Project: **End of life operations for disposal of mega-constellations**

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1 Introduction

1.1 Scope of the Document

This Executive Summary presents the results of the ESA GSP study “End of life operations for disposal of mega-constellations”.

1.2 List of acronyms

ACPL	Accepted Collision Probability Level
AOCS	Attitude & Orbit Control System
CA	Conjunction Assessment
CAM	Collision Avoidance Manoeuver
CDM	Conjunction Data Message
DoF	Degree of Freedom
DV	Delta V
EoL	End of Life
EOR	Electrical Orbit Raising
FoM	Figure of Merit
GNSS	Global Navigation Satellite System
GS	Ground Segment
GEO	Geostationary
GSO	Geo Synchronous Orbit
HW	HardWare
I/F	InterFace
ISL	Inter Satellite Link
JSpOC	Joint Space Operations Command
LEO	Low Earth Orbit
LV	Launch Vehicle
MEO	Medium Earth Orbit
MTTR	Mean Time To Repair
OD	Orbit Determination
OR	Orbit Raising
PMD	Post Mission Disposal
SK	Station Keeping
sma	Semi major axis
SW	SoftWare
TCA	Time of Closest Approach
TLE	Two Lines Elements
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking & Commanding
WP	Work Package

2 Study Objectives and Logic

2.1 Study Objectives

Recent mega-constellation concepts share critical issues w.r.t. their possible impact on the space debris environment, e.g.:

- **Large number of S/C** (significant combined mass) deployed to **high altitudes** (atmospheric decay very limited), collisions or self-induced fragmentation **will lead to long-lived debris**.
- **Mostly polar inclinations** where even under nominal conditions satellites of adjacent orbit planes might **come as close as few tens or hundreds of kilometres**.
- Large number of spacecraft, combined with **typical reliability figures → unneglectable number of S/C which fail** to reach their planned lifetime.
- **During orbit raising and orbit lowering the spacecraft traverse different orbital regimes** - in some cases a large number of satellites at a time

In order to cope with these issues new technologies as well as new manufacturing, testing, and operational procedures need to be developed.

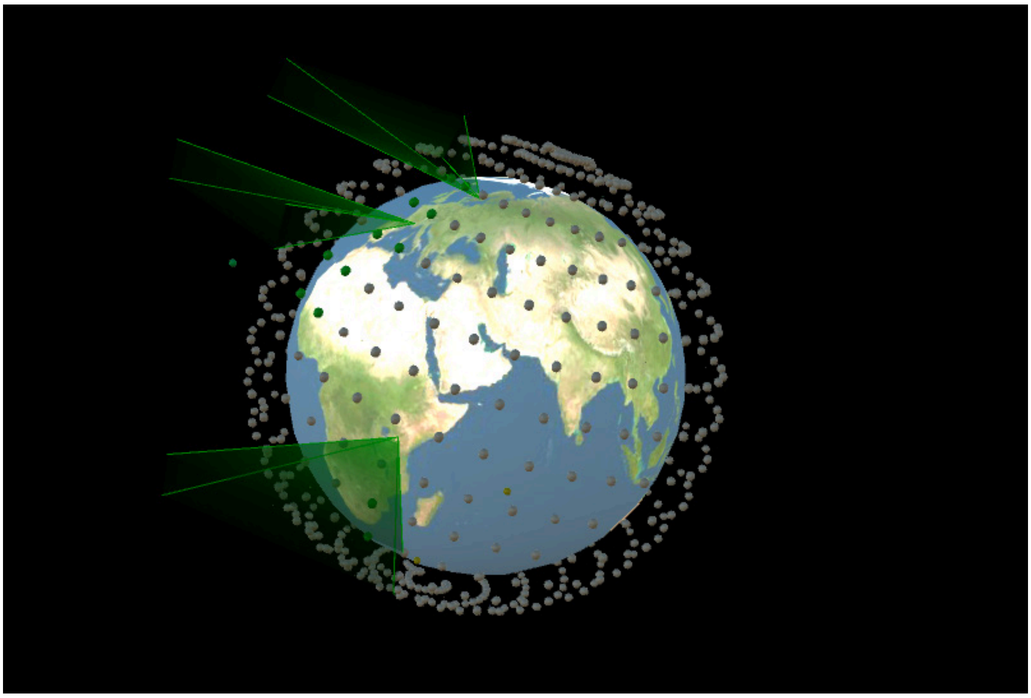

Figure 2-1: The study's baseline megaconstellation satellites and Space Surveillance and Tracking sensors.

The objective of this activity is therefore to understand the operational complexity of large mega-constellation systems, and the potential needs to operate these, including the complexity of the collision avoidance manoeuvres (CAMS).

This objective can be achieved by:

- **Assessing different EoL strategies** for mega-constellations of the size and complexity as foreseen for the future telecommunication mega-constellations.
- **Analysing the implications on space and ground segment design** to support execution of End of Life activities for each of the strategies identified (from the previous bullet) comparing the different ground and spacecraft conceptual architectures.
- **Analyse the execution of both debris and inter-satellite CAMs** during LEOP, orbit raising, routine phases and orbit lowering for mega-constellations.
- **Derive system and operational requirements on mega-constellations for End of Life activities** (EoL) and Space Debris mitigation.
- **Establish a baseline scenario for an operational concept** to handle Space Debris Mitigation for mega-constellations.

The overall study logic is shown in Figure 2-2:

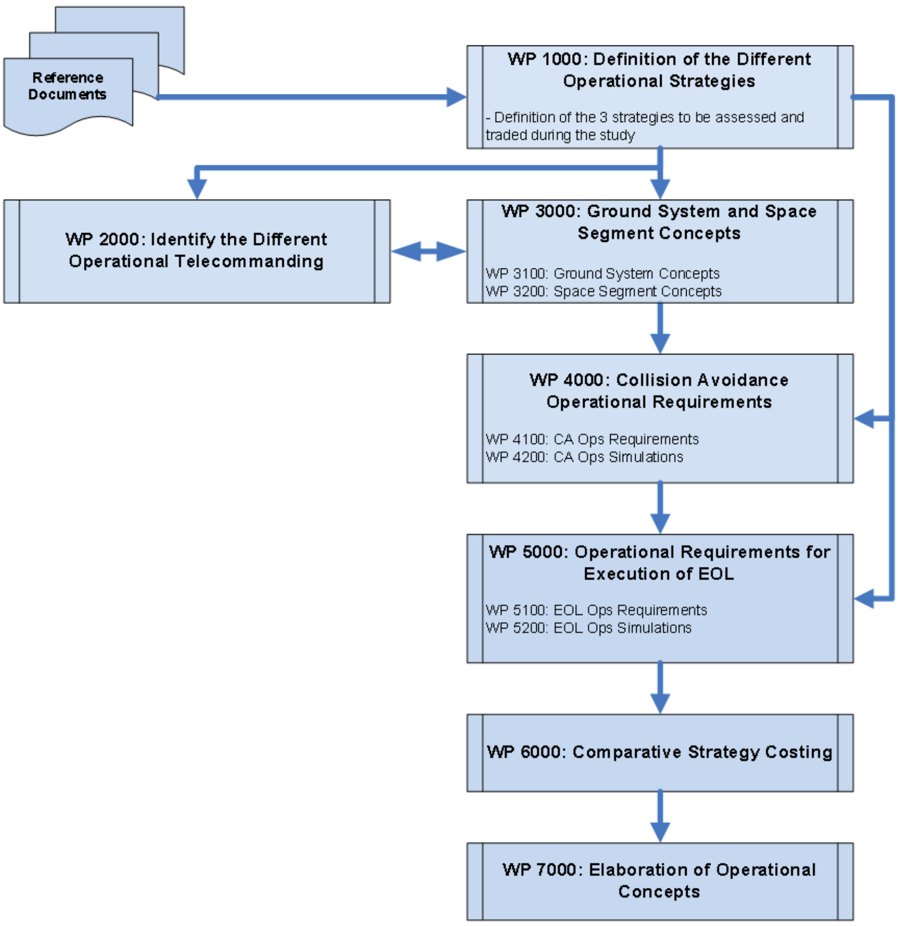

Figure 2-2: Study Logic

3 Definition of Operational Strategies

The first work package of the activity defines the reference scenarios to be assessed in the frame of the MEGACO study. The definition should be based on the exploration of the relevant degrees of freedom and the down selection of three candidate scenarios.

Following assumptions are used:

- Broadband telecom “mega” constellation
- ~1080 satellites nameplate capacity
- Operated on polar inclination @ 1100 km
- 200 kg class satellites

The different steps taken for the definition of operational strategies can be summarised as:

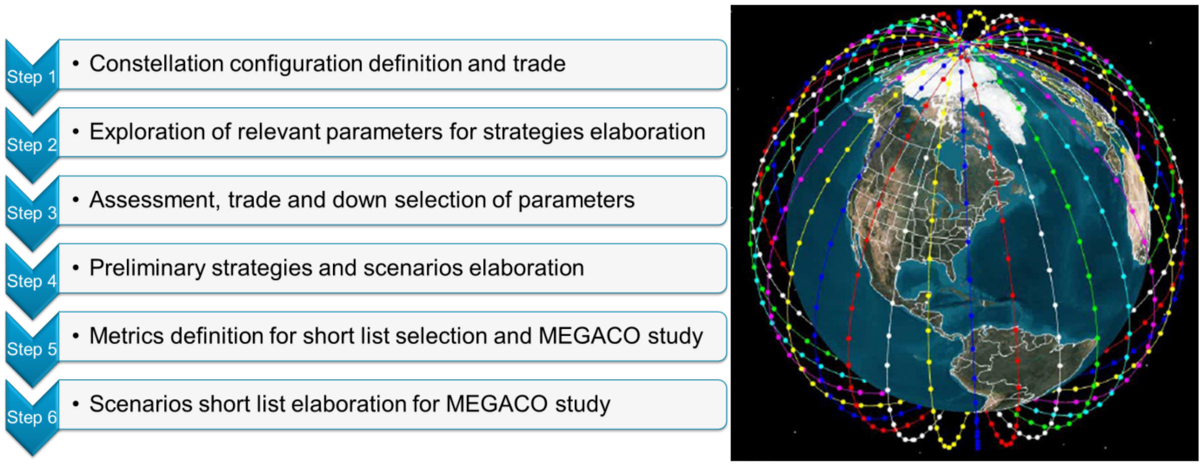

Figure 3-1: Steps taken for the definition of operational strategies.

For each operational strategy, called “scenario” in the rest of this document, the reference parameters relevant for subsequent analysis during the study are provided as output of this work package.

3.1 Step 1: Constellation configuration definition and trade

This section provides preliminary orders of magnitude and trade off elements for selection of the baseline constellation configuration. Two main options for constellation configuration trade off exist:

- Walker “star” pattern configuration
- Altitude separation configuration (a.k.a. “Teledesic” configuration)

The trade-off shows that the altitude separation option provides significant improvement of safety distances between satellites versus moderate mission impacts

As a consequence, the altitude separation option has been selected for MEGACO study.

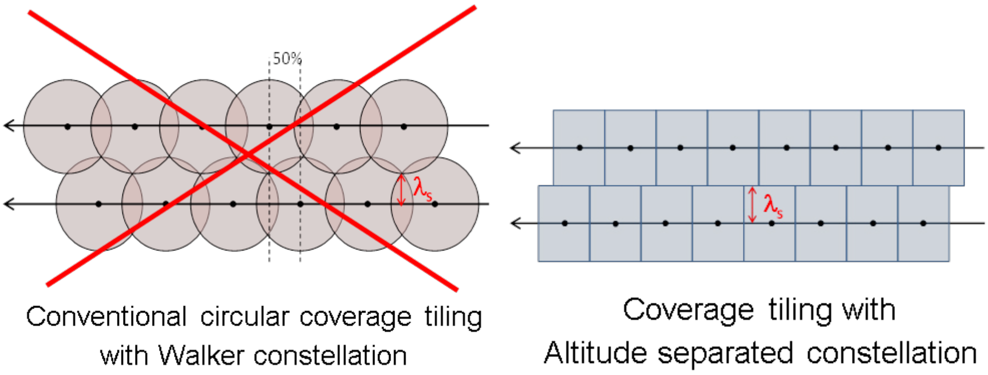

Figure 3-2: Coverage tiling for Walker and altitude separated constellations.

3.2 Steps 2 & 3: Exploration and down selection of relevant parameters

Step 2 consists in exploring in a reasonably “uncensored” manner the potential parameters (or degrees of freedom - DoF) which are relevant for the operational strategies.

Afterwards in Step 3 these parameters (or degrees of freedom - DoF) are assessed:

- Quantitative order of magnitude assessment when possible or relevant
- Pros & Cons trade off
- Identification of impacts/correlation/compatibility with other DoFs
- Discard of non-realistic/useless options

Upon step 3 completion, a reduced set of DoF is established, with links between them when relevant, so as to elaborate the preliminary strategies and scenarios during step 4.

Six domains have been explored in terms of options (degrees of freedom) for strategies definition.

1. Satellite propulsion options
   – Chemical propulsion variants
   – Electrical propulsion variants
2. Post Mission Disposal (PMD) approaches and options
   – PMD means
   – PMD orbit
   – PMD reliability
3. Constellation management possible concepts
   – Injection orbit (and transfer)
   – Population/replenishment strategy
   – PMD strategy
   – Spares management
4. Planned manoeuvers (SK, EoR, PMD) execution options
   – Layers
   – Autonomy
5. Collision Avoidance Manoeuvers concepts & options
   – Accepted Collision Probability Level (ACPL)
   – CAM trajectory
   – CAM timeline
   – CA means
   – CAM layer
   – CAM autonomy
6. System commanding architecture concepts & options
   – Inter Satellite Links
   – Ground stations coverages

Figure 3-3: The six explored domains and their options for strategies definition.

3 Definition of Operational Strategies

The respective options assessments, trades and mutual dependence analysis have been performed in a detailed way and are available in the WP1000 study report. Examples are given in the following figures.

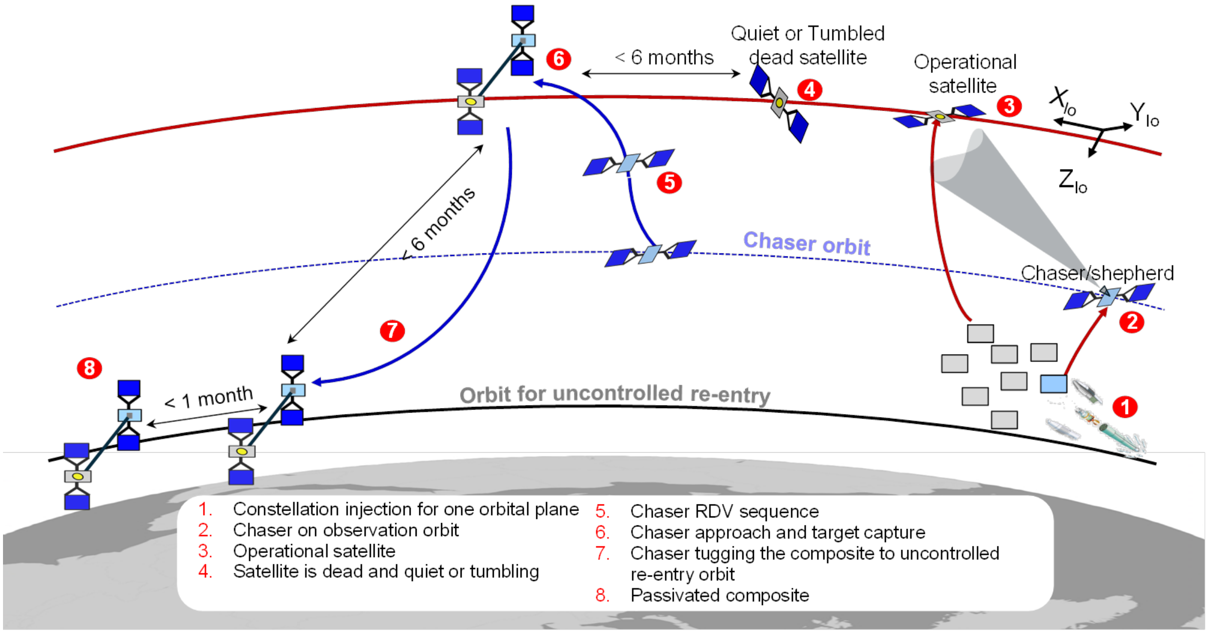

Figure 3-4: PMD means options: Zoom into “one off undertaker” option

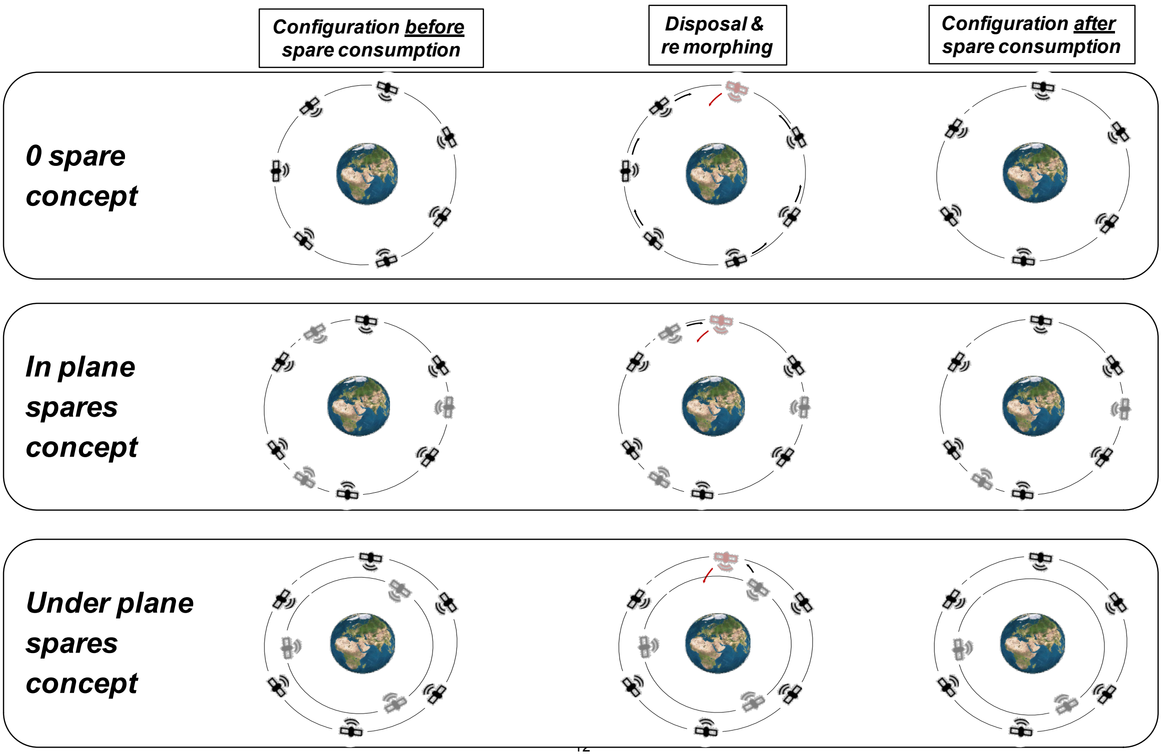

Figure 3-5: Constellation management options: Zoom on short MTTR spare options

Additionally to the explored CAM options within the MEGACO study, another interesting option could consist in embarking a small optical camera (or several) on each satellite of the constellation as an additional surveillance mean to improve resolution/accuracy of the debris catalogue crossing the constellation's orbit. Detection performance would be modest but, thanks to the mega constellation effect (1080 satellites), the proportion of monitored object could be augmented, thus reducing the collision risks and the false alarm rate.

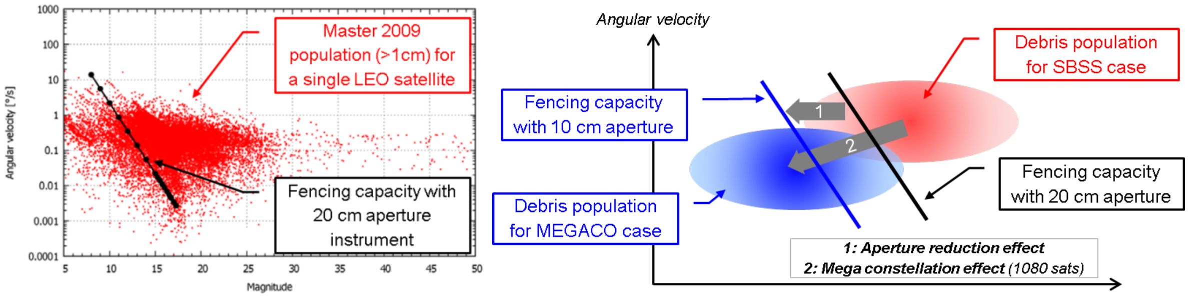

Figure 3-6: Left: Debris population surveillance capabilities for ESA SBSS Phase A study case; right: Possible debris population surveillance capabilities with small camera on each MEGACO satellite.

3.3 Step 4 – System and operator profiles

Step 4 consists in defining the candidate scenarios implementing the possible degrees of freedom (or options) identified during step 2 and preliminary assessed during step 3.

Six profiles are designed and used for candidate scenario elaboration:

- **Profile 1:**
  A high end system, operated by a major "established" telecom operator, supported by a major space agency and governmental organizations, taking full benefit of the most advanced available space technologies
- **Profile 2:**
  A low cost and low quality of service (low end), developed in a low cost of operations and access to space country, with medium to low sensitivity to space debris issues
- **Profile 3:**
  A medium to high quality of service, based on "more than proven" technologies, developed in an "easy" access to space country
- **Profile 4:**
  A very high quality of service system, also operated by an established telecom operator, developed according to a comprehensive approach for new technologies implementation on each successive satellite generation
- **Profile 5:**
  A high quality of service system developed by a powerful "new space /GAFA like " actor, implementing as much as possible advanced technologies and innovative concepts
- **Profile 6:**
  A medium quality of service system, with "medium" attributes for all dominant profile characteristics

The following table provides a summary of the candidate profiles and their criteria.

Table 3-1: Candidate profiles summary

Operator & program "profiles"	1	2	3	4	5	6
Quality of Service	Very High	Low	Medium to High	Very High	High	Medium to High
Satellites capacity & oversizing	Very High	Low	Low	Very High	Medium	Medium
Technological maturity	Very High	Very Low	Low	Very High	Very High	Medium
Techno risks aversity	Low	High	High	Progressive approach	Very Low	Medium
Cost of access to space	High	Low	Low	High	High	Medium
Cost of system operators	Very High	Very Low	Moderate	Very High	High	Medium
Sensitivity to debris matters	Very High	Low	Low	Very High	High	Moderate

The major technical decisions for each scenario and in accordance with each system/operator profile are shown in the next table:

Table 3-2: Scenarios and major technical decisions

Major features	1	2	3	4	5	6
Propulsion	Electrical with advanced options	Electrical "basic"	Chemical	Electrical with progressive options	Electrical "basic"	Electrical "basic"
Nominal Post Mission Disposal (PMD) Reliability	Very high 95%+	Medium 85%	High 90%+	Very high 95%+	High to very high 90%+	High 90%+
Accepted Collision Probability Level (ACPL)	10-4 to 10-5	10-3	10-3	10-4 to 10-5	10-4	10-3 to 10-4
Re entry orbit after PMD	Fast re-entry (0.5 yrs)	Long re-entry (25 yrs)	Fast re-entry (0.5 yrs)	Fast re-entry (0.5 yrs)	Fast re-entry (0.5 yrs)	Fast re-entry (0.5 yrs)
Injection orbit	Low altitude transfer orbit	Direct injection	Direct injection	Low altitude transfer orbit	Low altitude transfer orbit	Direct injection
Spare satellites management philosophy	0 spare (oversized) + on ground spares	In plane + under plane (close) spares	Under plane (close) spares	0 spare (oversized) + under plane (close) spares	In plane spares	In plane + under plane (close) spares
Additional PMD means	Degraded propulsion advanced modes	*Nothing*	*Nothing*	Degraded propulsion mode + space tug	Degraded propulsion mode + shepherd	De orbit kit
Conjunction Assessment (CA) means	Extra tracking + fencing facilities	CDM analysis	CDM analysis	Progressive: CDM only -> Tracking means -> Fencing means	Extra tracking facilities	CDM analysis
Autonomy	Advanced	*No autonomy*	Ground Segment automation	Progressive: GS automation -> Improved -> Advanced	Advanced	Ground Segment automation
Inter Satellite Links (ISL) & Ground Stations (GS)	Endogenous ISL + polar station	*No ISL* GateWay stations	*No ISL* polar station	Progressive: GS only -> Endogenous ISL	Endogenous ISL + polar station	GEO ISL + polar station

3.4 Step 5 – Metrics & Selection criteria

<u>**Four metrics are defined for scenarios assessment**</u>

(1) Impact of scenario on space **debris** generation
(2) Impact of scenario on telecommunication system **Quality of Service**
(3) Impact of scenario on system development and operation **costs**
(4) **Innovation** and implementation of **new technologies**

<u>**Two criteria for short list selection**</u>

(5) **Sensitivity** criteria: I.e. select the two “extreme” scenarios in terms of ranking according to the above metrics
(6) **Technology & innovation** criteria: Select the most “innovative” approach as the 3rd short listed scenario

Short list summary

Selected scenarios for further elaboration are:

- **Scenario 1: The high end system**, operated by a major "established" telecom operator, supported by a major space agency and governmental organization, taking full benefit of the most advanced available space technologies
- **Scenario 3: The system based on "more than proven" technologies** (e.g. chemical propulsion) and robust concepts, developed in an "eased" access to space environment
- **Scenario 5: The system developed by a powerful "new space /GAFA like" actor**, implementing as much as possible advanced technologies and innovative concepts

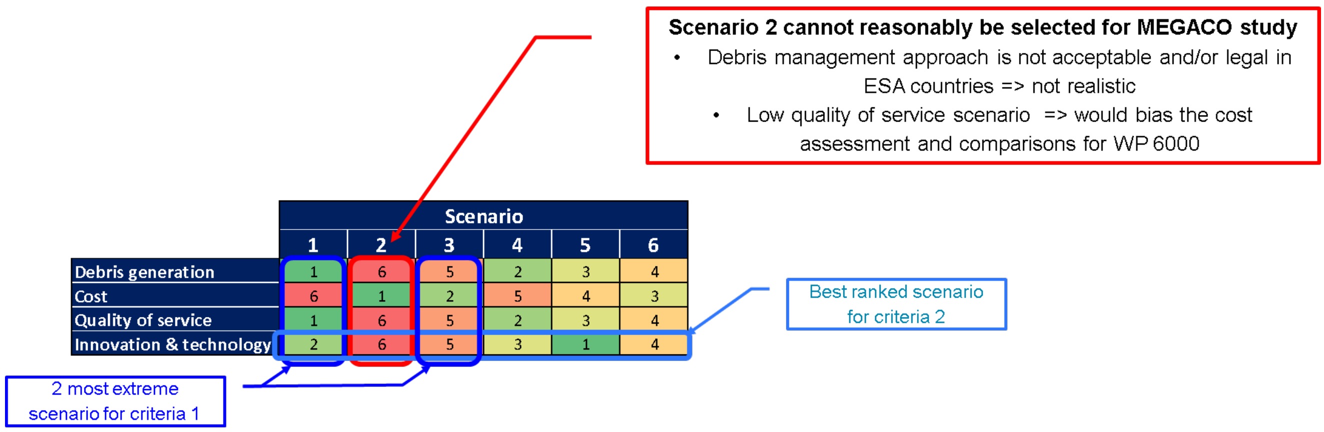

Figure 3-7: Candidate scenario ranking according to each metric.

3.5 Step 6 – Scenarios Elaboration

Detailed scenario characteristics have been elaborated and provided as part of step 6. Respective summary tables are available in the Final Report for the study.

4 Ground and Space Segment Concepts

4.1 Ground Segment

For the three scenarios selected in the previous step, the relevant ground segment concepts are elaborated.

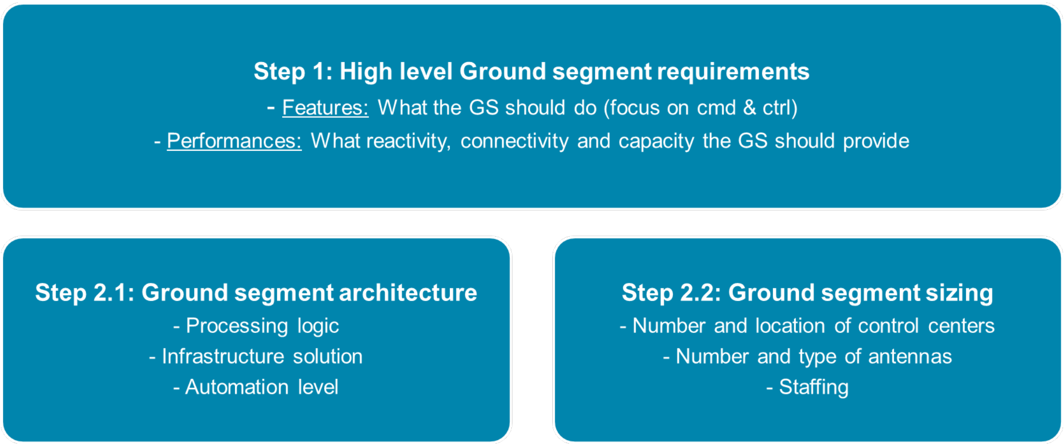

Figure 4-1: Steps taken in the definition of the ground segment concepts.

From the identified functional requirements, preliminary ground segment function architecture has been defined. This architecture splits processes between those who are expected to run permanently (constellation management) and those called on demand for a single satellite (typically, orbit control manoeuver) or for occasional constellation analysis.

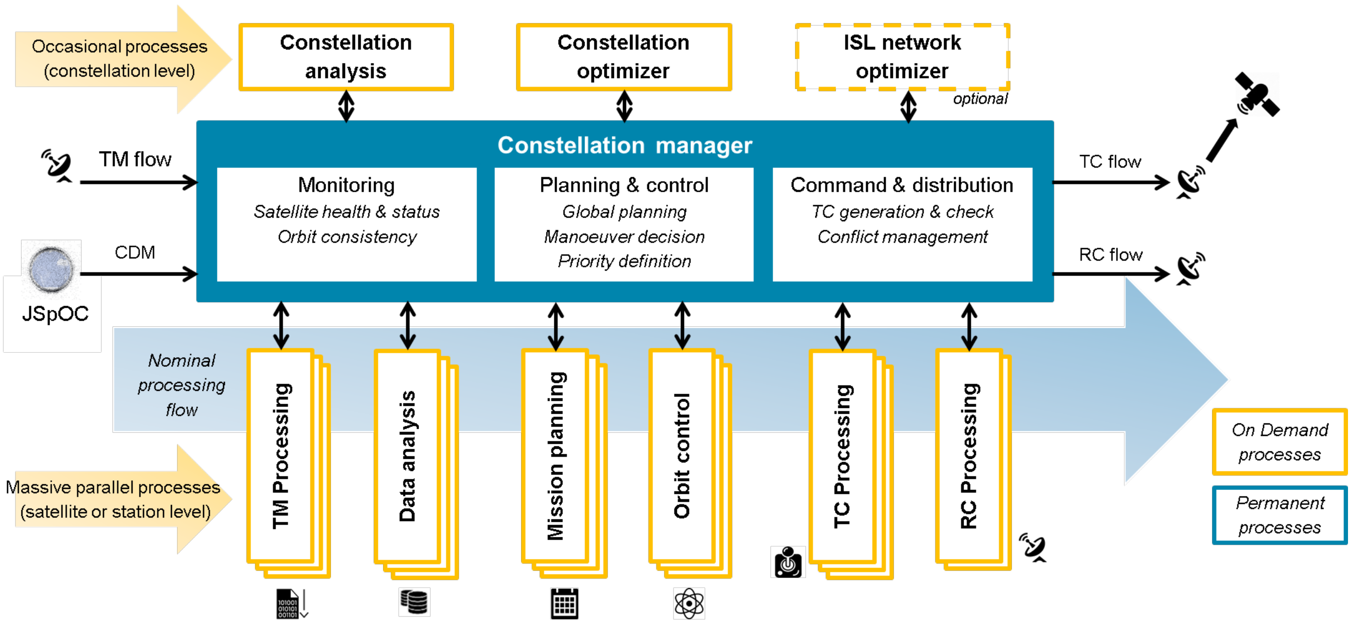

Figure 4-2: High-level ground segment function architecture.

The analysis of the ground segment concepts led to the following conclusions:

- Introducing ISL enables simpler TC distribution with less antennas during mission. However, direct links are still required during orbit transfer phases. Besides, an ISL network requires an additional management and monitoring at ground segment level.
- As expected, automation can significantly reduce the number of operators and should be seriously considered during design phase.
- Electrical propulsion leads to very long orbit transfers with more operations and a more complex management of collision risk

4.2 Space Segment

The objective of the space segment work packages is to analyse the implications on space segment design to support end-of-life activities for each of the strategies identified in WP1000, hence comparing the different spacecraft conceptual architectures.

In a nutshell the major results for the three scenarios are:

Scenario 1 (wet mass 245 kg)

- highest mass due to the strong mass increase of the power subsystem
- re-morphing of orbit + increase of P/L power to close the gap in case a satellite fails
- P/L and prop. system have to work in parallel and during eclipse

Scenario 3 (wet mass 213 kg)

- Gen. 1 between scenario 1 and 5, gen. 2 & 3 similar mass like Scen. 5
- Increase of mass due to the increase of fuel mass for chem. prop.
- S/C design might be very different to baseline due to chemical propulsion subsystem
- BUT: no PMD back-up & less satellites per launch due to high altitude injection

Scenario 5 (wet mass 203 kg)

- Low mass due to the decrease of power demand with a less demanding HET
- re-morphing of orbit + increase of P/L power to close the gap in case a satellite fails
- P/L and prop. system do not work in parallel, prop. System does not work in eclipse
- BUT: additional satellites needed as PMD back-up strategy (shepherd)

5 Collision Avoidance & End of Life Simulations

5.1 Collision Avoidance Simulation

In this chapter the influence of different cataloguing and tracking systems on the conjunction assessment process leading to collisions avoidance manoeuvres (CAMs) is determined. The three different constellation scenarios with their three phases (EOR, On Station and PMD) are analysed. Using the Radar System Simulator (RSS) software suite, developed by the Institute of Space Systems (IRAS), a generic 3rd party cataloguing service (similar to JSpOC's) and several tracking radar locations are simulated. The simulated radar measurements are processed by the orbit determination software and added to the catalogue. A conjunction assessment software predicts close approaches and based on a defined miss distance and accepted collision probability level (ACPL) creates collision warnings. The simulation approach is deterministic and based on the MASTER-2009 population for the debris particles (risk objects), that interfere with the simulated target objects (constellation satellites).

The collision analysis simulations are divided into two different parts. In the first part the "truth" is generated for the three mission phases, which gives the perfect population knowledge. The constellation satellites (target objects) are confronted with the background debris population (risk objects). The close approach analysis considers risk objects down to 4 cm in size, which are about 60.000 debris objects. From the collision approach results, which was performed with a rather big 20x50x20 km box around each target, 400 risk objects are picked randomly as a reference for the refined and more complex follow-up simulation in phase 2. In the second part the refined simulation is started, involving measurement generation and orbit determination for the risk objects to get a more realistic estimation of the orbit incl. covariance for the close approach and collision risk estimation. The close approach analysis is performed with a smaller spherical threshold. The measurement generation involves 1 or 2 tracking sensors, placed on different parts of the surface of the Earth. For the orbit determination an Unscented Kalman Filter approach is used. The results of the second simulation phase are analysis of the number of close approaches, incl. collision probability (PoC) and geometry over the simulation time of 7 days. The assumptions for the simulations are given in the following table.

Table 5-1: Assumptions for the collision avoidance simulations.

Satellite OD accuracy (rms)	Radial: 1.5m / ALT: 15 m / ACT: 15 m (GPS Sensors)
Cataloguing accuracy (rms)	Radial: 20 m / ALT: 282 m / ACT: 20 m ("JSpOC")
Catalogue update interval	1.5 days
Additional tracking sensor kind	"TIRA-kind"
Additional tracking sensor locations	Wachtberg(0), Nairobi(1), Shanghai(2), Kiruna(3)
Overall SST Resolution	10 cm or 4 cm with "Fencing" option
CAM criterion in On Station or PMD mission phase	Breach ACPL of 10^{-3}, 10^{-4} or 10^{-5} 1 day to the calculated event (based on the scenario)
CAM criterion in EOR mission phase	Threshold of radial: 2 km; Along-track 20 km
Number of Constellation Satellites	On Station: 1080 / EOR Scen. 1: 92; Scen. 5: 69 / PMD Scen. 1: 300; Scen. 5: 217

The output of simulation phase 1 shows a large number of encounters is recorded over the simulation time, up to 176 208 for the 1080 satellites in the "On Station" mission phase. These encounters happen in a large 20x50x20 km box around every constellation satellite, so that encounters re-simulated in simulation phase 2 can be found and mapped, as they are imprinted with uncertainty. Due to computational constraints 400 risk objects are selected randomly from each mission phase and scenario to be re-simulated on mission phase 2. For each day a conjunction report is generated containing a forecast of the conjunctions. Ideally the forecasts would show the results from simulation phase 1. But as this more complex simulation phase considers uncertainties in the GPS and Radar measurement as well as orbit determination, the thrusts of the electric propulsion system and the aging of the ephemerides in the catalogue the results will be degraded such that some conjunctions can be detected by the SST system but others are missing. In addition, false alarms are raised, that are not in the scope of the first simulation phase. The results show that the closer an event is the more certain is the predicted event. Based on the assumed SST system out of 118 conjunctions that are to be found (truth from simulation phase 1) only 18% - 40% are found in simulation phase 2, which means that 60% - 88% of the possible events could not be determined by the conjunction analysis tool, due to uncertainties in the ephemerides. Furthermore, 'false' conjunctions warnings are raised from objects that have bad ephemerides data. Applying the CAM criterions on these conjunctions results in a recommended collision avoidance manoeuvre. Due to the differences in the SST setups different CAM recommendations are the result. The basic catalogue (cat.) has a low resolution (10 cm) and low update frequency, which results in about 292 CAM recommendations within one year for the entire constellation. For an increased resolution of 4 cm (Cat. + Fence) 584 CAMs are forecasted. Using additional tracking means results in about 3800 to 4100 CAMs, which is comparable to output from statistical tools, like ARES as part of ESA's DRAMA tool suite. Running the EOR simulation phase 2 using the EOR CAM criterion of a threshold of a risk object approaching the constellation satellite spiraling up to the target orbit with a radial distance < 2 km; and along-track distance < 20 km results in very big number of CAMs, with a range of 79 000 - 127 000 per year. These numbers are driven by the 20x2 km threshold that has been defined for the thrusting constellation satellites in the EOR phase. The thrust uncertainty is assumed to be 3%, which means that in the conjunction forecast not the uncertainty in the risk objects (space debris) drives the high number of false alarms, but the uncertainties in the propagated constellation satellite’s state. A better cataloguing system or tracking sensor does not have a noticeable impact on the results of the EOR phase. A reduction of the ‘false’-positive close approaches maybe achieved by multiple measures:

- In the latter case decreasing the thruster uncertainties will improve on the results seen in the EOR mission phase. In turn the spherical threshold can be reduced, which results in a lower number of risk objects triggering a CAM.
- For the other mission phases ("On Station” and PMD), where the thrust uncertainty is not an issue, a decrease of the measurement uncertainty (lower measurement noise) or
- an improved processing back-end e.g. by using a MC conjunction assessment approach or a better performing orbital propagator could reduce the number of false alarms and increase conjunction event performance. The MC approach as well as the improved orbital propagation will demand more computational effort.

5.2 End of Life Simulations

In the frame of work package 5200, eight long-term projections of the space debris environment have been performed: two of these serve as reference cases, without considering a large constellation of satellites, which differ in the SSA system available to perform collision avoidance. In the six remaining scenarios, three large constellations of satellites as defined by other work packages have been superimposed to the overall space debris environment, three simulations were variations of one of these constellations. The constellations were simulated in much more detail than general payloads to be able to assess differences between the scenarios.

The results of these simulations were analysed in two regards: First, to measure the impact of the constellations on the environment and second to measure the impact on the constellations themselves.

For the environmental impact, two measures were used: a Wilcoxon Ranksum test, to assess the statistical relevance of differences between the scenarios and second an environmental criticality norm, to quantify possible differences. Using these tests, it was found that a large constellation of satellites not necessarily leads to a significant impact on the environment, in terms of increase of number of objects (after the operational time of the constellations) and cumulative number of catastrophic collisions (over the simulated time frame of 50 years). This was the case for the constellation scenario 1, and of lesser degree for constellation scenario 5. The latter one furthermore demonstrated the benefit of ADR to remove failed constellation satellites. On the other hand, it also could be shown that constellations of a generally similar layout but less reliability and more objects (compared to constellation scenario 1) can significantly increase both number of objects and especially the number of catastrophic collisions within the environment. A summary of the results is shown in Table 5-2.

Table 5-2: Summary of the environmental impact of different constellation scenarios. For an easier comparison of the impact, the criticality norms have been reduced to the interval [0, 3].

	Ranksum, #objects	Ranksum, collisions	ΣNorm, #objects	Norm. Rank	ΣNorm, collisions	Norm. Rank
Scenario 1	Insignificant impact*		1.07	0.8	0.034	0.14
Scenario 3	Significant impact		4.03	3	0.701	3
Scenario 5	Insignificant impact**		1.95	1.5	0.119	0.51
Scenario 5 (low reliability)	Significant impact		3.5	2.6	0.51	2.18
Scenario 5 (med. reliability)	Partly significant impact***		2.8	2.1	0.41	1.75
Scenario 5 (late ADR)	Partly significant impact***		2.54	1.9	0.33	1.41

* impact on the number of objects is visible during the operational lifetime of the constellation
** impact on the number of objects is visible during the operational lifetime of the constellation, and at some instances later-on during the simulation time frame
*** Impact is significant on the number of objects in the environment only.

For the impact on the constellation, three different analyses were performed: Firstly, the statistical collision rates from the long-term simulations were given and compared. Secondly, populations from the long-term simulations were post-processed to assess the expected number of collision avoidance manoeuvres for the different constellations in the future environment. Thirdly, deterministic close approach simulations were performed at different snapshots of the future space debris environment and compared against simulations performed with populations as of today. The results show that:

- A difference in the average number of expected collisions (both catastrophic and non-catastrophic) involving constellation objects between the scenarios can be observed. Lowest values were found for scenario 1, highest for scenario 5. It is important to note though that a large portion of this increase in expected collisions comes from a larger number of constellation objects in those scenarios. Therefore, to observe a clear impact on the constellations, the operational lifetimes of the constellations would be needed to be longer.
- A SSA system that is capable of completely and correctly cataloguing the 10 cm population is sufficient to avoid almost all catastrophic collisions. A SSA system with a lower detection threshold of 2 cm at 1100 km altitude mostly helps avoiding non-catastrophic collisions. The number of satellites lost due to non-catastrophic collisions is very low compared to the number of satellites lost due to general satellite reliability.
- The number of expected collision avoidance manoeuvres is very similar in the scenarios analysed, if the SSA system has the same detection threshold and identical ACPLs for the decision to perform a manoeuvre are applied. Else, a lower ACPL leads to a drastic increase of collision avoidance manoeuvres, as well as a lower detection threshold of the SSA system. If this enormous increase of effort is economical from the viewpoint of the constellation, needs to be judged by work package 6000.

- The number of close approaches increases with time. Over the operational lifetime of the constellation, this increase is mostly due to background population objects. Nevertheless, with time encounters with failed constellation objects become a major source. This is especially the case for constellations with lower reliabilities and/or post-mission disposal success rates. Failed constellation objects furthermore lead to about 5.2 more encounters than an average risk object. Nevertheless, the negative impact of failed constellation satellites only starts being important towards the end operational lifetime of the simulated constellation.

For future work, some open questions remain to be answered. First is the impact of using different ACPL on the number of collisions that actually would occur. The results presented in Chapter 5.1 show that the collision probability returned from collision avoidance algorithms not necessarily describe the situation on orbit correctly, therefore no simple estimation of this impact could be made. Secondly, the results indicate one important point regarding the intrinsic motivation of operators of large constellations to adhere to or even exceed space debris mitigation standards and guidelines. A general assumption is that a constellation with low reliabilities would threaten its own business case. As seen from the simulation results, the difference in the impacts on the constellations between the scenarios was only marginal, whereas the differences in the impact on the environment were clearly visible. For short- to medium-time frames, large-constellations could be operated without conflicting with their business case but with a strong impact on the environment. Therefore, the stated general assumption needs to be challenged and further investigated.

6 Comparative Strategy Costing

The objectives of WP 6000 are to compare the operational scenarios 1-3-5 as defined in WP1000 in terms of cost impact, and extract the most promising solution. The process started with the compilation of the analysis cost parameters generated by the preceding work packages. A custom WBS has been established and cost models constructed. The cost models were then run for the 3 scenarios, in our case for the launch, flight, ground and operations segments.

The costing was done either assuming existing cost models (for small satellites) or was build and customized for the need. External cost inputs were found to respond to the need for costing new services, when possible. Besides the fact that the design choices were inserted in various ways within the scenarios, it was found that the design elements that have the most influence on the constellation are the launch vehicle cost, the capacity for ground automation, the selection of the flight propulsion system and capacity for improving the reliability of the flight system.

The CAM strategies and PMD strategies were addressed and led to the conclusion that their complexity is driven by the type of propulsion system. The Electric Propulsion system brought challenges at various levels, and drove several cost items.

The insertion of on-board autonomy was done at a high level, and was found of interest but small relative to the overall segment or scenario cost.

The cost of advanced tracking capability was evaluated and is a major driver. However, the environmental benefits will be tangible if the cost/CAM can be reduced by a factor of 10 compared to current ground capabilities. The Fencing costs were also found of second order.

Scenario 1, with its highest reliability, and its equivalent scenario cost compared to other scenarios, may be the most desired technical solution. However, within the frame of this activity, a more realistic scenario (in terms of likelihood to happen) would be Scenario 5 for which external commercial entities have already engaged. It was thus recommended to continue with the design choices of Scenario 5 for the remainder of the study.

7 Technology Development Roadmap: Recommendations for the Selected Baseline Scenario

Shepherd Satellite

A major block for the selected scenario 5 is the shepherd satellite, offering the capability to

- Capture non-cooperative spacecraft
- Perform de-orbit of itself and the dead satellite

Needed Technologies:

- Close proximity navigation using active or passive sensors
- De-tumbling of non-cooperative spacecraft
- Capture of non-cooperative spacecraft with i.e.
    - robotic arm
    - net
    - harpoon
- Rigidization of chaser/target stack or, alternatively:
- De-orbit of tethered chaser/target stack

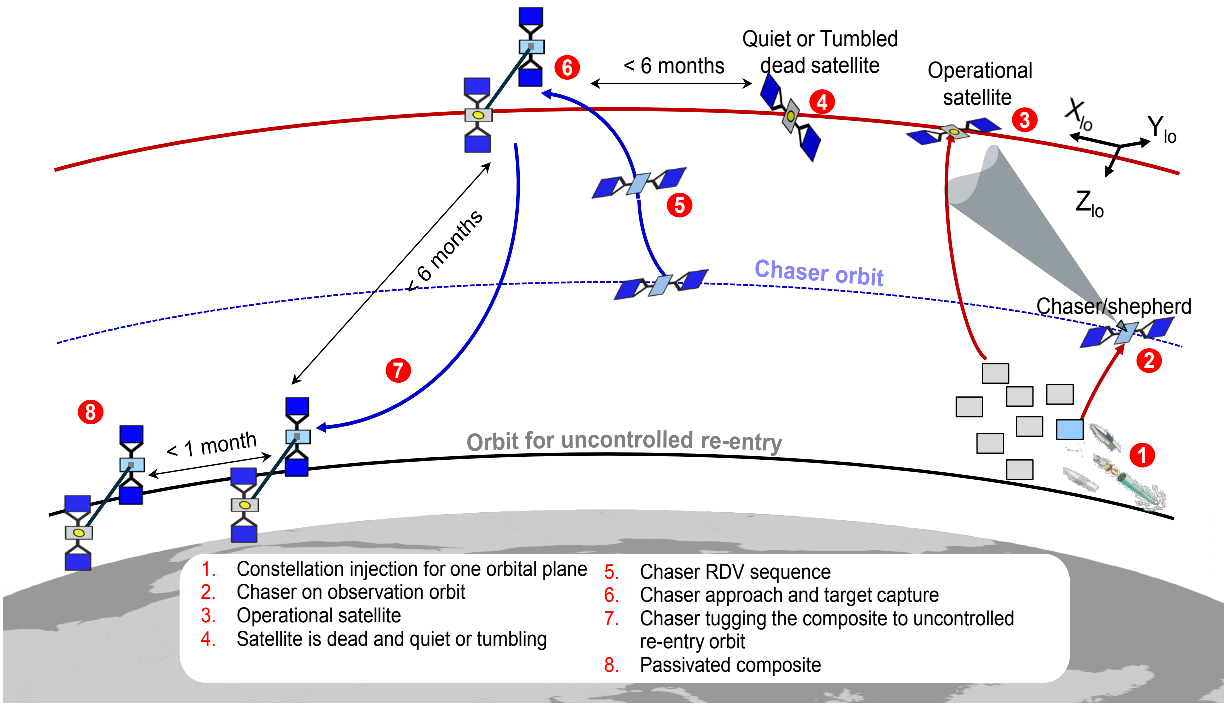

Figure 7-1: Shepherd Satellite Mission

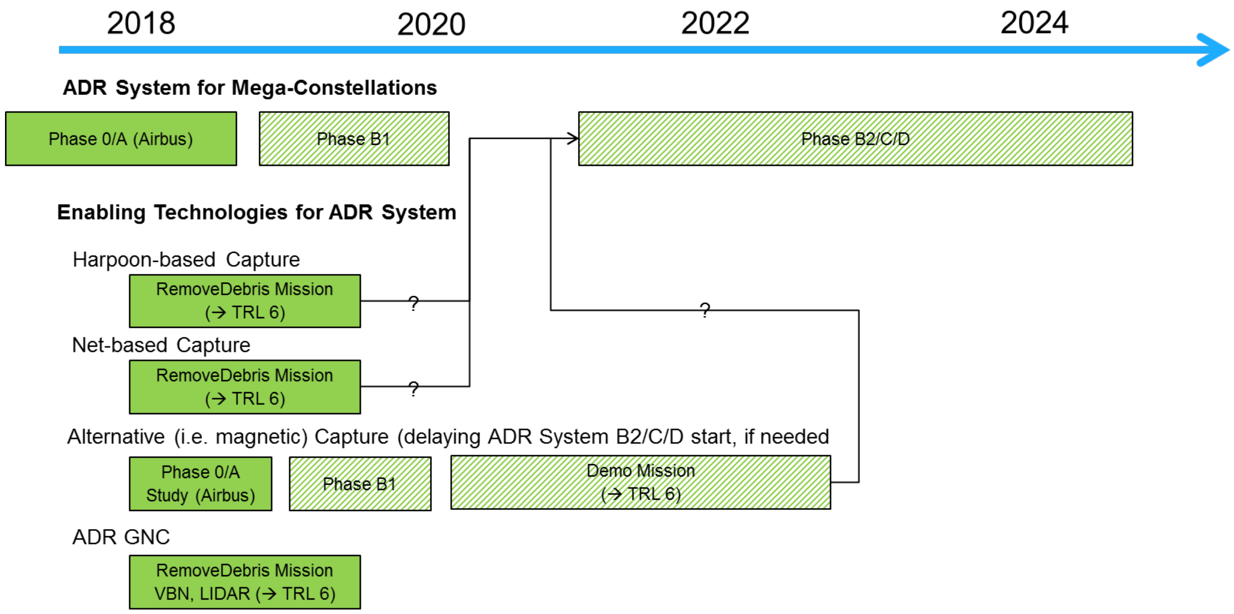

Figure 7-2: Shepherd Satellite / ADR Satellite / Constellation Cycler: Roadmap

In addition to the above mentioned capability for providing a backup post mission disposal that could be provided by a dedicated active debris removal / "Constellation Cycler" / "Shepherd" spacecraft, the following topics have been identified as necessary building blocks to on the one hand enable a closed loop trajectory control and on the other hand to provide an improved space situational awareness:

Closed Loop Trajectory Control

For the EOR and PMD phases, as well as for CAM and/or SK, a closed loop trajectory control would be an important building block:

- The basic idea is that the satellite follows a pre-defined trajectory elaborated on ground using GNSS navigator and despite propulsion dispersion (thrust module and direction). This is a similar approach as the one used i.e. for "orbit tube" maintenance of SAR satellites such as TerraSAR, Radarsat, ERS, etc.
- A possible study would essentially consist in assessing and trading the possible control algorithms options and associated performances vs GNSS (OD availability) and propulsion technology constraints
- Based on this, operational constraints (visibilities, required processing capability, ..) can be derived.

Improved Space Situational Awareness

In the course of the study, it has been shown that current and projected capabilities for providing space situational awareness with respect to object population relevant for assessing collision risks are not sufficient at all - with both the amount of undetected close encounters and also the amount of false alarms being at unacceptably high levels.

To improve the situation, it is proposed to assess in a dedicated study how a suitable SSA architecture for megaconstellations should look like. Tools and results from in preceding activities (as SBSS, for example) could enable to assess the efficiency of such systems. Such study should also involve an assessment which benefits could be provided by miniaturized optical payloads (e.g. customized star trackers) embarked on board of a large number of megaconstellation satellites. It is possible that such concept could provide an improved SSA accuracy for the constellation orbit altitude, reducing collision risk and the false alarm rates.