Feasibility of ADR for Mega-Constellations

Executive Summary Report

ESA STUDY CONTRACT REPORT		
ESA Contract No: 4000120151/17/NL/GL C/as	SUBJECT: Feasibility Study of Active Debris Mitigation for Mega Constellations	CONTRACTOR: Thales Alenia Space
NAME OF ESA STUDY MANAGER: Robin Biesbroek DIV: Directorate of Technical and Quality Management. Clean Space Section DIRECTORATE: D/TEC	ESA BUDGET HEADING: ESA´s General Studies Programme	

Approval evidence is kept within the documentation management system.

1. INTRODUCTION AND SUMMARY

The Thales Alenia Space study team have completed a 13 month contract to study the feasibility of Active Debris Removal within Mega-Constellations. Within the Clean Space initiative, ESA searches for pro-active answers to the environmental challenges which are faced both on Earth and in Space. IADC has already highlighted the important topic of mega constellations, which represent a step change in the future space environment due to the proliferation of small satellites. The study addresses the EOL disposal techniques considered for mega-constellations and the potential of Active Debris Removal solutions.

At the beginning of 2016, Euroconsult's evaluation demonstrated that the number of satellites entering LEO is increasing exponentially. A contributor to this in the coming decades will be mega-constellations. Therefore, the study commenced with market research to comprehend the range of different constellations expected in the coming years, including; OneWeb, THEIA, Globalstar, Iridium next, SpaceX, and so on. Based on this research, the team identified two different theoretical constellations, representative of the foreseen market. These two constellations were complimented by two study cases already defined by ESA to give a complete range of constellations.

Trade-off analysis was performed to compare several different solutions for debris mitigation, these solutions fell under two different branches; those utilising ADR and those without. ADR solutions considered implementation of a DOK on orbit, uncontrolled re-entry, controlled re-entry and re-orbiting to a graveyard orbit.

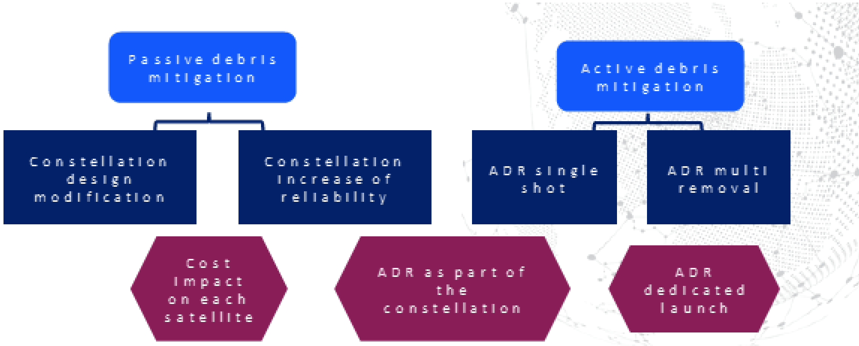

Figure 1-1: Constellation debris mitigation solutions

The trade-off allowed the team to select the two constellations for which an ADR solution would be most interesting; this was found to be the two constellations which boasted satellite numbers in the thousands, unsurprisingly as these are the constellations which will produce the greatest number of debris. For each one, an ADR configuration and optimal launch strategy has been traded and defined:

Table 1-1: The two constellations for which an ADR solution is most interesting.

Name	Number of Satellites	Altitude	Mass	ADR
TAS-3200	3200	800 km	380 kg	Electric Propulsion Multi-Mission Uncontrolled Re-Entry. Soyuz dedicated launch.
MEGA-1000	1080	1100 km	200 kg	Electric Propulsion Single-Shot Uncontrolled Re-Entry. Launched within the constellation.

The MEGA-1000 ADR is an adapted member of the constellation, with the communications payload replaced with the equipment necessary to become a chaser. It has been verified that the mass and volume made available by the removal of the payload is sufficient for the RDV and capture technology, as well as extra propellant, an increase in tank size and two additional thrusters. The capture is performed using a net capture system. Once capture has been achieved the ADR satellite will perform natural re-entry with the debris in tow, it is a "one-shot" system.

The TAS-3200 ADR draws on previous design work performed by Thales Alenia Space for the Space Tug. A dedicated launch with SOYUZ will put three ADRs into space at one time. Each one can service at least 35 pieces of debris, before performing an uncontrolled re-entry of itself. The capture process is performed using a robotic arm.

The mission phases of both missions are shown in Figure 1-2 below:

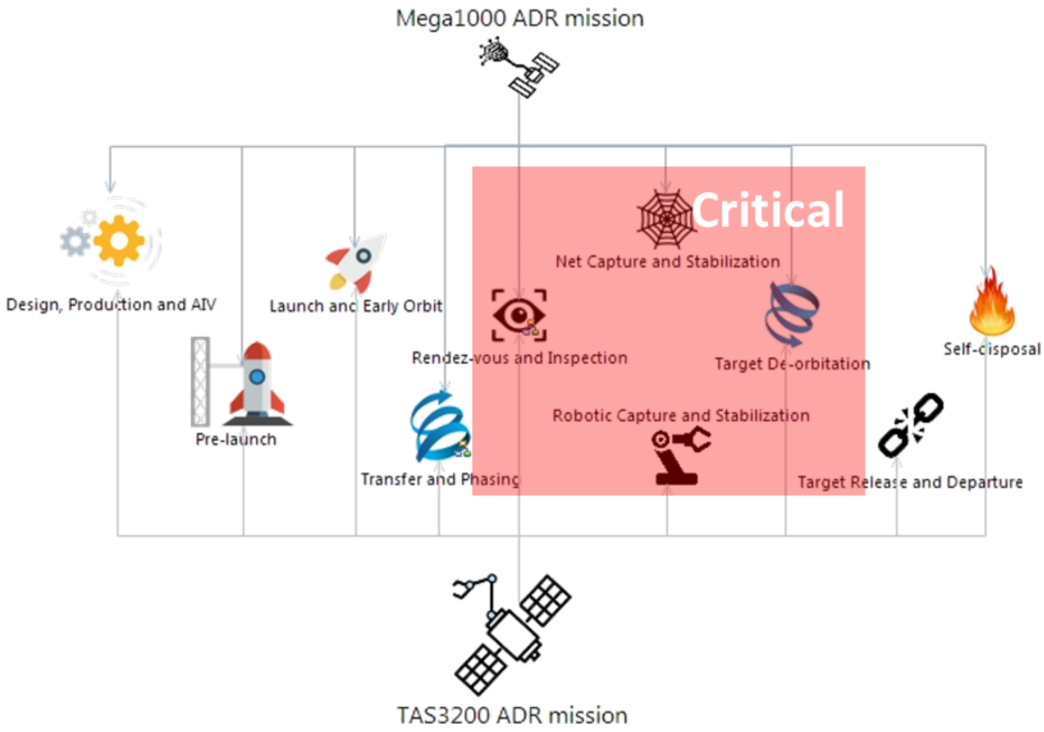

Figure 1-2: Mission phases (not all are shared).

Failures within constellations and the risk of collision will affect operator revenue. An ADR solution shall be considered if the effects on the operational orbit could cause a catastrophic collision, and consequently pollute it, making it unusable, for centuries to come.

The study concludes with the following recommendations, applicable to mega constellations, to be applied to the current policies and standards for space debris mitigation:

- re-entry within 1 to 5 years (depending on operational time and pollution of related orbits), instead of 25 years
- Mega-constellation satellites prepared for future ADR missions
- ADR solution to be considered within the operator's business plan to keep its business sustainable.

2. STUDY LOGIC AND COMPLETED ACTIVITIES

The study was kicked-off on 27/03/2017 and lasted for 13 months. The study logic has been shaped around assessing the EOL disposal in mega-constellations and the selection of promising ADR concepts.

This study included four work packages which ran essentially in series:

Task 1 – Constellations identification

Task 2 – ADR trade-off

Task 3 – Consolidation of ADR business plan with ADR conceptual design

Task 4 – Operational concept and Recommendations

The overall work logic is outlined in Figure 2-1. It consists of four phases lasting a total of 13 months.

During the first phase, the first task aimed at performing a comprehensive market analysis in order to identify four constellations which were representative of a range of future constellations. It was the occasion to gather the background on the future market of constellations and the possible debris mitigation solutions.

The PM#1 was held on October 5th, 2017, in this meeting the four reference constellations were agreed upon with ESA.

Extensive analysis was performed in order to identify the number of debris to be dealt with resulting from collisions and failures for each of the four reference constellations. This was followed by high level screening of the available debris mitigation solutions, assessing the most promising ones.

A progress meeting, held on December 1st, 2017 validated the work performed during task 2. The selection of the two most interesting cases for implementing ADR was agreed with ESA during this meeting, as well as the type of ADR solution.

Task 3 consisted of the definition of the architecture of the two ADR systems, including a trade-off to determine the capture and stabilization technology. This also included defining the mission phases and concepts of operation.

The two designs, along with the mission analysis, were presented to ESA on February 26th, 2018, for their review. The way in which to assess the business impact of implementing ADR (or not) for these constellations was also discussed and agreed with ESA.

The fourth phase consisted of finalising the overall architecture and budgets for the ADR systems, and assessing the programmatic timeline and costs. The business model for implementing ADR was defined. This was the occasion to formally define recommendations for amendments to policies and standards for debris mitigation of the future, particularly in respect to mega-constellations.

The final presentation was held on May 17th, 2018 highlighting the need for ADR solutions within the mega-constellations of the future and the further legislation required to provide sufficient debris mitigation.

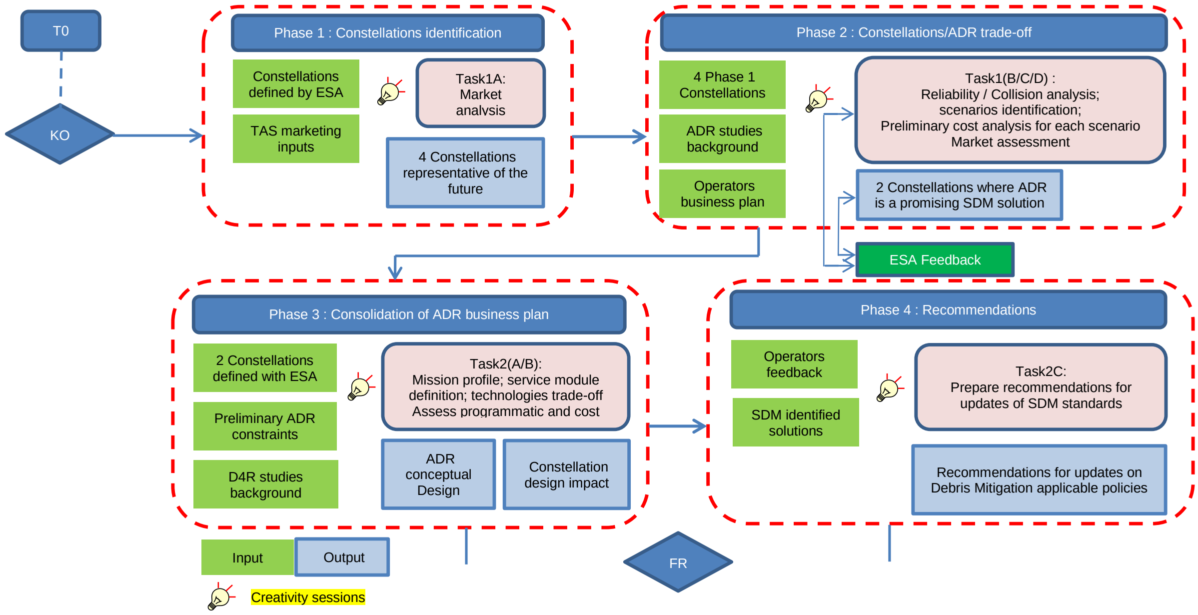

Figure 2-1: Study logic

The study team was put together to provide in-depth understanding of ESA's Clean Space initiative, and experience in mission analysis and phase-0 level definition of systems, with the distribution of WPs as per Figure 2-2, with the header colour indicating:

- Blue for Thales Alenia Space France
- Yellow for Thales Alenia Space Italy

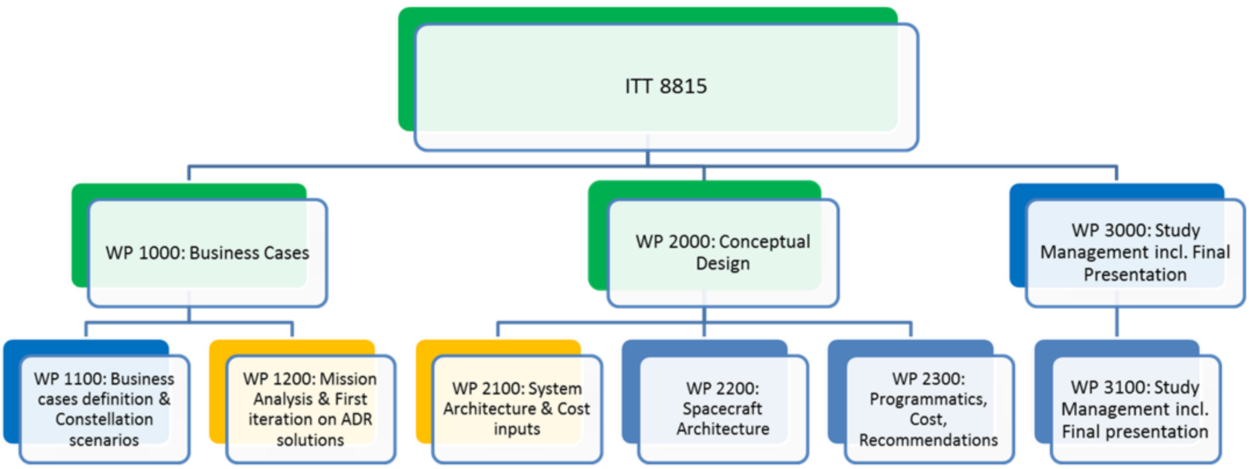

Figure 2-2: ADR study WBS.

3. CONSTELLATIONS STUDY CASES AND ASSOCIATED DEBRIS EVALUATION

Based on market trends, 4 mega-constellation study cases were identified to cover a large range of parameters, including; altitude, propulsion, number of satellites, mass and power. Different EOL disposal solutions are compared to identify the most cost-effective ADR solution. An evaluation of collision risk due to untracked debris or meteorites defines the threshold collision risk for each megaconstellation.

The LEO satellite market is mainly composed of observation satellites, telecommunication satellites and technology satellites. While the market trends for these LEO observation satellites appear to demonstrate an increasing tendency to mix the advantages of both families (high revisit rate and high resolution), the major market will remain dedicated to telecommunication satellites, with the emerging market being for the constellations.

Two constellations were defined by ESA and two were defined by Thales Alenia Space after performing market analysis. These four cases were representative of the constellations expected to come to fruition in the coming years.

Table 3-1: Selected reference megaconstellation study cases.

Megaconstellation-1000 System Characteristics		
Constellation	Number of satellites	1080
	Plane definition	20 planes with 54 satellites on each
	Altitude	1100 km
	Inclination	85 deg
Mission	January 2021 to January 2071 (constellation replenishment every 5 years)	
Constellation build-up	Year	2018 – 2020
	Launches	20 per year with 18 satellites per launch

Megaconstellation-1000 Satellite Characteristics			
Mass	200 kg		
Cross Section	1 m² effective cross section		
Propulsion	Hall Effect Thruster	Thrust	20 W/mN
		ISP	1600 s
Power	Between 50 and 250 W		
Equipment for Drama	Reaction Wheels	4	
	Magnetorquers	3	
	Propellant Tank	1	
Cost	500 k€ per satellite (recurrent)		
Operational Lifetime	7 years (1 year orbit raising, 5 years operational, 1 year deorbit)		
Reliability	0.9 at end of Operational Lifetime for the disposal function		

Megaconstellation-200 System Characteristics		
Constellation	Number of satellites	200
	Plane definition	10 planes with 20 satellites on each
	Altitude	1100 km
	Inclination	85 deg
Mission	January 2021 to January 2069 (constellation replenishment every 8 years)	
Constellation build-up	Year	2018 – 2020
	Launches	5 per year with 10 satellites per launch

Megaconstellation-200 Satellite Characteristics			
Mass	1000 kg		
Cross Section	4 m² effective cross section		
Propulsion	Chemical	Thrust	350 N
Power	Between 1500 - 2000 W		
Equipment for Drama	Reaction Wheels	4	
	Magnetorquers	3	
	Propellant Tank	1	
Cost	50000 k€ per satellite (recurrent)		
Operational Lifetime	10 years (1 year orbit raising, 8 years operational, 1 year deorbit)		
Reliability	0.9 at end of Operational Lifetime for the disposal function		

TAS-3200			
System Characteristics			
Constellation	Number of satellites	3200	
	Plane definition	2 times 32 planes with 50 satellites on each	
	Altitude	Two different altitudes : 780 km for 1600 satellites 820 km for 1600 satellites	
	Inclination	53° @ 780 km altitude 53.8° @ 820 km altitude	
Mission	Telecommunications		
Constellation build-up	Year	2020-2025	
	Launches	26 per year with 25 satellites per launch	
Satellite Characteristics			
Mass	380 kg (dry mass)		
Cross Section	2.6 m²		
Propulsion	Electrical	Thrust	40 N
		Isp	280 s
Power	500W		
Equipment for Drama	Reaction Wheels	4	
	Magnetotorquers	3	
	Propellant Tank	1	
Cost	950 k€ per satellite (recurrent)		
Operational Lifetime	5 years		
Reliability	0.9 at end of operational lifetime for the disposal function EOL strategy with less than 1 year re-entry		

TAS-100			
System Characteristics			
Constellation	Number of satellites	108	
	Plane definition	6 planes with 18 satellites on each	
	Altitude	1400 km	
	Inclination	90°	
Mission	Telecommunications		
Constellation build-up	Year	2018-2021	
	Launches	5/6 per year with up to 8 satellites per launch	
Satellite Characteristics			
Mass	1200 kg		
Cross Section	18 m²		
Propulsion	Electrical	Thrust	0.15 N
		Isp	1500 s
Power	Between 2000 W – 3000W		
Equipment for Drama	Reaction Wheels	4	
	Magnetotorquers	3	
	Propellant Tank	1	
Cost	42000 k€ per satellite (recurrent)		
Operational Lifetime	10 years		
Reliability	0.9 at end of operational lifetime for the disposal function		

For each case, reliability and collision analyses were carried out to attain the total number of defunct satellites resulting from each constellation. Assuming a reliability of 0.9 it can be estimated that 10% of the satellites from each constellation will fail and become space debris, therefore the greater the number of satellites in the constellation then the greater the amount of debris. In addition, the risk of losing a satellite due to an impact with untrackable and trackable debris has been added:

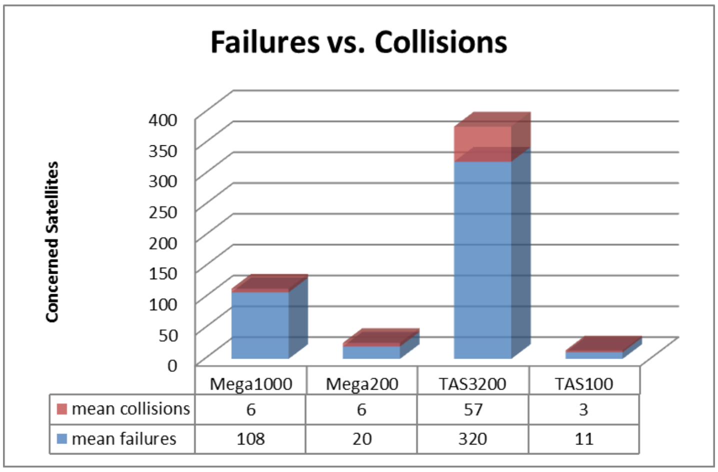

Figure 3-1: Graph to show the number of defunct satellites per constellation, for the first set.

The risk of collisions with trackable debris has been calculated for satellites unable to perform a CAM or deactivated, and this is highly dependent on the presence of the ADR and on the selection of the decay orbit. Figure 3-2 TAS3200 - amount of defunct satellites on operational orbit (left) and in decay orbit as function of decay time (right) shows the amount of satellites in the operational orbit and in the decay orbit for TAS3200. In such case it has been calculated a risk up to 9 catastrophic collisions in 50 years, just considering the ESA MASTER 2009 environment and the operational orbit. Such evaluations justify the need for preventive actions.

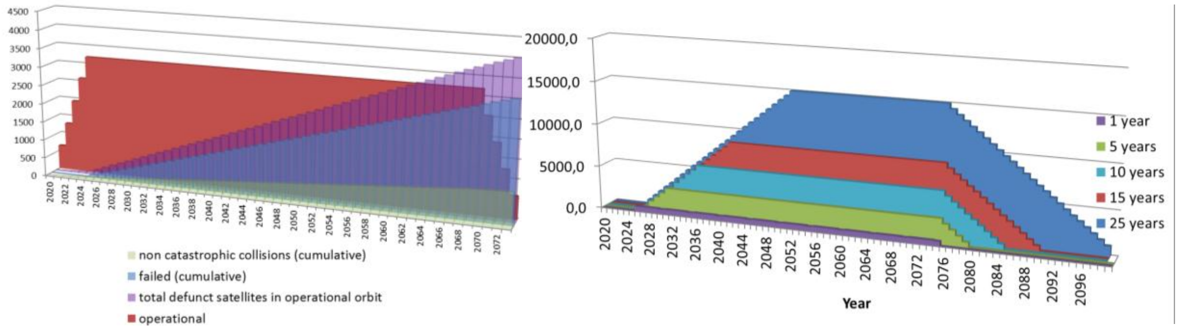

Figure 3-2 TAS3200 - amount of defunct satellites on operational orbit (left) and in decay orbit as function of decay time (right)

An assessment was then made of the various debris mitigation options for each of the four constellations, options which included both ADR and those without. The assessment identified the two constellations for which ADR is the most cost-effective solution and the type of ADR solution which gave this result. The assessment was based on comparing an initial baseline against the positive impact of implementing an ADR solution. The different ADR solutions considered included the EOL strategy; re-orbiting, affixing a DOK and de-orbiting the debris, the use of chemical or electrical propulsion, whether the servicer should be capable of dealing with one satellite or multiple, and the launch strategy:

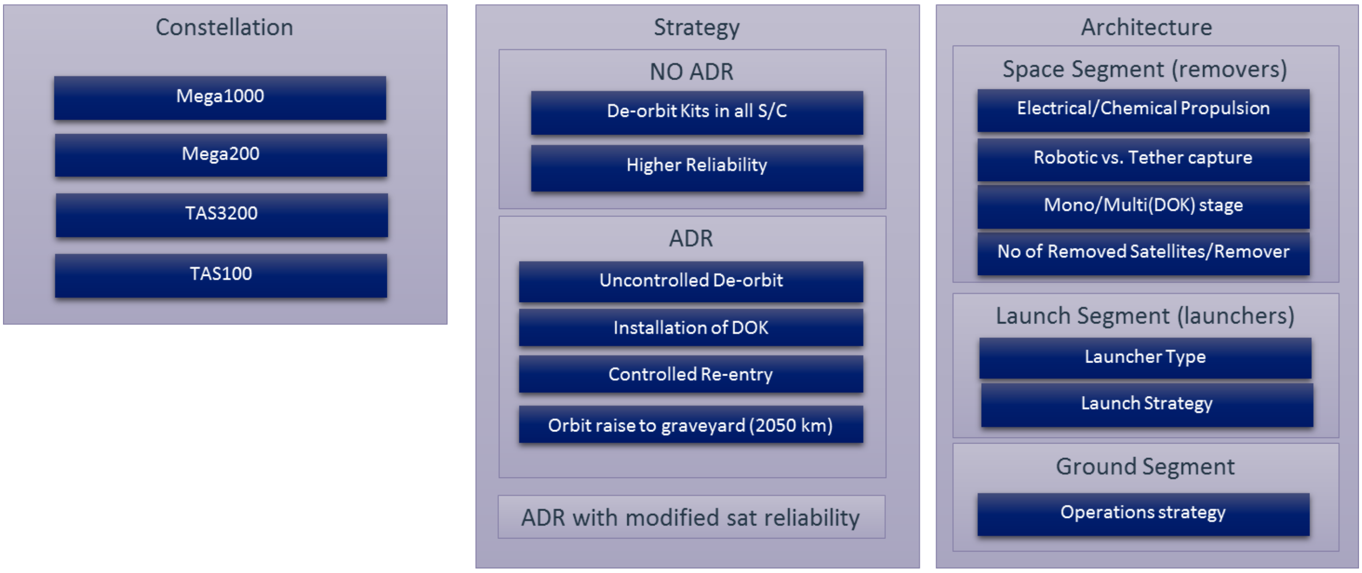

Figure 3-3 – Possible scenario compared

The differences between the two constellations meant that two different ADR solutions were selected:

- TAS-3200 - a multi-mission electrical propulsion ADR which will deposit a defunct satellite into a decay orbit then perform orbit-raising to collect the next. It will have its own launch using SOYUZ.

  Interesting points to be addressed included optimising the launch strategy and defining the debris removal method.

- MEGA-1000 - a one-shot mission using the same bus as that of the rest of the constellation and will be launched among them.

  Interesting points to be addressed included implementing a simple capture system on a small platform, and identifying the alterations required to convert the MEGA-1000 satellite into a chaser.

Many capture and stabilization strategies have been analysed through a detailed trade-off for both ADR vehicles which led to:

- TAS-3200 – robotic capture and stabilization. It can be assumed that the target will be prepared for capture by having an interface such as a handle for the robotic arm to grab. FEEP on-board the ADR would be able to decrease the tumbling rate if needed through plume impingement.
- MEGA-1000 – net capture and flexible link during re-entry.

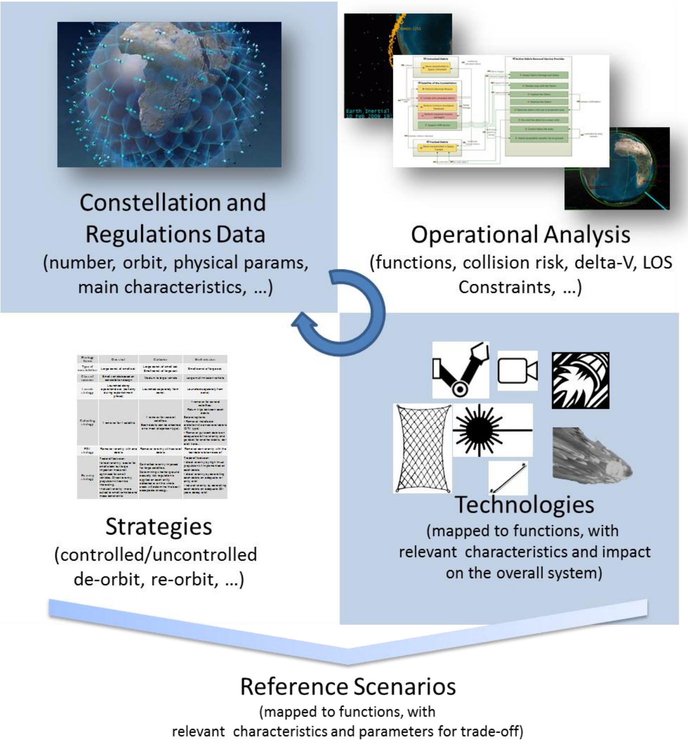

Figure 3-4 – Evaluation approach.

4. MEGA-1000 ADR

One-shot ADR mission using the same bus as that of the rest of the constellation and will be launched among them. A simple flexible capture system is implemented, allowing a safe approach toward a debris with unknown status.

4.1 Functional architecture and concept of operations

The overall functional architecture for the MEGA-1000 ADR is given below.

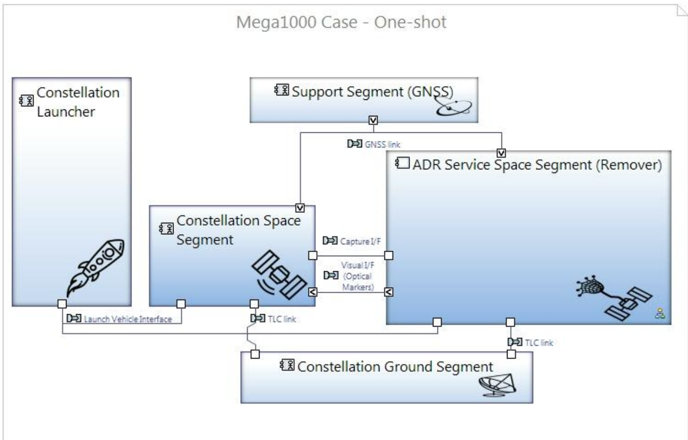

Figure 4-1: MEGA-1000 ADR functional architecture.

For this scenario the ADR will be launched among the constellation in the same launcher; with between 18 and 36 satellites being launched together (depending on the launcher). The ADR's operations will follow same logic as those of the constellation: to minimize the impact of BOL failure, the launcher will inject the satellite into a lower orbit where the in-orbit tests are performed. Any failures detected during this phase will induce a natural re-entry compliant with SDM recommendations. If no failures are detected the ADR will move to a higher orbit and will wait to perform phasing operations when RDV and capture is needed. Once the defunct satellite has been captured the two satellites will perform a natural re-entry together.

For such a mission, the ADR satellite will need to carry around 13 kg of propellant.

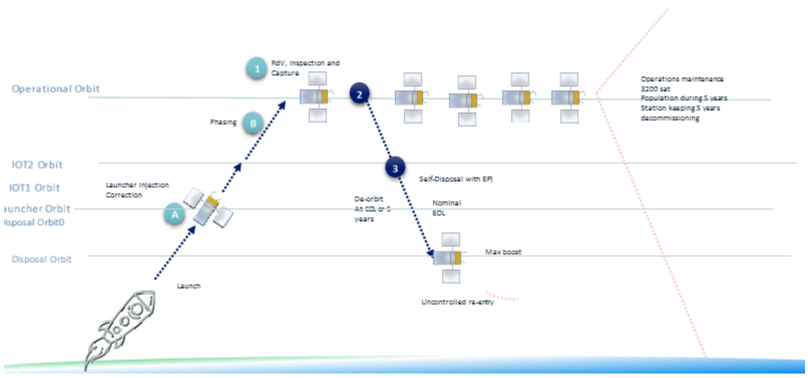

Figure 4-2: MEGA-1000 ADR mission profile.

4.2 Architecture

To ensure the satellite can be launched with the rest of the constellation much of the design is kept unchanged. The platform has dimensions 800mm X 1000mm X 800mm.

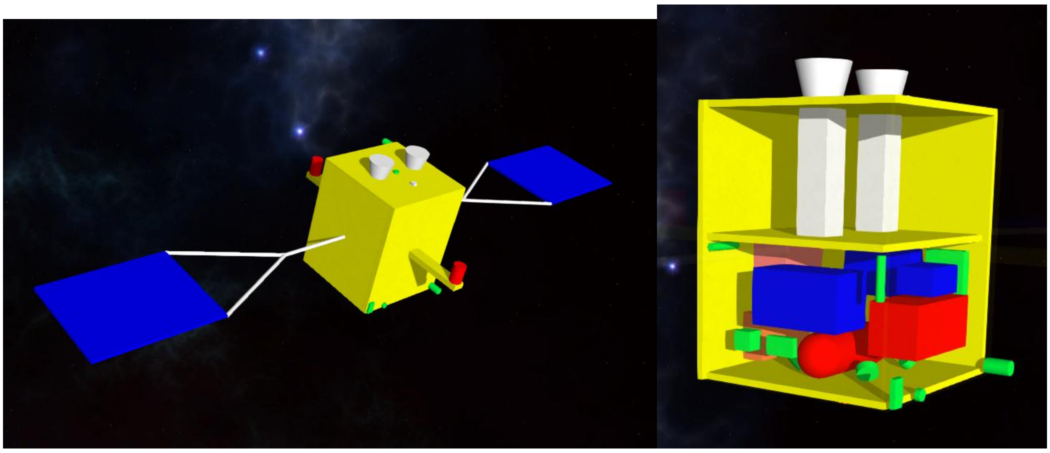

Figure 4-3: MEGA-1000 ADR one-shot satellite.

The communications payload is removed from the ADR satellite to convert it to a chaser whilst keeping the mass budget and volume the same as the rest of the constellation. The necessary things to implement on the satellite are a larger tank (ARDÉ 8l Xenon tank), two BUSEK 13mN thrusters to provide thrust in the anti-velocity direction, two arms to accommodate them, an additional battery to power the thrust during eclipse, 2 cameras to provide stereoscopic vision for rendezvous and a net capture system (below is Bertin's inflatable net technology designed for Envisat, which is scaled down for the smaller target).

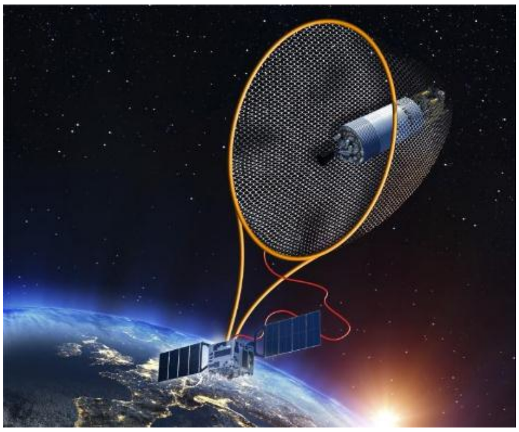

Figure 4-4: Net capture (Credit: BERTIN).

There is the capacity to accommodate two nets for redundancy and there remains space to implement a dedicated ICU if deemed necessary.

5. TAS-3200 ADR

Multi-mission ADR will deposit a defunct satellite into a decay orbit then perform orbit-raising to collect the next. SOYUZ is considered to launch ADR in batches of 3 vehicles.

5.1 Functional architecture and concept of operations

The overall functional architecture for the TAS-3200 ADR is given below.

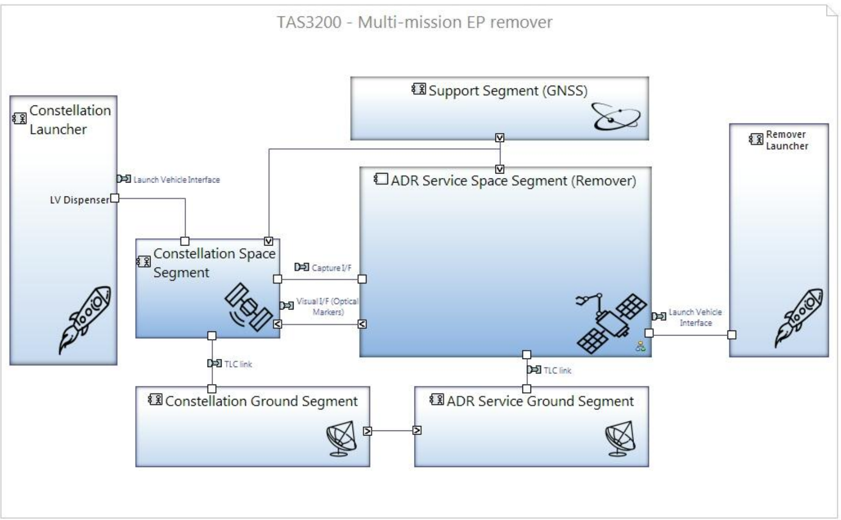

Figure 5-1: TAS-3200 ADR functional architecture.

For this scenario the ADR is launched with a dedicated launch, separately from the constellation. The ADR's operations will follow the same logic as for the constellation: to minimize the impact of BOL failure, the launcher will inject the satellite into a lower orbit where the in-orbit tests are performed. If no failures are detected the satellite will then wait until phasing operations commence to begin the RDV and capture process, once a service is needed. The ADR will take care of one piece of debris after another. At EOL, the ADR will release the last piece of debris that it is able to remove, and will then perform natural re-entry of itself.

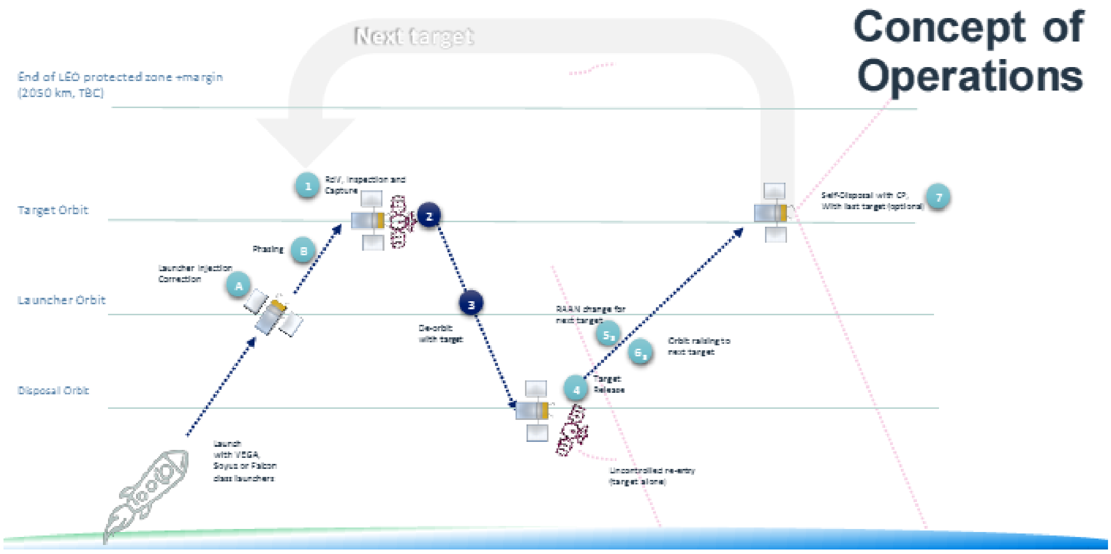

Figure 5-2 : TAS-3200 ADR mission profile.

5.2 Trade-offs

Several trade-offs have been performed in order to optimise the design of the multi-mission ADR vehicle.

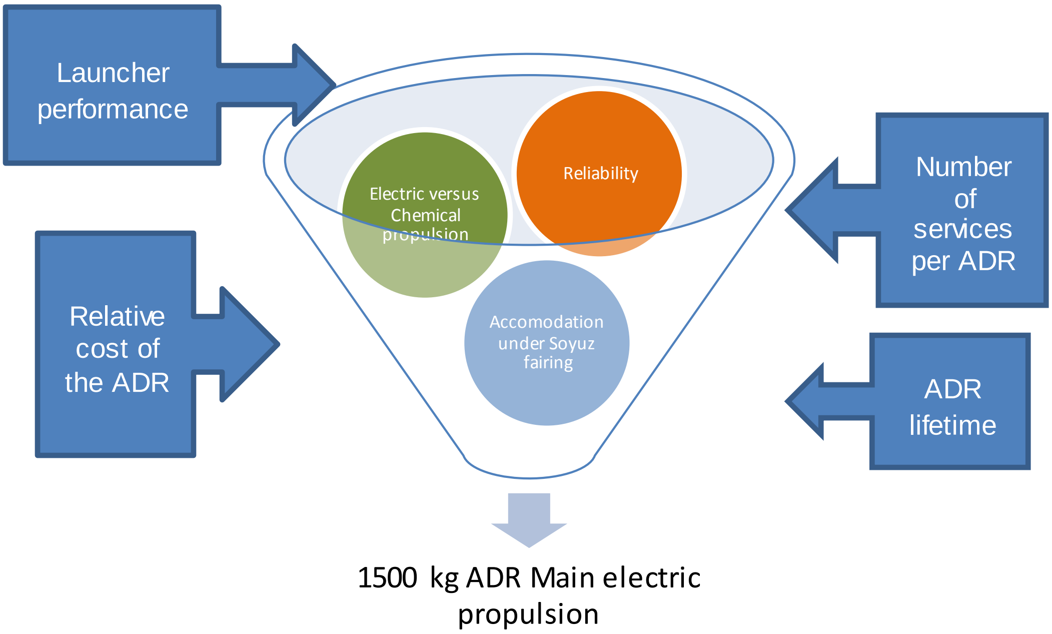

Figure 5-3 : TAS-3200 ADR satellite.

The TAS-3200 ADR vehicles will be launched using the SOYUZ launcher, so the available mass per launch is 4500 kg. Trade-off analysis defined the optimum size of the ADR as being 1500 kg, so having three ADRs per launch.

5.3 Architecture

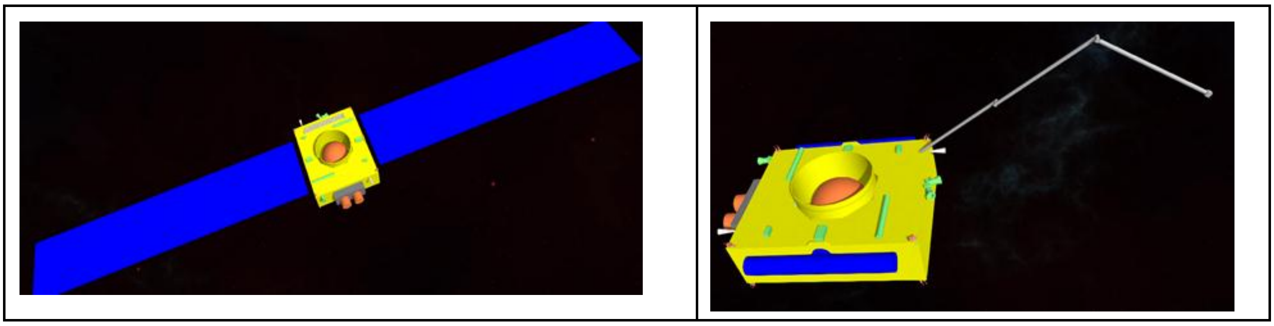

Figure 5-4 : TAS-3200 ADR satellite

The ADR Platform is sized for a stacked configuration inside the narrowest part of the SOYUZ launcher (3640mm); it has dimensions 2.6 X 2.1 X 0.8m and the central tube is sized for the 1194mm launcher interface. It includes a 300l Xenon Tank and two Qinetic T6 thrusters, with an additional chemical propulsion subsystem for the rendezvous manoeuvres. Flexible solar arrays are sized for a power demand of ~6200 W and the refolding capability will be used to ease capture. A robotic arm with six degrees of freedom, complete with touch sensors and clamping mechanism will capture the target. X-band communication will provide high-speed image telemetry to support the capture process when the link is available

6. CONCLUSION

The number of debris in LEO orbit continues to increase with a large step size when taking into account mega constellations. This is a key threat to space sustainability, with potential disruption created by the phenomenon. Even if post-mission disposal is implemented in the business model, Active Debris Removal remains the only possible mitigation measure in the case of in-orbit failures, whereby the satellite can no longer perform re-entry.

The constellation operators will have a huge number of satellites to manage, and they will have to consider potential failures in their business model. Two cost-effective ADR solutions have been identified to compliment the current debris management solutions. Both represent an equivalent “cost-per-debris” impact on the business plan.

The study highlighted the following point:

- ADR becomes a necessary solution when the number of debris in the operational orbit becomes unmanageable, rendering parts of the orbit unusable and thereby affecting the services offered by the constellation operator.
- ADR solution is mandatory when probability of collision is approaching 1.
- 2 promising ADR architectures have been defined to limit impact on business model

It is recommended that changes in standards and policies must be made in order to prevent orbits becoming overpopulated with debris and to drive the constellation operators to use space responsibly and sustainably.

Despite impact on business plan, an ADR solution shall be considered if the effects on the operational orbit could cause a catastrophic collision and consequently pollute it, making it unusable, for centuries to come.