high degree of standardization which is favorable for on-orbit servicing. However future satellite generations must also be designed for enhanced service, which is not the case for the recently renewed constellations. In general small communication constellations are assessed to be viable client satellites with a market prospective to evolve from limited to enhanced on-orbit service including future augmentation to upgrade the satellites for new applications and technologies.

The MEO region is predominantly utilized by GNSS. The number of distribution of MEO client satellites is comparable to small communication constellation in LEO. Galileo satellites for example are distributed over 3 planes of the same inclination with 10 satellites in each plane. In general MEO constellations are assessed to be viable client satellites with a market prospective to evolve from limited to enhanced on-orbit service including future augmentation to upgrade the satellites for new applications and technologies.

The GEO markets holds still the largest share of the commercial space market producing about 50% of the revenue expected over the decade. The market for GEO satellites itself is however widely reported stagnating or even declining. Annual orders have decreased from over 25 satellites down to 10 to 15 satellites in the last years. This trend is expected to continue in the coming years. Considering the average duration from order to launch is between 3 to 4 years, it is estimated that until 2030 approximately 130 new civilian satellites are launched to GEO, in comparison to 230 satellites from 2010 to 2020. The decrease in orders is attributed in part to the uncertainties arising from the implementation of the LEO mega constellations. In addition, telecommunication service providers have already completed their fleets to full coverage in the past years. Therefore new satellites will only replace retired satellites or extend the service capabilities. Other satellites types as meteorology and navigation satellites present

only a small part of GEO satellites and due to their purpose are also not expected to increase significantly in the coming decades. Nevertheless, the GEO space has one of the most valuable regions in Earth orbit, the geostationary ring and is therefore a promising location for a range on-orbit services. Overview On-Orbit Services

A preliminary service tree was established differentiating planned and unplanned services. Unplanned services respond to failures either of the satellites itself or of the upper stage leaving the satellite stranded in a useable orbit. Considering that only one or two failures occur overall per year and not all are in fact remediable, unplanned services are not perceived as the core activity of on-orbit servicing. In addition, only failed spacecraft within the reach of the established OOS infrastructure can be responded to otherwise costly dedicated missions are required.

Planned services are perceived as the core activity of on-orbit servicing and drive the OOS infrastructure and functionalities. Planned services are performed according to predetermined schedules and service intervals. On top-level six service categories are identified:

- Refurbishment
- Manufacturing
- Orbit Correction
- Decommissioning
- Augmentation (Growth)
- Recycling

Top level service are either divided into subservices or directly further detailed into a sequence of tasks and subtasks comprised in the service. Fabrication and assembly, for example, are subservices of manufacturing. Refurbishment is directly detailed into a sequence of tasks to be performed in order to refurbish a satellite unit, e.g. capturing, disassembly, unit exchange etc. Different services can also be part of a larger service chain as indicated by the flow jumps icons in the service tree.

The services, subservices and task in are colour-coded according to their expected feasibility timeframe. Green represents near term while blue represent medium and grey represents far term feasibility. As depicted in Figure 2–3, some subservices or task are feasible in the near-term future whereas the upper-level service is not, see for example, fabrication. Extrusion is a fabrication method feasible in-orbit in the near term future. The other fabrication methods and tasks are only feasible in the far term, therefore the full upper level service fabrication is also only feasible in the far term future and hence coded grey.

The colour-code of the service tree also visualized the possible evolution of the OOS infrastructure over time. The initial on-orbits services for instance include assembly of structures and/or assisted deorbits, in a second step refurbishment and augmentation activities are added and extended afterwards. As new technologies become available the OOS infrastructure is gradually enhanced and expanded until the full service catalogue is offered to customers.

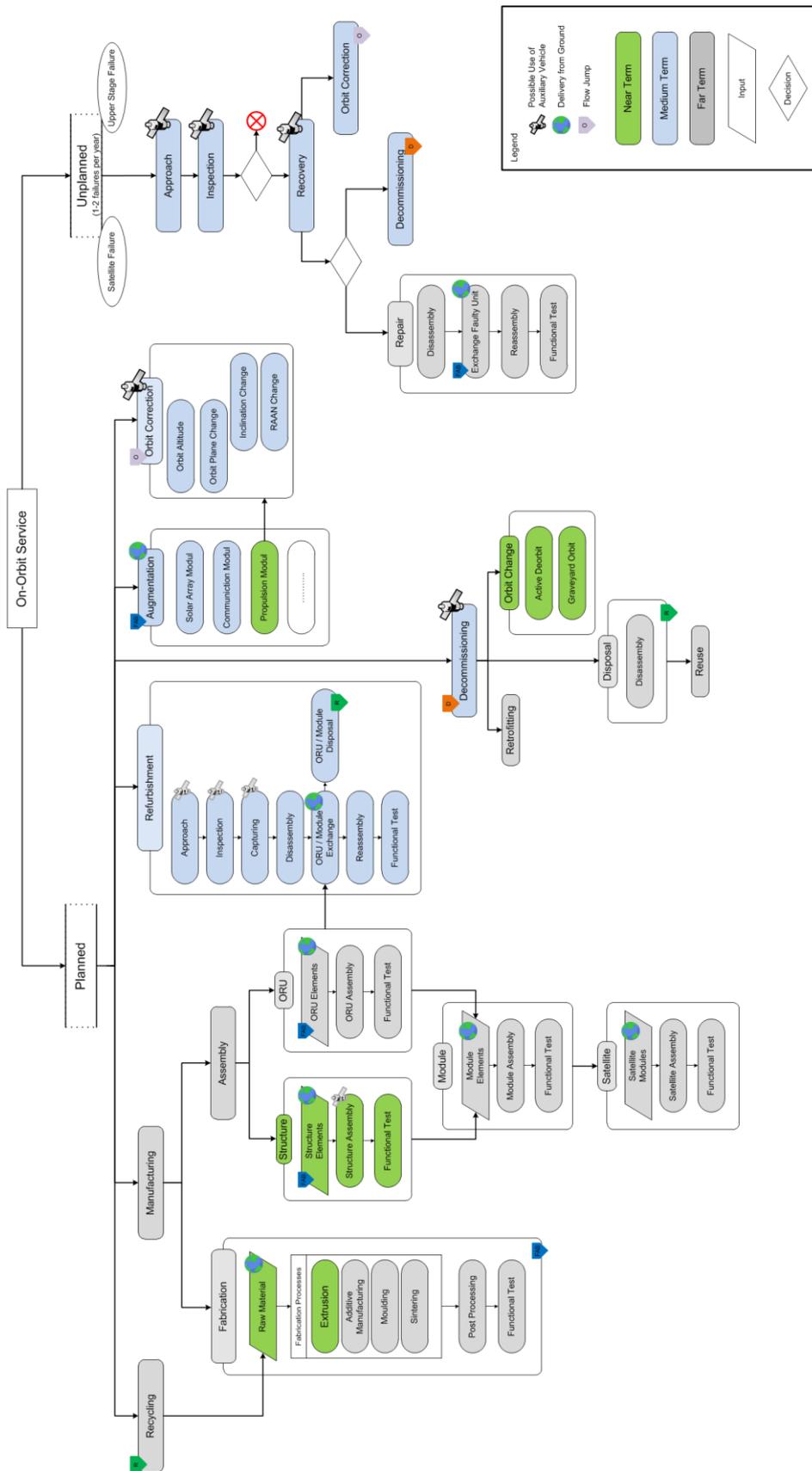


Figure 2-3: Preliminary On-Orbit Service Tree

3 MISSION SCENARIOS

It is evident that the orbital region is a driving strategical factor for the servicing station. As became clear, especially Earth observation and telecom satellites in LEO are very feasible clients. As was clear, these were primarily large or very large cluster of satellites. Considering the market, it would both be interesting to refurbishing existing satellites, or completely manufacture and assemble satellites from scratch. Based on this, the following four LEO scenarios can be identified:

- LEO1: Large telecom constellation refurbishment
- LEO2: Medium-sized telecom constellation refurbishment
- LEO3: Large telecom constellation manufacturing and assembly
- LEO4: Medium-sized telecom constellation manufacturing and assembly

Furthermore, in the literature review it was discussed how particularly the SSO orbit regime is an interesting one, considering the many satellites. Indeed it would be particularly interesting to either refurbish satellites or manufacture parts for satellites. Alternatively, these two options could be combined to a station that completely manufactures and assembles spacecraft from scratch. Therefore, the following SSO scenarios have been identified. Note that the LEO identifier is used as opposed to SSO, since these scenarios fall under the LEO orbital regime.

- LEO5: Refurbishment facility in dawn-dusk SSO
- LEO6: Additive manufacturing plant in dawn-dusk SSO
- LEO7: Satellite manufacturing and assembly plant in dawn-dusk SSO

Finally, considering the very current topic of minimizing space debris, it would be a very interesting feature to be able to provide controlled re-entry capabilities to satellites by means of a de-orbit kit. Therefore, an additional scenario has been identified:

- LEO8: Provide in-flight upgrade of SSO satellite platforms, to make them compatible with controlled re-entry by means of a de-orbit kit at EOL

Another orbit that is currently interesting for servicing missions, as was clear from the literature study, is GEO. In particular, servicing expensive telecom satellites in this orbital regime. Similarly to LEO5 and LEO7, it would be interesting to provide the same services, however in GEO. Furthermore, as mentioned earlier recycling is not the focus of this study, however identifying a scenario that includes this service is useful for understanding the trade-space. Due to GEO satellites sharing many aspects among each other, it seems feasible to provide a recycling facility in the GEO regime. Therefore, the following three GEO scenarios have been identified:

- GEO1: Recycling station near GEO graveyard
- GEO2: Refurbishing facility near GEO
- GEO3: Satellite manufacturing and assembly plant in GEO

While less populated, it has been identified that MEO would also be an interesting orbital regime. The availability of a servicing station in this orbital region could be favourable for many GNSS constellations. Therefore the following scenario has been identified:

- MEO1: GNSS constellation refurbishment or upgrade

In order to perform a preliminary down-selection of the scenarios, they need to be traded-off against each other on the basis of applicability, feasibility and added value. The number of

scenarios proposed for further investigation in the study has been reduced to five. The scenario selection is shown in Figure 3–1.

LEO8 and GEO1 have been identified as unique scenarios that have only little similarities with the other scenarios at least with respect to the considered aspects (OOS orbit, type of service, timeframe and level of preparation/ cooperation). Therefore, the scenarios LEO8 and GEO1 have been selected for further investigations.

GEO2 and MEO1 differ only regarding the orbit. However, due to the inclusion of scenario GEO1, the geostationary orbit is already part of the scenario space that is going to be investigated further in this study. Therefore, scenario MEO1 has been selected also for further investigation instead of GEO2. Thereby, also one scenario including the medium earth orbit is part of further investigations.

The scenarios LEO2 and LEO5 as well as LEO4 and LEO7 are also very similar although differing regarding the orbit conditions (inclination, RAAN) and the client satellites` missions. To include both kind of orbits and all types of servicing, one scenario of LEO2 and LEO5 as well as one scenario with contrary conditions of LEO4 and LEO7 have been selected. Because of the increased effort for enabling in-orbit manufacturing compared to refurbishment, the scenario with more satellites and expected less cost per satellite has been selected for the manufacturing scenario, namely LEO4 rather than LEO7. In turn, LEO5 has been selected to include refurbishment of observation satellites in LEO.

Finally, LEO4 and GEO3 have been traded against each other. LEO4 is proposed for further investigation in the frame of this study instead of GEO3. All conditions of GEO3 are covered by other scenarios. LEO4 has been preferred compared to GEO3 due to the decreasing GEO market as explained in the literature review. Therefore, the added value of scenario LEO4 combined with the feasibility have been assumed to be preferred compared to GEO3.

For each scenario different high-level mission profiles are defined and the potential candidates traded according to selected parameters. For each mission profile candidate concept of operations are defined and the impacts on the identified mission segments are assessed. Further the main mission elements for the space and ground segment are identified and their role is defined. For each main element of the space segment a functional analysis is performed at system level and identified function are allocated to the elements on a high-level. The interfaces and boundaries between the functions and elements are identified. The preliminary system architecture for each main element is established and the operational interfaces identified. In conclusion three mission scenarios were down-selected for further investigation based on their domains of application and range of use cases. These scenarios are:

- Medium-sized telecom constellation manufacturing and assembly (LEO4)
- Refurbishment facility in dawn-dusk SSO (LEO5)
- GNSS constellation refurbishment or upgrade (MEO1)

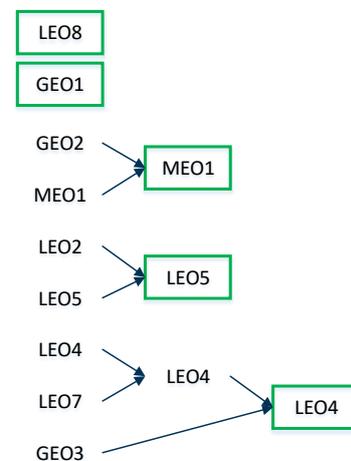


Figure 3–1: Scenario Selection

3.1 Medium-size Telecommunication Constellation Manufacture and Assembly

The mission scenario comprises an in orbit manufacturing and assembly station (IOAM station) in low Earth orbit. The IOAM station is operated to build the satellites of a medium-size telecommunication constellation. The structural parts of the satellites are fully manufactured in orbit utilizing additive manufacturing methods. The modules of the other subsystems are supplied from ground as ORUs. In orbit the ORUs are assembled to the structure to form the full satellite. The fully functional satellite is released from the IOAM station.

The IOAM station operates in a lower orbital shell as the constellation orbit in order to utilize the J2 effect. Due to the difference in altitude and/or inclination the IOAM station possesses a higher RAAN precession rate than the constellation orbit causing the IOAM station to drift from one constellation orbit planes to the next without the need for costly plane change manoeuvres. The satellites are produced during the orbit drift duration. Once the orbital planes phase the released satellites transfer to the constellation orbit by themselves via orbit elevation.

The mission profile and timeline is mainly driven by the required production time for the satellite structure using additive manufacturing methods resulting in long mission durations of 15 years if only one IOAM station is deployed. To reduce the production time and thereby the mission duration either the production capacity of the station has to be increased or the number of IOAM stations has to be increased. In both cases the required number of total launches is also increased. The details of mission profile depend on the specific study case investigated, mainly on the inclination of the telecommunication constellation orbits. In case of constellations in near-polar orbits an increase production capacity entails an IOAM station operational orbit farther away resulting in higher delta v demand of the client satellite. Therefore from the customer point of view it is preferable to increase the number of stations. The stations are equally spaced in RAAN. The resulting mission durations and number of total launches for one, two and three stations in summarized in Table 3-1.

While the general mission profile for each station is similar, the detailed timeline varies depending on the orbit illumination conditions and batch production approach. As example the mission profile and timeline for the study case 1 is depicted in Figure 3-2. During no-eclipse periods the structure for two satellites is manufactured. Afterwards the satellites are assembled in subsequent order. In the meantime the structural parts for the seconded are stored inside the station. The diagram in Figure 3-3 recaps the diverse operations to perform for the production of a single satellite.

Table 3-1: Comparison of Number of IOAM stations

| Number of Stations | 1 | 2 | 3 | 6 |
|--|----|-----|----|-----|
| Mission Duration, years | 15 | 7.5 | 5 | 2.5 |
| Constellation Planes covered by each Station | 6 | 3 | 2 | 1 |
| Number of Total Launches | 10 | 12 | 12 | 18 |

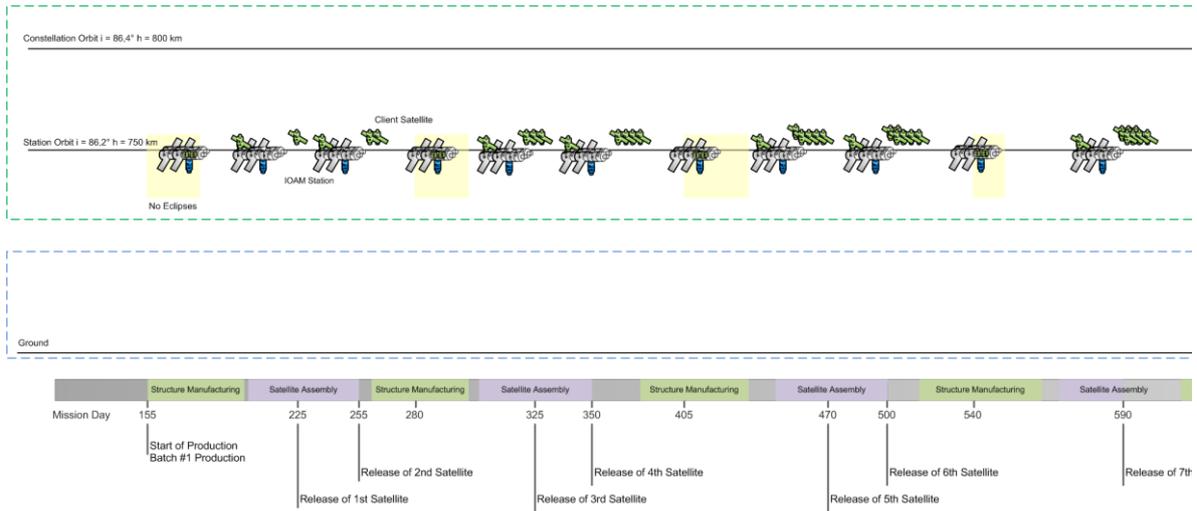


Figure 3-2: Operational Phase Mission Profile and Timeline – Case 1

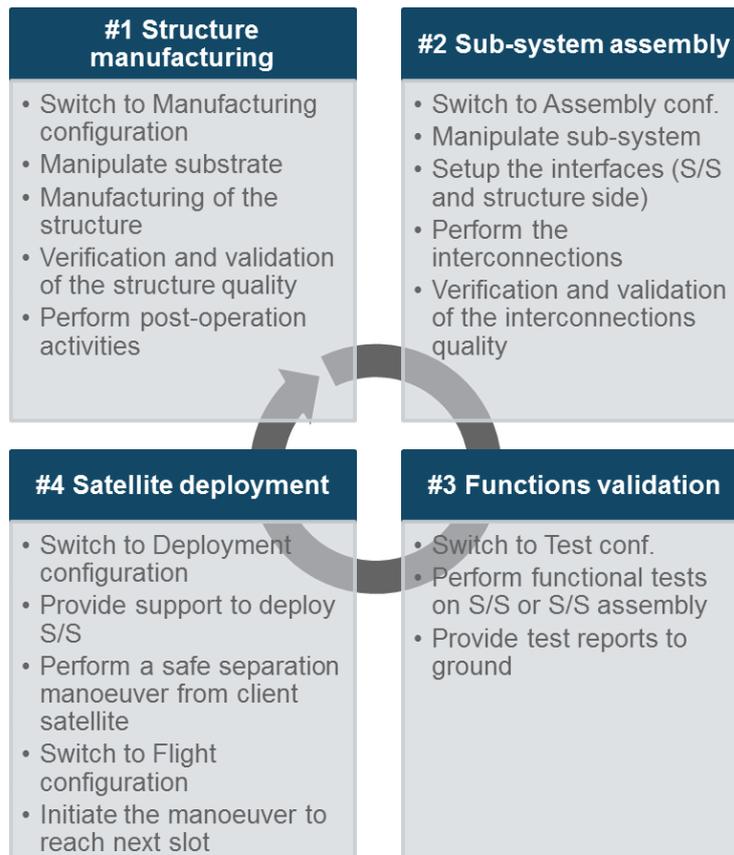


Figure 3-3: OSS operational phase sequences

The total IOAM station mass budget is presented in Table 3-2. Including 20% on system level, the total wet mass with all margin has been estimated with 12170 kg. For the operational phase, also the attached resupply vehicle has to be respected (expect of the propellant mass

of the resupply vehicle that will be consumed prior to docking). The wet mass of the total stack (IOAM station with docked resupply vehicle) sums up to roughly 24 t.

Table 3-2: LEO4 IOAM station mass budget

| Module | Mass [kg] |
|---|--------------|
| Service module | 2000 |
| Manufacturing module | 3175 |
| Assembly module | 1800 |
| Release module | 1500 |
| System dry mass without margin | 8475 |
| System dry mass with margin (20 %) | 10170 |
| System wet mass with all margin | 12170 |

Due to the time consuming structure manufacturing and the limited production capacity of the IOAM station the production time for the constellation is considerably longer than for conventional on-ground production. Even though the production time can be reduced by employ more than one IOAM station the number of required launches for the total mission exceeds the number of launches required for conventional on-ground production. Relatively long build time is mainly driven by the additive manufacturing step, resulting in the:

- need to improve existing additive manufacturing capabilities
- need to consider different type of structures and/or materials
- need to also ship equipped structure from the ground

As added value in-orbit manufacturing and assembly should be factored against:

- Reduction of the size of clean rooms and test facilities on the ground which will mean also a reduction in the carbon footprint of the space sector
- Reduction in the number of people required to build the constellation depending on the automation level
- Ability to assemble satellites in space would open new types of applications by ending existing limitations due to available fairing volume
- Promote design modularity which would facilitate heritage and enable in-flight upgrades
- Reduction of engineering man.hours thanks to overall design simplification

3.2 Refurbishment Facility in Dawn-Dusk SSO

The mission scenario involves the refurbishment of earth observation satellites in sun-synchronous orbits (SSO). A in orbit refurbishment station (IOR station) is used to provide the refurbishment services to the client satellites. The satellites parts that are replaced during the refurbishment are provided from ground as ORUs with resupply vehicles. In addition the satellites are also refuelled. The refurbishment services aim to enhance the mission life time of the client satellites and also possibly to repurpose the satellite with a new payloads, e.g. instruments. Further the scenario also involves unplanned on-call services that respond to satellite failures. The orbital planes of 10 to 15 satellites in SSO orbit tend to stay close together and form clusters. The orbital plane of IOR station is located in the individual cluster and it

moves from one satellite to the other using a combination of minor plane change manoeuvres and drift orbits. During the drift the station utilizes the J2 effect to save propellant.

The mission profile and timeline is mainly driven by the required transfer durations and delta v of the IOR station to reach the satellites that are scheduled for refurbishment. Therefore the at least one resupply launch for propellant is required for the IOR station operation. In case the IOR station is used in more than one cluster an additional launch is required to provide the propellant for the transfer. The total number of launches per cluster is summarized in Table 3-3.

Table 3-3: Number of Launches per Cluster

| | Number of Launches |
|---------------------------------|--------------------|
| Commission Phase | |
| IOR Station Assembly | 1 |
| Resupply (Materials) | 1 |
| Operational Phase | |
| Resupply (Propellant) | 1 |
| Transfer Phase | |
| Resupply (Propellant) | 1 |
| Disposal Phase | |
| Resupply (Propellant) | 1 |
| Number of Total Launches | 5 |

While the general mission profile for each cluster is similar, the detailed timeline varies depending on number of client satellites. As example the mission profile and timeline for the reference cluster is depicted in Figure 3-4. The total mission duration per cluster is expected to be about 2 years. The optimization of delta v and transfer duration needs to be tailored to each specific cluster serviced. Therefore the mission duration for other clusters may be shorter or longer, expected to range from 1 to 5 years mainly depending on the distribution of the client satellites orbits.

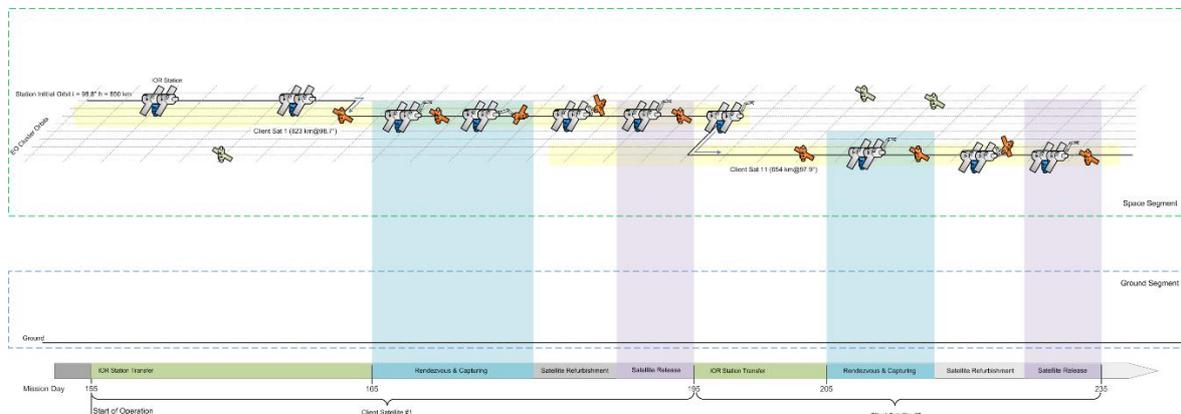


Figure 3-4: Operational Phase Mission Profile and Timeline

Once the IOR has performed the manoeuvre to reach a client satellite, the capture operation is executed by the IOR means. Once the IOR is correctly fixed to the client satellite, the refurbishment operations shall start, according to the CONOPS in Figure 3–5.



Figure 3–5: LEO5 IOR operations on client satellite CONOPS

Accounting for all modules as well as 20% system margin, the resulting mass budget of the IOR station is presented in Table 3-4 for different propellant demands. For deriving the wet mass of the total stack, the total mass of the resupply vehicle has to be added to the wet mass of the IOR station again, which is presented in last row in Table 3-4.

Table 3-4: LEO5 IOR station mass budget

| Module | Case: | Mass [kg] | | | | |
|---|-------|--------------|--------------|--------------|--------------|--------------|
| | | 1 | 2 | 3 | 4 | 5 |
| Service module | | 2000 | 1800 | 1400 | 1500 | 1300 |
| Propellant mass | | 4680 | 4240 | 3350 | 3500 | 2970 |
| Docking and Release module | | 1500 | 1500 | 1500 | 1500 | 1500 |
| Refurbishment module | | 1500 | 1500 | 1500 | 1500 | 1500 |
| System dry mass without margin | | 5000 | 4800 | 4400 | 4500 | 4300 |
| System dry mass with margin (20 %) | | 6000 | 5760 | 5280 | 5400 | 5160 |
| System wet mass with all margin | | 10680 | 10000 | 8900 | 8630 | 8130 |
| Total stack wet mass | | 16800 | 16120 | 15020 | 14750 | 14250 |

Comparing the number of launches required to refurbish the satellites with one cluster to the number of launches required to replace the all satellites at the end of its life the refurbishment seems more beneficial. As the satellites are not part of a constellation they are usually launched individually resulting in higher number of launches to replace every satellite. Viability will be mainly driven by the cost of the auxiliary vehicle and station compared to the value offered to the 12-15 clients. In particular, the size of the cluster (number of satellites and distance between the different satellites) shall be carefully tuned as the delta v requirement, size of the station and mass of ORUs are driven by this choice. In particular, a smaller cluster size or cluster with less distant satellites could also facilitate this scenario, e.g one servicing station for (Copernicus) radar missions and one servicing station for (Copernicus) optical missions. Furthermore, cost of the IOR assets depends on different factors:

- Complexity of the RDV and docking with the client → Need the clients to be equipped with a standard capture I/F and navigation markers
- Complexity to unmount/mount new equipment → Need standard ORU mechanical and electrical I/F definition with lowest possible number of connectors
- Number of launches / launcher performance

The value offered to the clients will depend on the mass of refurbishment ORUs that can be hosted in the station internal warehouse and the number of clients that can be serviced by a single station. Trade-offs to be conducted in future project phases should therefore focus on

the cluster size and the benefits of electrical propulsion to maximize the mass that can be allocated to the ORU payloads.

3.3 GNSS Constellation Refurbishment / Upgrade

The mission scenario involves the refurbishment of GNSS satellites in MEO. A in orbit refurbishment station (IOR station) is used to provide the refurbishment services to the client satellites. The satellites parts that are replaced during the refurbishment are provided from ground as ORUs with resupply vehicles. In addition the satellites are also refuelled. The refurbishment services aim to enhance the mission life time of the client satellites. During the refurbishment spare satellites temporarily replace satellite in order to ensure the uninterrupted operation of the constellation. Further the scenario also involves unplanned on-call services that respond to satellite failures.

The mission profile and timeline is mainly driven by the required transfer durations and delta v of the IOR station to reach the satellites that are scheduled for refurbishment. In addition the low launcher payload mass is also a driving aspect. Only if the refurbishment mass is limited to the refurbishment of the atomic clocks and refuelling of the satellites, a “one shot” strategy is feasible and no resupply launches are required during the operational phase. In this case six launches are required to refurbish the entire constellation of 30 client satellite as summarized in Table 3-5.

Table 3-5: Total Number of Launches

| | |
|---------------------------------|----------|
| Number of Stations | 3 |
| Commission Phase | |
| IOR Station Assembly | 3 |
| Resupply (Materials) | 3 |
| Number of Total Launches | 6 |

The mission profile depicted in Figure 3-6 applies to each IOR station. The total mission duration is expected to be about 3 years.

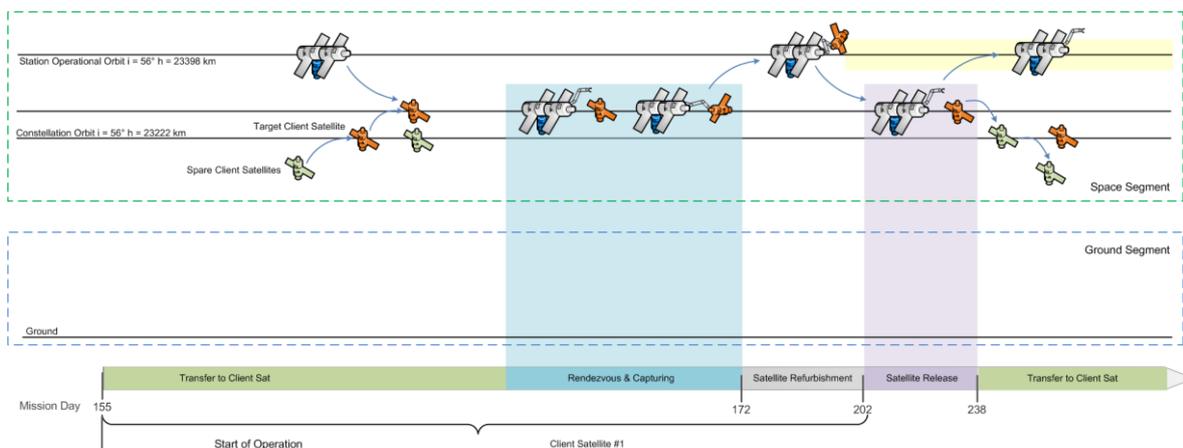


Figure 3-6: Operational Phase Mission Profile and Timeline

The IOR stations captures client satellite, whereas the client satellites provide a mechanical ‘anchor’ that will be the mechanical interface between the client satellite and the IOR during the refurbishment operations. Further visual markers are provided by the satellite in order to support the pre-capture phase. Once the IOR is correctly attached to the client satellite, the following operations shall happen:



Figure 3-7: Focus on the refurbishment operations for MEO1

The total mass budget of the IOR station is presented in Table 3-6 for three cases of propellant. It is expected that case 3 could be within the Ariane 64 performance for injection into MEO (expected launcher performance 3 – 4 t). In turn, this would allow 55 – 60 m/s delta-v per client satellite. Given the resupply vehicle with a current total mass of 2900 kg, some propellant mass could also be delivered by the supply vehicle resulting in a potential IOR launch mass reduction. Depending on the final launcher performance, this could also result in the feasibility of case 1 or 2 allowing faster transfer to the next client satellite due to an increased delta-v performance.

Table 3-6: MEO1 IOR station mass budget

| Module | Case: | Mass [kg] | | |
|---|-------|-------------|-------------|-------------|
| | | 1 | 2 | 3 |
| Service module | | 1014 | 700 | 460 |
| Propellant mass | | 2367 | 1632 | 1075 |
| Docking and Release module | | 600 | 600 | 600 |
| Refurbishment module | | 1500 | 1500 | 1500 |
| System dry mass without margin | | 3114 | 2800 | 2560 |
| System dry mass with margin (20 %) | | 3737 | 3360 | 3072 |
| System wet mass with all margin | | 6104 | 4992 | 4147 |
| Total stack wet mass | | 9004 | 7892 | 7047 |

Comparing the number of launches required to refurbish the GNSS constellation to the number of launches required to replace the entire constellation at the end of its life the refurbishment seems more beneficial as shown in Table 3-7.

Table 3-7: Comparison IOR vs From Ground Replacement

| | Refurbishment | Replacement |
|--|---------------|-------------|
| Number of Launches* | 6 | 9** |
| Duration, years | 3 | 2 - 3 |
| * based on Ariane 64; ** max 4 Satellites per launch | | |

Like scenario LEO5, viability will be mainly driven by the cost of the auxiliary vehicle and station compared to the value offered to the clients. The value offered to the clients is linked with the refurbishment ORUs while the cost of the IOR assets will depend on different factors

- Complexity of the RDV and docking with the client → Need the clients to be equipped with a standard capture I/F and navigation markers
- Complexity to unmount/mount new equipment → Need standard ORU mechanical and electrical I/F definition with lowest possible number of connectors
- Number of launches / Launcher performance

The value offered to the clients will depend on the mass of refurbishment ORUs that can be hosted in the station internal warehouse and the number of clients that can be serviced by a single station. Unlike LEO5, the client base is more clearly defined and limited delta v for this scenario should allow a relatively smaller mass of the IOR assets.

4 CONCLUSIONS AND OUTLOOK

The main objective of the OMAR mission architecture study was to identify viable mission architectures which are capable to provide in-orbit services. In the course of the study various mission scenarios in LEO, MEO and GEO were identified and investigated. From these mission scenarios three deemed most viable and versatile in terms of use cases were selected for more detailed analysis in order to establish comprehensive mission architectures and assess the feasibility of technical and economic aspects. For the three selected mission scenarios, LEO4, LEO5 and MEO1, the general feasibility from a mission architecture point of view was demonstrated in the study provided several critical technological gaps are closed in the near and medium term future. The mission architectures established for the three detailed investigated scenarios can also be applied with a few modifications in other scenarios identified, for example the refurbishment of GEO satellites.

The LEO4 mission scenario involves the manufacturing and assembly of telecommunication satellites in low Earth orbit. The analysis of the scenario demonstrated the utilization of the J2 effect to access different constellation planes with one IOAM station without the need of costly RAAN plane change manoeuvres. This approach proved viable for constellation with near-polar inclinations planes as well as with mid-latitude inclinations planes. The inclination of the constellation planes entails different advantages and drawbacks for the LEO4 mission architectures. Mid-latitude inclinations yield higher launcher payload performances (from CSG) and lower delta v demand for the client satellite transfer to the constellation orbit. While the near-polar inclinations provide more favourable illumination conditions and therefore power generation conditions for energy intensive manufacturing processes. There are future markets for telecommunication constellation in both inclination region. Constellations in near-polar inclinations provide better ground coverage of remote regions and are used by emergency responses activities. Therefore constellations deployed in near-polar orbits might prove to be a steadier client base with higher value satellites.

The detailed analysis of the LEO4 scenario also revealed major obstacles in regard to the economic competitiveness of in orbit manufacturing. Due to limitations of feasible production capacities of IOAM stations the production times are longer than for conventional on-ground production. The LEO4 scenario is based on additive layer manufacturing for the entire satellite structure proving to be time consuming methods with the current state of the art processes. To achieve the competitiveness of full satellite manufacturing in orbit the production time have to be significantly reduced, various technology gaps have to be overcome and alternative methods taken into account. Therefore a more competitive strategy for the near and medium future is to focus on utilization of volume saving structure launch kits that are manufactured on ground and assembled in orbit.

The LEO5 and MEO1 scenario both involve the in-orbit refurbishment of satellites, each focusing on different on orbit conditions and client types. For both scenarios viable mission architectures were established. The in-orbit refurbishment of satellites proves competitive to the replacement of the satellites from ground in the near and medium term future.

The investigation results of LEO5 scenario demonstrate the feasibility to refurbish individual earth observation satellites in different high value sun-synchronous orbits with one IOR station. This facilitates the market for in-orbit services for clients outside of satellite constellations. It provides also an option to counter space debris generation by upgrading, repurposing and increasing the lifetime of satellite already in orbit in addition to active deorbiting. The refurbishment service in sun-synchronous orbits however requires a high delta v capability of

the IOR station even though it also utilizes of the J2 effect. The satellite orbits differ slightly in inclination and considerably in altitude which the IOR station has overcome with impulsive manoeuvres summing up delta v to visit each client satellite. Nevertheless it assumed feasible based on current technology to equip the IOR station with a suitable propulsion system to achieve the required delta v.

The MEO1 scenario involves the refurbishment of GNSS constellations, with focus on replacing atomic clocks and refuelling of satellites to enhance their operational life. In this scenario one IOR station is located in every constellation plane resulting in the operation of three stations to refurbish the entire constellation. The refurbishment of GNSS constellations in MEO is constrained by the limited launcher payload performance, this is however also true for the replacement of satellites from ground. The analysis results of the MEO1 scenario indicate that life limiting units of the satellite can be refurbished requiring lower number of launches than required to replace all satellites in all three planes. As it is also very costly to return payload mass from MEO to Earth, the IOR station is also a valuable asset in failure investigation.

In course of the mission architecture study also various critical topics were revealed that are beyond the scope of the current study and require an investigation in future follow-up activities. These topics involve technical, economic and programmatic as well as legal aspects. The technical aspects aim predominantly at suitable in orbit manufacturing methods. There are numerous past, ongoing and upcoming studies on wide range of facets of manufacturing process and robotics. The results of these studies have to be evaluated in the context of in-orbit servicing to identify suitable methods for individual satellite components and tackle critical technology gaps. Another critical topic concerns the handling of electrostatic discharge especially in the MEO region. It has to be determined which system functions are required and how they are fulfilled to cope with electrostatic discharge, e.g. before docking operations are performed. In summary the technical and operational topics of future activities need to involve:

- Developments in in-orbit manufacturing methods and process as well as their application and use cases
- Developments in automation, robotics and artificial intelligence
- Communication strategies and requirements
- Redundancy considerations, e.g. dissimilar redundancy strategies
- Handling of electrostatic discharge issues
- Benefits of electrical propulsion
- Effects of the integration of on-call and failure response services on mission and system operation

Economic and programmatic topics of follow up studies should aim at strategies to overcome the “hen-egg” problem the in-orbit service development efforts still face and to secure investors by raising confidence level in the market. Further investigations are needed to establish roadmaps for the evolution of the in-orbit infrastructure leading to the breakeven point where in-orbit servicing inherently become more economical than conventional on ground production. Legal topics involve for example the need for new legal and regulatory requirements, as according to recent market reports, “the lack of strict regulations remains one of the biggest constraints for the in-orbit servicing market.”