D4R AIDING CONCEPTS: EXECUTIVE SUMMARY

D4R

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DOCUMENT STATUS SHEET

Version	Date	Pages	Changes
1.0	16/06/2017	56	Initial version
1.1	07/07/2017	57	Updated version to include Final Presentation comments: - D4R-FP-ACT-2: Section 8.2.3 has been updated to justify the end-of-life rotational state considered for the GEO case study. - Section 8.1.1 has been updated to introduce a reference to the support provided by retroreflectors to the rotational state estimation when ground measurements are combined as defined by [RD.9]. - Section 6.2, Table 6-4 that defines the applicability of the proposed SDRS aiding concepts has been updated to take into account ESA comment regarding the first civilian operational use of GNSS receivers in GEO. - Section 8.4 has been updated to include a description of the next steps to be considered to include the proposed aiding devices in future missions.

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LIST OF TABLES AND FIGURES

1. INTRODUCTION

1.1. PURPOSE

The purpose of this document is to provide a summary of the analyses and results of the activities performed during the D4R project based on ESA SOW, [AD.1], and GMV and ADS proposal, [AD.2].

1.2. SCOPE

The scope of this document is the review of the activities performed in the frame of D4R project as defined in D4R contract, [AD.3].

This document is organised as follows:

- Section 2 contains the applicable and reference documents
- Section 3 contains the D4R overview and the approach followed during D4R activities.
- Section 4 contains the D4R aiding concepts derived from the review of the SDRS technologies.
- Section 5 contains the selected case studies to be considered in the frame of D4R study.
- Section 6 contains the results of the preliminary assessment of the D4R aiding concepts.
- Section 7 contains the conceptual design of the selected D4R aiding concepts.
- Section 8 contains the results of the design and integration of the selected D4R aiding devices and the results of the system impact analyses of the ADR Aiding Devices Subsystem in the project activities for the selected case studies or scenarios.
- Section 9 contains the conclusions and recommendation derived from D4R activities.

1.3. ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 1-1 Acronyms

Acronym	Definition
AD	Applicable Document
ADR	Active Debris Removal
ADR-ADS	Active Debris Removal Aiding Device Subsystem
AIT	Assembly, Integration and Testing
AOCS	Attitude and Orbit Control System
CAD	Computer Aided Design
CAP	Capture
COM	Centre of Mass
COTS	Commercial Off-the-Shelf
D4R	Design for Removal
DISP	Disposal
EOL	End-Of-Life
ESA	European Space Agency
GEO	Geosynchronous Equatorial Orbit
GNC	Guidance Navigation and Control
I/F	Interface
INSP	Inspection
ISAR	Inverse Synthetic Aperture Radar
LED	Light-emitting Diode
LEO	Low Earth Orbit
LIDAR	Laser Imaging Detection and Ranging
MCI	Mass, Centring and Inertia
MLI	Multi-Layer Insulation

Acronym	Definition
MPD	Multiple Payload Dispenser
OOS	On-Orbit Servicing
RD	Reference Document
RdV	Rendezvous
RF	Radio Frequency
RFID	Radio Frequency Identification
S/C	Spacecraft
SA	Situational Awareness
SDRS	Situational Awareness, Active Debris Removal and On-Orbit Servicing
SER	Servicing
SLR	Satellite Laser Ranging
SSO	Sun Synchronous Orbit
SST	Space Surveillance and Tracking
STAB	Stabilisation
TRL	Technology Readiness Level

2. REFERENCES

2.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.X]:

Table 2-1 Applicable documents

Ref.	Title	Code	Version	Date
[AD.1]	SoW: ESA Express Procurement EXPRO Design for Removal	ESA-TEC-SC-SOW-2015-001	1.0	06/05/2015
[AD.2]	Detailed Proposal Design for Removal	GMV 11337/15 V1/15	1.0	24/07/2015
[AD.3]	ESA Contract No. 4000115775/15/NL/GLC	ESA-IPL-PTE-AS-mo-LE-2015-1094	1.0	26/11/2015

2.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.X]:

Table 2-2 Reference documents

Ref.	Title	Code	Version	Date
[RD.1]	SDRS Technologies and Aiding Concepts	CS-D4R-TN1	2.3	22/06/2016
[RD.2]	Case Studies and Preliminary Evaluation	CS-D4R-TN2	1.1	14/09/2016
[RD.3]	D4R Aiding Concepts: Conceptual Design	CS-D4R-TN3	1.2	24/01/2017
[RD.4]	D4R Aiding Concepts: System Impact Analyses	CS-D4R-TN4	1.0	05/05/2017
[RD.5]	Compendium of Space Debris Mitigation Standards Adopted by States and International Organizations	-	-	Feb 2016
[RD.6]	Orbital Debris Mitigation Standard Practices, US Government. http://orbitaldebris.jsc.nasa.gov/library/USG_OD_Standard_Practices.pdf	-	-	-
[RD.7]	Eddy Currents Applied to De-Tumbling of Space Debris: Analysis and Validation of Approximate Proposed Methods, IAC-14,A6,6,2,x22528, in Proceedings of the 65th International Astronautical Congress, Toronto, Canada. Ortiz Gómez et all.	-	-	2014
[RD.8]	Optical Survey of the Tumble Rates of Retired GEO Satellites, U.S. Naval Research Laboratory, C. R. Binz, M. A. Davis, B. E. Kelm, C. I. Moore.	-	-	-
[RD.9]	Determining, Monitoring and Modelling the Attitude Motion of Potential ADR Targets, T. Schildknecht, H. Krag, T. Flohrer. Clean Space Industrial Days, 23rd-27th May 2016	-	-	May 2016
[RD.10]	GPS Receiver On-Orbit Performance for the GOES-R Spacecraft, S. Winkler, G. Ramsey, V. Frey, j. Chapel, D. Chu, D. Freesland, A. Krimchansky, M. Concha. 10th International ESA Conference on Guidance, Navigation and Control, 29th May – 2nd June 2017			May 2017
[RD.11]	In-Flight Guidance, Navigation and Control Performance Results for the GOES-16 Spacecraft, J. Chapel, D. Stancliffe, T. Bevacqua, S. Wrinkler, B. Clapp, T. Rood, D. Freesland, A. Reth, D. Early, T. Walsh, A. Krimchansky. 10th International ESA Conference on Guidance, Navigation and Control, 29th May – 2nd June 2017			May 2017

3. D4R OVERVIEW AND STUDY APPROACH

The population of non-operational objects in the space environment is raising, increasing concern about the safety of operations for current and future space activities.

In this respect, space agencies and in particular ESA with its ESA/ADMIN/IPOL (2014) have established policies to mitigate space debris creation. Please refer to the compendium of space debris mitigation standards adopted by states and international organizations, [RD.5], for additional information. This basically implies that satellites in LEO and GEO shall perform an End Of Life (EOL) disposal with a reliability of 90%. This, however, does not therefore exclude a priori the necessity of having to actively remove the satellite, as there still is left some considerable risk that the EOL is not properly carried out. Moreover, according to recent studies, even if end of life disposal is performed with a 90% success rate, active debris removal is still required to contain the growth of space debris.

Active Debris Removal is, however, a complex mission which has not been fully demonstrated so far, as it has also been recently highlighted by ESA in which states:

"The retrieval of a space system and return to Earth by means of an external chaser vehicle (Active Debris Removal) is an option that currently cannot be considered yet as a feasible baseline solution for all spacecraft and launch vehicle orbital stages due to high operational costs and low technology readiness".

The objective of D4R activity stems from the above statement and it is therefore to increase the feasibility of an ADR mission (both in terms of cost and technically) by identifying concepts that could be hosted on board a spacecraft to facilitate such future ADR mission, if the spacecraft fails to perform its nominal disposal manoeuvres.

The concepts to be identified within the D4R study shall support the ADR mission in the following:

- Aids to support tracking and pose estimation of the debris (from ground and on-orbit), since it is essential to have, first, good knowledge of the orbital position of the debris, and then, of its tumbling state to size the ADR mission and perform the proximity operations, as well as to have more precise re-entry predictions.
- Space systems attitude stabilization, as a tumbling debris can impose strong requirements on the capture, stabilisation and disposal of the debris.
- Aids to facilitate capture, which would be needed in capturing and disposing the debris.

In the frame of D4R activity the following definitions shall be considered:

- **SDRS**: Situational Awareness, Active Debris Removal and On-Orbit Servicing.
- **SDRS Segment**: segments of an ADR or OOS (On-Orbit Servicing) mission:
  - Situational awareness, SA. This segment is related to gathering all the information from ground and/or from orbit about the orbital status of defunct satellites, including its kinematic state.
  - Rendezvous, RdV. This segment is related to the phase of the mission where a chaser spacecraft gets in proximity to a target spacecraft, which in the frame of D4R should be considered non-operational, using relative state measurements.
  - Inspection, INSP. This segment is related to the remote inspection of the non-operational satellite, needed in order to precisely determine its tumbling status and the strategy to capture it.
  - Stabilization or detumbling, STAB. This segment deals with the stabilization of the debris, depending on the dynamics of the debris AND if the capture or deorbiting mechanism requires such stabilization. Stabilization is meant as the reduction of the uncontrolled rotational/tumbling status of the debris down to a level manageable for Active Debris Removal or On-Orbit Servicing operations.
  - Capture, CAP. The capture is related to achieving a link (either rigid or flexible) between the chaser and the debris, in order to, then, attain debris disposal or servicing operations.

  - Servicing, SER. This phase is related to the operations of in-orbit reparations or refuelling of a damaged object, such as data/electric/fuel exchange or parts replacements of a malfunctioning satellite.
  - Disposal, DISP. The disposal is related to the last phase of an Active Debris Removal mission, that ultimately attains the goal of remediating the problem created by the debris by either de-orbiting it or raising it to a proper disposal orbit.
- **SDRS technologies**: methods/systems/devices used, according to the current state of the art, to fulfil the requirements and necessities of each SDRS segment. They are reviewed in section 5 of [RD.1].
- **SDRS aiding concepts (or simply SDRS concepts)**: systems/devices that could be hosted on board a spacecraft to facilitate an ADR missions in case it becomes non-functional. It could be also a spacecraft design strategy, so not necessarily foreseeing a specific element to be installed on-board. The SDRS aiding concepts are defined in section 4. .

3.1. D4R STUDY APPROACH

This section provides a description of the different tasks that have been conducted in order to select the most promising aiding concepts to be considered in the development of an ADR Aiding Devices Subsystem, ADR-ADS.

The following main activities have been performed in the frame of D4R study:

- Identification of SDRS aiding concepts.
- Selection of case studies.
- Preliminary assessment of SDRS aiding concepts.
- Conceptual design of D4R aiding devices to select the aiding concepts to be included in the ADR-ADS and to assess its impact at system level.
- Assessment of system impact of D4R aiding devices for the considered scenarios. A design and integration of the D4R aiding devices in the selected case studies.

The identification of the SDRS aiding concepts has been performed considering the following steps that were applied for each SDRS segment:

- Review the state of the SDRS technologies based on literature review, outcomes from running Clean Space branch 4 activities, consortium internal expertise, advice and guidelines from ESA.
- Identification and analysis of the problematic aspects or areas of the SDRS technologies in order to identify potential enhancements.
- Definition of SDRS aiding concepts based on the identified possible enhancements.

The results of this identification are reported in the technical note “SDRS Technologies and Aiding Concepts”, see [RD.1]. The SDRS aiding concepts are provided in section 4. .

The selection of case studies and preliminary evaluation of the SDRS aiding concepts have been performed considering the following steps:

- Selection and definition of four case studies to be considered in the frame of the D4R study for the trade-off analyses of the SDRS aiding concepts.
- Definition of evaluation criteria to be considered for the trade-off analyses.
- Preliminary assessment of SDRS aiding concepts in the four scenarios according to the defined evaluation criteria.

The results of the selection of case studies and of the preliminary assessment are reported in the technical note “Case Studies and Preliminary Evaluation”, see [RD.2]. The selected case studies are provided in section 5. .A summary of this assessment is provided in section 6. .

The conceptual design of the selected aiding concepts has been performed considering the following steps:

- Selected aiding concepts. As an outcome of the preliminary assessment a set of aiding concepts were identified in order to perform a conceptual design.
- Definition of a baseline design supported by cost estimation and mission risk reduction assessment.
- Definition of a preliminary set of design and functional requirements to be considered in the next development phases.

The results of the conceptual design of the selected aiding concepts are reported in the technical note "D4R Aiding Concepts: Conceptual Design", see [RD.3]. The most promising ADR aiding concepts are defined in section 7. .

The system impact analysis of the selected subset of the aiding concepts has been performed considering the following steps:

- Applicable aiding devices. A review of the functionality and applicability of the aiding concepts have been performed in order to set the starting point for the different case studies.
- End-Of-Life state definition. The characterization of the end-of-life state has been performed based on operational mission definition and S/C data. The purpose is to estimate the disposal manoeuvres, rotational state and rendezvous strategies that constitute key elements in the design of the ADR Aiding Device Subsystem, ADR-ADS.
- ADR-ADS design and integration. Design and integration of the applicable aiding devices to the different case studies have been performed.

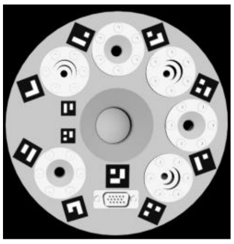
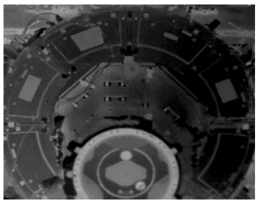
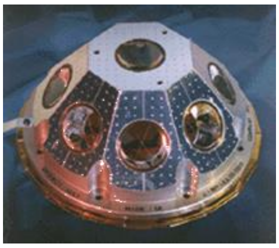
The results of the system impact analysis of the selected aiding concepts are reported in the technical note "D4R Aiding Concepts: System Impact Analyses", see [RD.4]. A summary of this analysis is provided in section 8. .

4. SDRS TECHNOLOGIES AND AIDING CONCEPTS

This section contains the results of the review of the SDRS technologies. The proposed aiding concepts have been derived in order to mitigate the identified problematic areas for the different technologies applied in the different segments.

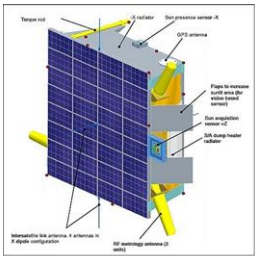
The following table provides a description of the SDRS aiding concepts related to the state estimation of the defunct satellite.

Table 4-1 State Estimation SDRS Aiding Concepts

SDRS Aiding Concept ID	SDRS Aiding Concept Name	Description	Image/Graphical Representation
SDRS #1	Optical markers	Improve state estimation in the following areas: - Relative navigation for close range operations (below 10m) with optical navigation. - Different types of markers, patterns, could be considered during different operational ranges. - Identification of grasping points and aid capture mechanism (if it uses optical camera). - Mounted on the different faces of the satellite to accurately determine tumbling state of the debris.	 Example of markers on ASSIST refuelling interface
SDRS #2	Phosphorent markers	Improve state estimation for non-directly illuminated areas with the support provided by an illumination unit mounted on the chaser.	 ISS Emergency Egress Guidance System (EEGS) photo-lumininescent markers
SDRS #3	Thermal markers	Improve the operational range of infrared cameras to close proximity operations, 1-2 m, as robust backup sensor.	 Infrared camera image
SDRS #4	Large retroreflectors	Large retroreflectors may assist tracking from ground with laser and long range rendezvous phase (> 10 km), improving meaningfully both the absolute and relative navigation solution and permitting having a first estimate of the rotational state of the debris (with a number and accommodation of retroreflectors to be studied and depending on orbital conditions as well as shape of the S/C). Also, this would help more precise debris orbital estimation to compute higher efficiency Collision Avoidance Manoeuvres and re-entry predictions.	 Hemispherical Retroreflector Array
SDRS #5	Small retroreflectors	Improve state estimation in the following areas: - Proximity navigation with LIDAR (including fine relative attitude). - Identifying grasping points and aid capture mechanism, if it uses LIDAR. - Mounted on the different faces of the satellite to accurately determine tumbling state of the debris.	 Multiple Reflector Array

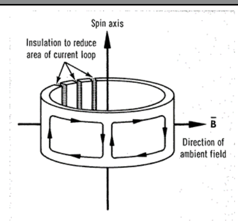
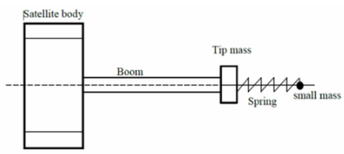
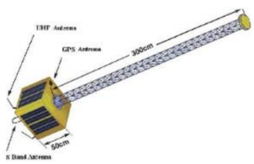
The following table provides a description of the SDRS aiding concepts related to the active navigation aids.

Table 4-2 Active Navigation SDRS Aiding Concepts

SDRS Aiding Concept ID	SDRS Aiding Concept Name	Description	Image/Graphical Representation
SDRS #6	GNSS receiver	Installation of one GPS receiver and a communication link in order to perform relative navigation with the chaser. Applicable to LEO spacecraft.	 ISS GPS antenna for long-mid range relative navigation
SDRS #7	Radio frequency	Installation of a transmitter to broadcast the signal to be acquired by the chaser spacecraft.	 KURS radio system used by ISS and SOYUZ and PROGRESS
SDRS #8	LEDs	Installation of LEDs on the target spacecraft in order to improve the performances of the image processing algorithms during poor illumination conditions. It is also possible to set dedicated patterns in order to try to derive the relative attitude between chaser and target spacecraft. These devices require power from the system. They require very low power and could rely on a redundant power supply to be activated after the operational life.	 LEDs installed on TANGO spacecraft

The following table provides a description of the SDRS aiding concepts related to the detumbling of the defunct satellite.

Table 4-3 Detumbling SDRS Aiding Concepts

SDRS Aiding Concept ID	SDRS Aiding Concept Name	Description	Image/Graphical Representation
SDRS #9	Eddy current enhancer	Enhance energy dissipation rate and ability to generate currents when moving through the Earth magnetic field in order to stabilize the tumbling motion of the debris.	
SDRS #10	Mechanical vibration dampers	Help dissipating rotational energy, permitting stabilizing the tumbling motion of the debris. The following examples can be considered: - Spring dampers. - Ball in tube dampers.	
SDRS #11	Gravity gradient boom	The presence of an extendable boom would permit increasing the end of life gravity gradient torque, aligning the satellite minimum inertia axis vertically and so reducing the tumbling motion.	

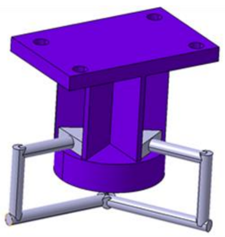
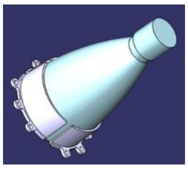
The following table provides a description of the SDRS aiding concepts related to the spacecraft design.

Table 4-4 Design SDRS Aiding Concepts

SDRS Aiding Concept ID	SDRS Aiding Concept Name	Description
SDRS #12	Reduction of vibrations	- Reduce the amplitude of vibrations by structural design of the target spacecraft. - Ensure by design that vibration modes are not excited during robotic capture. This will avoid unintended breakups and will facilitate the design of the post-contact controller.
SDRS #13	Inertia matrix constraint	Take into account during satellite design phase such that gravity gradient is the largest torque at the end of life, e.g. constraint to S/C inertia. This will facilitate the tumbling stabilization of the spacecraft.
SDRS #14	Flat zone around COM	Take into account during satellite design phase a flat zone around COM in order to help shepherd SDRS technologies.
SDRS #15	Access to disposal devices	Take into account during satellite design phase the possibility to activate disposal devices externally, e.g. access to activate the device by a robotic arm.
SDRS #16	Reinforce structural hard points	Take into account during satellite design phase the possibility to reinforce structural hard points to allow transmitting force and torques to the load bearing structure.
SDRS #17	Dedicated zone for disposal kit installation	Take into account during satellite design a dedicated zone to install a disposal kit.
SDRS #18	Detailed spacecraft documentation	Availability of detailed documentation for future ADR mission: - Ensure that the MCI properties and uncertainties of the object plus the vibration modes of debris are well known. This will help the design of stabilization and de-orbiting controllers. - Detailed CAD model availability. This will strongly help the relative navigation based on optical or laser devices as well as ground based ISAR imaging. - Data sheet of suitable grasping points, providing position, structural properties, etc. - Detailed information on markers and/or retroreflectors installed on-board

The following table provides a description of the SDRS aiding concepts related to the structural fixtures that contribute to the capture of the defunct satellite.

Table 4-5 Structural Fixtures SDRS Aiding Concepts

SDRS Aiding Concept ID	SDRS Aiding Concept Name	Description	Image/Graphical Representation
SDRS #19	Robotic arm grappling fixture	It is necessary to include in the spacecraft structure grappling points able to transmit forces and torques to the load-bearing structure. The position of the grappling point has to be studied for each case. In general they shall be close to the most probable rotation axis of the debris (to limit or avoid synchronized flight and enable approach over the rotation axis), and as much as possible in the vicinity of the CoM, in order to reduce torques during the post-contact phases.	
SDRS #20	Clamping mechanism interface	The best option to be used as a clamping point is the interface ring in the rear part of the spacecraft. It is a fixed part, rigid and big enough so as to be grabbed.	
SDRS #21	Grasping mechanism for apogee nozzle	Use as clamping point the apogee nozzle. It is a fixed part, rigid, accessible and quite separated from the rest of the payload.	

5. SELECTION OF CASE STUDIES

Using representative examples of spacecraft and multiple payload dispensers, the SDRS aiding concepts proposed in section 4. are studied using a two-step approach in order to analyse the applicability of the proposed aiding concepts.

The first step corresponds to a preliminary assessment of them w.r.t. a set of criteria in representative scenarios identifying the most suitable aiding concepts for each one, i.e. LEO, MPD, GEO and mega-constellation, and for each category of the aiding concepts, i.e. state estimation enhancements, active navigation aids, detumbling devices, design rules and structural fixtures. The results of this step are provided in section 6.

The second step corresponds to the detailed analysis of the aiding concepts identified in the frame of the first step taking into account the case studies proposed as representative candidates of the different applicable scenarios. The results of this step are provided in sections 7. and 8.

The following scenarios are considered in the frame of D4R study:

- LEO satellite scenario. The SEOSAT/INGENIO satellite is proposed as case study for the LEO satellite scenario, a satellite of around 750 kg flying in a 670 km Sun synchronous orbit. The AS250 platform has been used for several missions and is representative for Earth observation satellites.
- Multiple payload dispenser scenario. Last stages of current European launchers like VEGA, Ariane 5 and Soyuz performs deorbitation manoeuvres in order to re-enter Earth, and they have not fail until the moment. For this reason, it has been considered more relevant to analyse the multiple payload dispenser platforms of these launchers, i.e. Sylda for Ariane 5, Vespa for VEGA and Asap-S for Soyuz, which remains indefectibly in the space after their mission. These platforms have a common feature, which is that they have standard I/F with the payload (diameter 937 or 1194 mm).
- GEO satellite scenario. Eurostar 3000 platform, delivered from Airbus DS, is proposed as study case of the GEO satellite scenario due that it is commonly used for telecommunication satellites. In this case the assessment of the aiding concepts should be focused on the payload relocation by failure of the end-of-life manoeuvre, or even in its refurbishment.
- Mega-constellation satellite scenario. A generic mega-constellation platform is selected as case study for this type of scenario.

5.1. MAIN DRIVERS

The selection of the case studies is driven by the following two elements:

- Representative scenario.

  The scenario, from a generic point of view is defined by two different main parameters, the type of orbit and the payload mass/dimensions/shape. They both have a strong influence on grasping fixtures to be considered, because the removal solution could be quite different according to them.

  Mitigation standard procedures for spacecraft or upper stages highly depend on the type of orbit where the structure is located. Currently, the different disposal methods for final mission orbits are classified hereinafter based on [RD.6]:

  - Atmospheric re-entry for LEO orbits will limit the lifetime of the spacecraft to no longer than 25 years after completion of the mission. According to [RD.6], if a space structure is to be disposed by re-entry into the Earth’s atmosphere, the risk of human casualty shall be less than 1 in 10,000.
  - A second option is the manoeuvring to a storage orbit. The storage regimes to be considered are:

    I. Between LEO and MEO: Manoeuvre to an orbit with perigee altitude above 2000 km and apogee altitude below 19,700 km (500 km below semi-synchronous altitude).

    II. Between MEO and GEO: Manoeuvre to an orbit with perigee altitude above 20,700 km and apogee altitude below 35,300 km (approximately 500 km above semi-synchronous altitude and 500 km below synchronous altitude).

III. Above GEO: Manoeuvre to an orbit with perigee altitude above 36,100 km (approximately 300 km above synchronous altitude).

IV. Heliocentric, Earth-escape: Manoeuvre to remove the structure from Earth orbit, into a heliocentric orbit.

- Last case to be considered is the direct retrieval, i.e. to retrieve the structure and to remove it from orbit as soon as possible after completion of its operational mission.

The following table gathers and summarizes the different types of orbits and satellites, together with the proposed capture/disposal method:

Table 5-1 Capture Technologies for Different Scenarios and Structures

<table>
<tr><th>Structure Type</th><th>LEO</th><th>GEO</th><th>Upper stage</th></tr>
<tr><td rowspan="5">Large structures (> 1000 kg)</td><td rowspan="3">Harpoon</td><td rowspan="3">Harpoon</td><td>Harpoon</td></tr>
<tr><td>Net</td></tr>
<tr><td>Clamping mechanism</td></tr>
<tr><td>Net</td><td>Net</td><td rowspan="2">Robotic arm and clamping mechanism (*)</td></tr>
<tr><td>Robotic arm and clamping mechanism (*)</td><td>Robotic arm and clamping mechanism</td></tr>
<tr><td rowspan="4">Medium structures (500 – 1000 kg)</td><td>Drag augmentation device (**)</td><td>Harpoon</td><td>Clamping mechanism</td></tr>
<tr><td>Net (**)</td><td>Net</td><td>Net</td></tr>
<tr><td>Tether (**)</td><td rowspan="2">Robotic arm</td><td rowspan="2">Robotic arm with/without clamping mechanism (*)</td></tr>
<tr><td>Robotic arm with/without clamping mechanism (*)</td></tr>
<tr><td rowspan="4">Mini structures (100 – 500 kg)</td><td>Drag augmentation device</td><td>Harpoon</td><td>Clamping mechanism</td></tr>
<tr><td>Net</td><td>Net</td><td>Net</td></tr>
<tr><td>Tether</td><td>Robotic arm</td><td rowspan="2">Robotic arm</td></tr>
<tr><td>Robotic arm</td><td>Clamping mechanism</td></tr>
<tr><td rowspan="5">Nano/micro structures (1 – 100 kg)</td><td>Clamping mechanism or tentacles</td><td>Clamping mechanism or tentacles</td><td>Clamping mechanism or tentacles</td></tr>
<tr><td>Net</td><td>Net</td><td>Net</td></tr>
<tr><td>Robotic arm</td><td rowspan="3">Robotic arm</td><td rowspan="3">Robotic arm</td></tr>
<tr><td>Drag augmentation device</td></tr>
<tr><td>Tether</td></tr>
</table>

* Controlled re-entry. The combination of robotic arm with clamping mechanism is driven by the constraint of transferring the deorbitation ΔVs properly, ensuring that the attitude of the stack is the correct one and compliant with the robotic arm joints.

** Uncontrolled re-entry.

- Available information at consortium level

The proposed case studies have been selected taking into account those platforms with in-house information in order to exploit the available data.

5.2. SELECTED CASES

5.2.1. LEO SATELLITE

SEOSAT/Ingenio mission is based on an Earth Observation Satellite devoted to provide high resolution multispectral land optical images to different Spanish civil, institutional and governmental users. Managed by Spanish governmental instances with technical and support from the ESA, Airbus D&S in Spain is the prime contractor leading the industrial consortium,

It is composed by the satellite platform, the primary payload (the optical instrument) and three complementary scientific ones: the Sensosol (light incident angle sensor), two towers (proton dosimeter & spectrometer) and the UVAS (UV Visible and NIR Atmospheric Sounder)

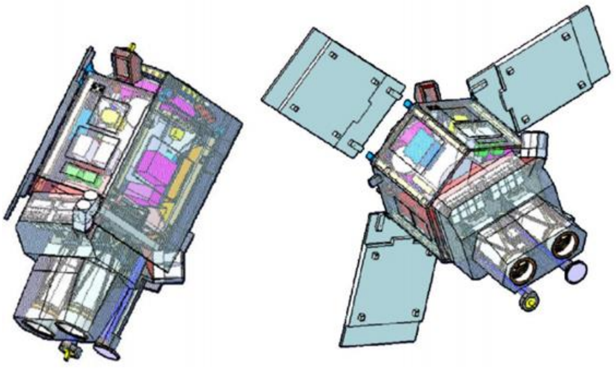


Figure 5-1 SEOSAT Overview

5.2.2. MULTIPLE PAYLOAD DISPENSER PLATFORM

There are a great spectra of payload adapter structures and the awareness of the space debris problem is something relatively new. For this reason there are large amounts of such structures orbiting the Earth. Such systems require many times several orbital manoeuvres to detach the multiple payloads and the encapsulation structure. Among the big chunks of debris, several small pieces are generated, but are not taken into account.

Three different multiple payload dispensers are proposed for this study:

- For Ariane 5 is Sylda (SYstème de Lancement Double Ariane).
- For Vega is Vespa (VEga Secondary Payload Adapter.
- For Soyuz ST is ASAP-S.

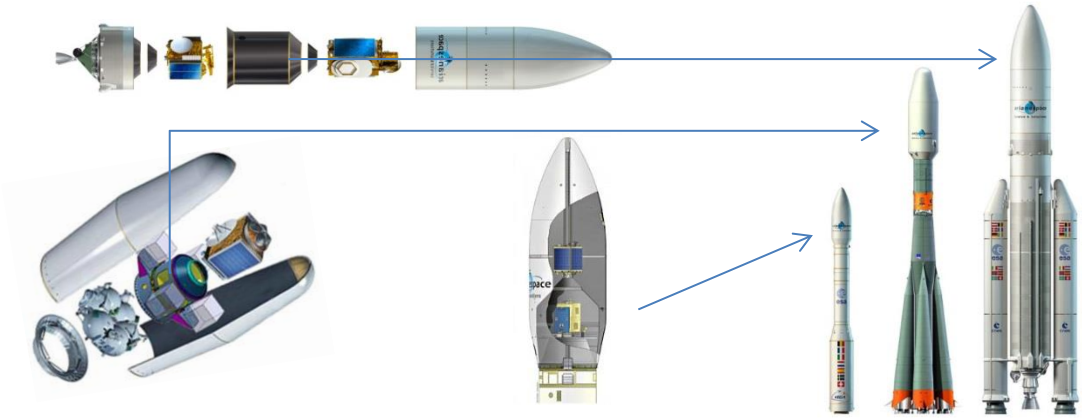


Figure 5-2 Multiple Payload Dispenser Concept and Launchers

Figure 5-3 Platforms, SYlda (left), Vespa (centre), ASAP-S (right)

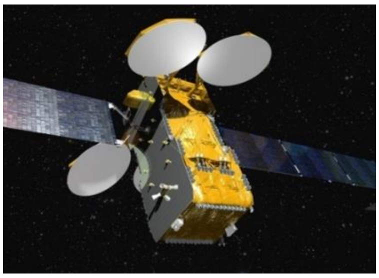
Next table provides a summary of main launcher characteristics, i.e. orbit, adapter mass and upper stage.

Table 5-2 Summary of Launcher Data

Launcher	Adapter	Orbit	Adapter Mass	Upper Stage
Ariane 5	SYLDA 5	GTO	425-550	ESC-A
Vega	VESPA	LEO/SSO	80-110	AVUM
Soyuz ST	ASAP-S	LEO/SSO	170-190	FREGAT

5.2.3. GEO SATELLITE

The Eurostar 3000, from Airbus D&S has been selected as reference platform for the case study of GEO satellites because is the most commonly used today for commercial and military purposes. This bus can be modified to meet customer requirements, but most of these satellites have a launch mass of between 4,500 and 6,000 kg.



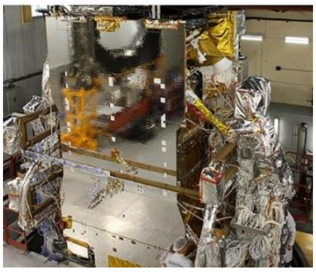


Figure 5-4 Eurostar 3000 Platform-Based Satellites.

5.2.4. MEGACONSTELLATION SATELLITE

A generic satellite constellation of 700 satellites in charge of providing global internet broadband service to individual consumers is considered. These communication satellites of around 150 Kg of mass will operate in circular low Earth orbit in 18 orbital planes at 1,200 km altitude.

The satellites will be designed to comply with "orbital debris-mitigation guidelines for removing satellites from orbit and, for low-orbit satellites, assuring that they re-enter the Earth's atmosphere within 25 years of retirement, but in order to cope with possible failures of the disposal strategy, the platform is equipped with a mechanical fixture to grasp the satellite.

Figure 5-5 Mega-Constellation Satellite

6. PRELIMINARY ASSESSMENT OF D4R AIDING CONCEPTS

This section introduces the preliminary assessment of the system impact of the selected SDRS aiding concepts derived from the review of the SDRS technologies and contained in section 4. in order to identify and select the most promising aiding concepts for the conceptual design and integration in the selected case studies with the purpose of identifying a set of recommendations for their integration in future spacecraft.

6.1. EVALUATION CRITERIA AND ASSESSMENT APPROACH

This section introduces the criteria used in order to assess the impact of the different proposed aiding concepts on ADR missions for the different selected scenarios, i.e. LEO, MPD, GEO and MC.

Not only the criteria and their score are introduced, the approach followed in the preliminary assessment is also presented. Afterwards the applicability of the selected SDRS aiding concepts is introduced and finally the results of the assessment are presented.

6.1.1. DEFINITION

The evaluation criteria are organized in three different categories in order to cover different points of view of the impact of the proposed SDRS aiding concepts under analysis. These categories are performance, technical and programmatic. For each category a set of different criteria are introduced and some of them are divided into sub-criteria in order to ease the assessment of the SDRS aiding concepts in the selected scenarios and case studies.

The following levels are identified in the evaluation criteria:

- Level 1 represents the three main categories of the evaluation criteria, i.e. performance, technical and programmatic.
- Level 2 and 3 represents the different criteria to be considered for each category.
- Level 4 represents the different sub-criteria that can be used in order to characterise the criterion to which they belong. A dedicated score is defined for each single sub-criterion in order to characterise the impact of the aiding concept under analysis on the ADR mission.

The following tables provide a description of the proposed criteria to be applied. The information provided in the "Clarifications" column defines the purpose of each single criterion to be assessed.

The following table contains the criteria included in the performance category.

Table 6-1 Performance Criteria

Level 2	Level 3	Level 4	Clarifications
Reduction in mission risk	Collision risk	Attitude motion not precisely known	Characterization of the support provided by the aiding concept in the frame of the target attitude estimation.
		GNC operation at design limits	Characterization of the support provided by the aiding concept in order to reduce the operation of the chaser GNC.
		Ability of mechanical interface to withstand capture and detumbling loads	Characterization of the support provided by the aiding concept to transfer loads and torques during capture and stabilization phases.
	Debris generation risk	Tearing of MLI	Characterization of the support provided by the aiding concept in order to reduce the tearing of MLI during direct contact between chaser and target.
		Jettison of capture device	Characterization of the support provided by the aiding concept in order to reduce the jettison of the capture device.
	Unsuccessful detumbling	-	Characterization of the support provided by the aiding concept in the frame of target attitude stabilization.
Complexity	-	Complexity of rendezvous and synchronisation	Characterization of the support provided by the aiding concept during the rendezvous and synchronisation phases.
		Complexity of capture	Characterization of the support provided by the aiding concept during the capture phase.
		Complexity of detumbling	Characterization of the support provided by the aiding concept during the stabilisation phase.
		Chaser design complexity	Characterization of the support provided by the aiding concept in the chaser design reducing its complexity.
Synergy with In-Orbit Servicing	-	-	Characterization of the applicability of the aiding concept to in-orbit servicing.
Flexibility	-	Applicability to multiple SDRS segments	Characterization of the applicability of the aiding concept to different SDRS segments or phases.
		Applicability to multiple SDRS technologies	Characterization of the applicability of the aiding concept to different SDRS technologies.
		Use during nominal and end-of-life operations	Characterization of the operability of the aiding concept during nominal and end-of-life operations.

The following table contains the criteria included in the technical category.

Table 6-2 Technical Criteria

Level 2	Level 3	Level 4	Clarifications
Power	-	Active or passive device from target point of view	Characterization of the aiding concept power needs.
Mass	-	-	Characterization of the impact of the aiding concept on the S/C mass.
Dimensions/Accommodation	-	-	Characterization of the impact of the aiding concept on S/C dimensions and equipment accommodation.
Inertia	-	-	Characterization of the impact of the aiding concept on S/C inertia.
TRL	-	-	Characterization of the maturity of the technology applied/used by the aiding concept.

The following table contains the criteria included in the programmatic category.

Table 6-3 Programmatic Criteria

Level 2	Level 3	Level 4	Clarifications
Impact at system level		Impact on design phase	Characterization of the impact of the aiding concept on S/C design phase.
		Impact on manufacturing	Characterization of the impact of the aiding concept on S/C manufacturing.
		Impact on AIT	Characterization of the impact of the aiding concept on S/C AIT phase.
Development cost	-	-	Characterization of the aiding concept development cost.
Recurrent cost	-	-	Characterization of the aiding concept recurrent cost.

6.1.2. SCORING METHOD

The scoring method for the SDRS concepts w.r.t. a particular criterion can be defined based on different rating approaches. The following groups of rating approaches are applicable to the evaluation criteria to be considered for SDRS aiding concept assessment:

- Specific quantity. If a particular aspect of a concept can be measured, counted, quantified or otherwise specified in detail, then the quantity itself can be used to score a concept. For instance the number of segments at which the aiding concept can be applied.
- Binary rating. In some cases, a concept either has a characteristic or it doesn't: it's either capable or incapable of doing something, has or doesn't have a certain desirable quality. For example, a system can be either passive or active. If passive systems are desirable, then all concepts that are passive would have a high score and all concepts that are active would have a low score.
- Qualitative or semi-qualitative rating. In many cases the score needs to be assigned by means of guided engineering judgement. In this case, the range of allowable scores should preferably lie between 3 and 5 (for example {good, intermediate, bad} is an example of a scoring range of 3 and {very good, good, middle, bad, very bad} is an example of a scoring range of 5), because it is still possible to discriminate between divisions.

Taking into account these different rating approaches the following elements shall be considered in order to define the scoring method:

- Lower bound: It defines the minimum value assigned during the rating of a particular criterion.
- Upper bound: It defines the maximum value assigned during the rating of a particular criterion.
- Normalized score. It defines the rating scale to be applied to compare the different concepts based on a group of criteria.

For this study it has been deemed desirable to obtain final scores ranging from 1 to 10, where 1 is the lowest, least desirable score and 10 is the highest, most desirable score. The rating score is therefore normalized to be between 1 and 10. The conversion between the value assigned to a criterion and the score from 1 to 10 is given by:

Linear: $Score = \frac{V-V_0}{V_{max}-V_0} \cdot 9 + 1$ Inverse: $Score = 10 - 9 \cdot \frac{V-V_0}{V_{max}-V_0}$

where

V is the value assigned to the alternative

V_0 is the minimum possible value in the range for the trade criterion under consideration

$V_{\max}$ is the maximum possible value in the range for the trade criterion under consideration

6.1.3. PRELIMINARY ASSESSMENT METHOD

The following lines provide a description of the method applied in the preliminary assessment of the SDRS aiding concepts w.r.t. the evaluation criteria for the selected case studies.

The following steps are followed to get the score:

- Every single criterion from level 4 is characterised by its score.
- Every single criterion from level 2/3 is characterised by the weighted score of the available sub-criteria.
- Each category score is then obtained as the weighted score of the available criteria within the category.

One advantage of this approach is that it is possible to characterise one criterion by decomposition into simpler elements, sub-criteria that may be easier to score. Then with these dedicated marks, it will be possible to get the corresponding mark for the criterion of the upper level.

In this preliminary assessment all the sub-criteria are equally considered or weighted to build up the score of each single criterion and in the same way all the criteria are equally considered to get the score for each category.

6.2. AIDING CONCEPT APPLICABILITY

The following table contains a preliminary assessment of the applicability of the proposed SDRS aiding concepts to the selected case studies. The following notation is used in the table:

- ✓✓ stands for high applicability.
- ✓ stands for low applicability.
- × stands for no applicability.

Table 6-4 Applicability of Proposed SDRS Aiding Concepts

Proposed SDRS Aiding Concept	LEO S/C	MPD	GEO S/C	Mega-constellation S/C	Remarks
State Estimation Enhancement					
Optical marker	✓✓	✓✓	✓✓	✓✓	Markers are applicable to all scenarios.
Photo-luminescent marker	✓✓	✓✓	✓✓	✓✓	Markers are applicable to all scenarios.
Thermal marker	✓✓	✓✓	✓✓	✓✓	Markers are applicable to all scenarios.
Large retroreflector	✓✓	✓✓	✓✓	×	Not applicable to mega-constellation taking into account mass and dimensions constraints.
Small retroreflector	✓✓	✓✓	✓✓	✓✓	Retroreflectors are applicable to all scenarios
Active Navigation Aids					
GNSS receiver	✓✓	×	×	✓	Applicable to LEO and with power supply during operational lifetime. Less suitable for mega-constellation due to moderate to high mass for inter-satellite communication equipment. The first civilian operational use of GNSS at GEO is reported in [RD.10] and [RD.11], but this aiding device is not considered in the present study for GEO.
Radio frequency	✓✓	×	✓✓	✓	Applicable to scenarios with power supply during operational lifetime. Less suitable for mega-constellation due to moderate to high mass.
LEDs	✓✓	×	✓✓	✓✓	Applicable to scenarios with power supply during operational lifetime. No suitable for Multiple Payload Dispenser.

Proposed SDRS Aiding Concept	LEO S/C	MPD	GEO S/C	Mega-constellation S/C	Remarks
Detumbling Devices					
Eddy current enhancer	✓✓	✓✓	✗	✓✓	Applicable to LEO scenarios. Low magnetic field in GEO.
Mechanical vibration damper	✓✓	✓	✓✓	✓✓	Suitable to stabilize attitude. Less suitable for MPD if deployable mechanisms are considered and to be compliant with accommodation.
Gravity gradient boom	✓✓	✗	✓	✓✓	Applicable to LEO scenario. No applicable to MPD to avoid including deployable mechanisms. Less suitable for GEO.
Design Rules					
Reduction of vibrations	✓✓	✓✓	✓✓	✓✓	Applicable to all scenarios.
Inertia matrix constraints	✓✓	✓✓	✓	✓✓	Less suitable for GEO because of lower gravity gradient.
Flat zone around COM	✓	✓	✓	✓	Shepherding techniques fairly insensitive to geometry; it is more important to have a large area to mass ratio.
Access to disposal devices	✓✓	✓✓	✗	✓✓	Passive disposal devices are not suitable for GEO.
Reinforce structural hard points	✓✓	✓✓	✓✓	✓✓	Applicable to all scenarios.
Dedicated zone for disposal kit installation	✓✓	✓✓	✓	✗	Less suitable for GEO, trade-off of RdV and CAP with chaser w.r.t. disposal sub-satellite. Not suitable for mega-constellation platform, accommodation constraints.
Detailed spacecraft documentation	✓✓	✓✓	✓✓	✓✓	Applicable to all scenarios.
Structural Fixtures					
Robotic arm grappling fixture	✓✓	✓✓	✓✓	✓✓	Applicable to all scenarios.
Clamping mechanism interface	✓✓	✓✓	✓✓	✓✓	Applicable to all scenarios.
Grasping mechanism for apogee nozzle	✗	✗	✓✓	✗	Only applicable to GEO platform. Other scenarios do not have a nozzle to be considered as the based on which the grasping mechanism is mounted.

6.3. ASSESSMENT RESULTS

This section contains the results of the preliminary assessment of the proposed aiding concepts from section 4. for the selected scenarios, LEO, Multiple Payload Dispenser, GEO and mega-constellation, in order to identify the most promising concepts.

6.3.1. LEO SCENARIO

This section contains the results of the preliminary assessment of the system impact for the different types of aiding device categories in the frame of LEO scenario.

- State estimation enhancement devices: Optical markers and small retroreflectors are identified as the most promising aiding devices in order to enhance the state estimation in the LEO scenario. The performance and technical categories are ruled by the optical markers and small retroreflectors and the programmatic category by the markers because their impact at system level and cost should be lower than the retroreflector cost.
- Active navigation aids: LEDs are the most promising active navigation aid in LEO scenario, higher scoring in the three categories. The higher scoring in the performance category is driven by the reduction in mission risk provided by these elements that can support the relative attitude estimation. In the technical category LEDs get higher scoring from their lower mass w.r.t. GNSS receiver and radio frequency devices and lower impact on payload accommodation and inertia. Finally in the programmatic category lower impact at system level and cost makes LEDs also the most promising aiding devices in the frame of active navigation aids.
- Detumbling devices: Eddy current enhancers are identified as the most promising detumbling devices for LEO scenario based on their higher scoring in the programmatic category, lower impact at system level and cost. The scoring of the technical category is very similar for all of them and in the performance category eddy current enhancers get the same scoring as the mechanical vibration dampers.
- Design rules: It is very clear that detailed S/C documentation is identified as the most promising design rule to support the future design and operation of ADR missions. In a second group, those design rules that support the capture and disposal segments are identified as potential candidates to be explored, i.e. reduction of vibrations, inertia matrix constraints and reinforcement of structural hard points.
- Structural fixtures: The robotic arm grappling fixture is identified as the most promising aiding concept based on the scoring in the technical and programmatic categories, but it is also important to take into account that a possible combination of these two aiding devices is needed in order to ensure a proper application of the disposal burns in a controlled re-entry, based on S/C mass and payload to ensure a safe re-entry.

6.3.2. MPD SCENARIO

This section contains the results of the preliminary assessment of the system impact for the different types of aiding device categories in the frame of MPD scenario.

- State estimation enhancement devices: The same remarks as the ones derived for LEO scenario can be derived for MPD, but it is important to take into account that the retroreflectors have a higher impact on the design and AIT activities for the MPDs and then their scoring is lower in this scenario. Optical markers and small retroreflectors are identified as the most promising aiding devices in order to enhance the state estimation in the MPD scenario. The performance and technical categories are ruled by the optical markers and small retroreflectors and the programmatic category by the markers because their impact at system level and cost should be lower than the retroreflector cost.
- Detumbling devices: Eddy current enhancers are identified as the most promising detumbling devices for MPD scenario based on their higher scoring in the programmatic category, lower impact at system level and cost. The scoring of the technical category is higher for the eddy current enhancers and in the performance category eddy current enhancers get the same scoring as the mechanical vibration dampers.
- Design rules: It is very clear that detailed S/C documentation is identified as the most promising design rule to support the future design and operation of ADR missions. In a second group, those design rules that support the capture and disposal segments are identified as potential candidates to be explored, i.e. reduction of vibrations, inertia matrix constraints and reinforcement of structural hard points.
- Structural fixtures: The robotic arm grappling fixture is identified as the most promising aiding concept based on the scoring in the technical and programmatic categories.

6.3.3. GEO SCENARIO

This section contains the results of the preliminary assessment of the system impact for the different types of aiding device categories in the frame of GEO scenario.

- State estimation enhancement devices: The same remarks as the ones derived for LEO scenario can be derived for GEO, but it is important to take into account that the retroreflectors have a higher impact on the possible accommodation in the S/C and on the design and AIT activities for the GEO S/C and then their scoring is lower in this scenario. Optical markers and small retroreflectors are identified as the most promising aiding devices in order to enhance the state estimation in the GEO scenario. The performance and technical categories are ruled by the optical markers and small retroreflectors and the programmatic category by the markers because their impact at system level and cost should be lower than the retroreflector cost.
- Active navigation aids: LEDs are the most promising active navigation aid in GEO scenario, higher scoring in the three categories. The higher scoring in the performance category is driven by the reduction in mission risk provided by these elements that can support the relative attitude estimation. In the technical category LEDs get higher scoring from their lower mass w.r.t. radio frequency devices and lower impact on payload accommodation and inertia. Finally in the programmatic category lower impact at system level and cost makes LEDs also the most promising aiding devices in the frame of active navigation aids.
- Detumbling devices: Mechanical vibration dampers are identified as the candidates to act as detumbling devices for GEO scenario based on their higher scoring in all the categories.
- Design rules: Detailed S/C documentation is identified as the most promising design rule to support the future design and operation of ADR missions. In a second group, those design rules that support the capture and disposal segments are identified as potential candidates to be explored, i.e. reduction of vibrations, inertia matrix constraints and reinforcement of structural hard points.
- Structural fixtures: The robotic arm grappling fixture is identified as the most promising aiding concept based on the scoring in the technical and programmatic categories, but it is also important to take into account that a possible combination with the clamping mechanism or apogee nozzle could be needed in order to ensure a proper application of the disposal burns to reach the cemetery orbits.

6.3.4. MC SCENARIO

This section contains the results of the preliminary assessment of the system impact for the different types of aiding device categories in the frame of MC scenario.

- State estimation enhancement devices: The same remarks as the ones derived for LEO scenario can be derived for MC, but it is important to take into account that the retroreflectors have a higher impact on the design and AIT activities for the MC and then their scoring is lower in this scenario. The retroreflectors are still considered because they provide support to rendezvous phases where the markers are not able of acting as aiding devices. Optical marker and small retroreflectors are identified as the most promising aiding devices in order to enhance the state estimation in the MC scenario. The performance and technical categories are ruled by the optical markers and small retroreflectors and the programmatic category by the markers because their impact at system level and cost should be lower than the retroreflector cost.
- Active navigation aids: LEDs are the most promising active navigation aid in MC scenario, higher scoring in the three categories. The higher scoring in the performance category is driven by the reduction in mission risk provided by these elements that can support the relative attitude estimation. In the technical category LEDs get higher scoring from their lower mass w.r.t. GNSS receiver and radio frequency devices and lower impact on payload accommodation and inertia. Finally in the programmatic category lower impact at system level and cost make LEDs also the most promising aiding devices in the frame of active navigation aids.
- Detumbling devices: Eddy current enhancers are identified as the most promising detumbling devices for MC scenario based on their higher scoring in the programmatic category, lower impact at system level and cost. The scoring of the technical category is very similar for all of them and in the performance category eddy current enhancers get the same scoring as the mechanical vibration dampers.
- Design rules: It is very clear that detailed S/C documentation is identified as the most promising design rule to support the future design and operation of ADR missions. In a second group, those design rules that support the capture and disposal segments are identified as potential candidates to be explored, i.e. reduction of vibrations, inertia matrix constraints and reinforcement of structural hard points.
- Structural fixtures: The robotic arm grappling fixture is identified as the most promising aiding concept based on the scoring in the technical and programmatic categories.

6.4. CONCLUSIONS

Based on the preliminary assessment outcomes reported in previous section it is possible to define the most promising aiding concepts to be considered in the conceptual and integration phases in order to analyse their impact at system level and try to derive a set of recommendations for their integration in the future spacecraft.

The following table defines the most promising aiding concepts to be further analysed. The applicable scenarios for each selected concept are defined in the table and additional remarks are added in order to complement the summary.

Table 6-5 Selected Most Promising Aiding Concepts for Conceptual Design Phase

Aiding Concept Category	Aiding Concept	Applicable Scenario	Remarks
State Estimation Enhancement	Optical marker	LEO, MPD,GEO and MC	Passive element, no power supply is needed.
	Retroreflector	LEO, MPD,GEO and MC	Passive element, no power supply is needed.
	Radio-frequency identification tag	LEO, MPD,GEO and MC	Passive element, no power supply is needed. This element has not been considered in the preliminary assessment, but it is identified as an interesting device to be included in the D4R conceptual design phase.
	LEDs	LEO, MPD,GEO and MC	Active elements, power supply is needed. These elements can be connected to solar arrays to get the needed power.
Detumbling Devices	Eddy current enhancers	LEO, MPD and MC	Applicable to multiple payload dispensers that operates in LEO.
	Mechanical vibration damper	GEO	
Design Rules	Detailed spacecraft documentation	LEO, MPD,GEO and MC	The type of documents that provide useful information from the D4R point of view are going to be defined in the frame of D4R conceptual design phase.
	Reduction of vibrations	LEO, MPD,GEO and MC	
	Inertia matrix constraints	LEO, MPD,GEO and MC	
Structural Fixtures	Robotic arm grappling fixture	LEO, MPD,GEO and MC	
	Reinforcement of structural hard points	LEO, MPD,GEO and MC	

7. CONCEPTUAL DESIGN OF D4R AIDING DEVICES

The following tables provides the outcomes of the conceptual design of the selected D4R aiding devices and define those aiding devices and concepts to be considered for the design and integration activities to derive the system impact analyses for the selected case studies, see section 8. .

Table 7-1 D4R Selected Aiding Concepts for System Impact Analyses (State Estimation Category)

Category	Aiding Concept	Selection Flag	Justification
State estimation enhancement for SST and RdV	Optical markers	✓	This aiding concept has been identified as the most promising one in terms of support provided during the rendezvous operations based on visual navigation. They provide support to identify the different S/C panels and grasping point and support the relative navigation in terms of translational and rotational state. The impact on the development cost is low taking into account their low impact on manufacturing and AIT processes. It is also important to highlight that design activities to define the patterns and location of the markers can be standardized in order to define guidelines or rules to be applied for other spacecraft.
	Retroreflectors	✓	This aiding concept has been selected as the only device that can support the SST segment of ADR missions based on the use of laser ranging stations on ground. This aiding concept also provides important support to RdV segment in terms of identification of grasping point and estimation of translational and rotational state of the target spacecraft based on laser navigation sensors available on chaser. The possible use of COTS retroreflectors can reduce the cost associated to the use of these aiding devices in the frame of future S/C developments and will provide an important support to ADR missions.
	Radio-frequency tags	✗	This aiding concept has been discarded for the system impact analyses because of the small support provided during RdV segment based on: - Only S/C panel identification is possible. - Short operation range. - Need of dedicated sensor to activate and read the RFID tag information, RFID reader.
	LEDs connected to solar array	✗	This aiding concept has been discarded because its complex operation, i.e. shall be activated at the end of operational life and would be active only during periods where the sun is illuminating the solar panels.

Table 7-2 D4R Selected Aiding Concepts for System Impact Analyses

Category	Aiding Concept	Selection Flag	Justification
Detumbling devices	Eddy current enhancer	✓	This passive attitude stabilization concept is applicable to LEO spacecraft and the system impact analyses for the selected study cases can identify those areas that shall be investigated to implement this aiding concept. For example, the computation of the magnetic matrix and the integration of these elements in the structure.
	Mechanical vibration dampers	✓	This passive stabilization concept could represent an option to stabilize the attitude of spacecraft located in MEO and GEO region.
Design rules	Detailed spacecraft documentation	✓	The support provided by detailed spacecraft documentation shall be analysed based on the information that is available for this study. If some useful information is needed to perform the system impact analyses for the rest of aiding concepts and it is not available, the document that should contain the requested information could be identified. With this approach it is possible to provide justification to support the need of detailed documentation for ADR mission design.
	Inertia matrix constraints	✓	In the frame of the system impact analyses the inertia matrix of the different spacecraft will be used and additional recommendations for future development could be identified.
	Reduction of vibrations	✓	In the frame of the system impact analyses the reduction of vibrations will be a topic that shall be addressed and additional recommendations for future development could be identified.
Structural fixtures	Robotic arm grappling fixture	✓	This aiding concept has been selected in order to focus the effort devoted to system impact analyses on the capture mechanism with more heritage and experience in space missions and in this way maximise the outcomes. Furthermore the reinforcement of S/C structure shall also be addressed under the consideration of this aiding device in order to ensure that the capture and disposal loads are correctly handle.
	Reinforcement of structural hard points	✘	This aiding concept has been discarded for the system impact analyses because the reinforcement criteria shall be applied in the frame of the system impact analyses for robotic arm grappling fixture.

The following table provides a summary of the aiding concepts that are going to be considered in the frame of System Impact Analyses and the case studies for each aiding concept:

Table 7-3 D4R Selected Aiding Concepts and Case Study Applicability for System Impact Analyses

Category	Aiding Concept	Case Study
State estimation enhancement for SST and RdV	Optical markers	LEO-SEOSAT MPD-SYLDA5 MPD-ASAP-S MPD-VESPA GEO- EUROSTAR3000 MC- SC
	Retroreflectors	LEO-SEOSAT MPD-SYLDA5 MPD-ASAP-S MPD-VESPA GEO-EUROSTAR3000 MC-SC
Detumbling devices	Eddy current enhancer	LEO-SEOSAT MPD-ASAP-S MPD-VESPA MC-SC
	Mechanical vibration dampers	GEO–EUROSTAR3000
Design rules	Detailed spacecraft documentation	LEO-SEOSAT MPD-SYLDA5 MPD-ASAP-S MPD-VESPA GEO-EUROSTAR3000 MC-SC
	Inertia matrix constraints	LEO-SEOSAT MPD-SYLDA5 MPD-ASAP-S MPD-VESPA GEO-EUROSTAR3000 MC-SC
	Reduction of vibrations	LEO-SEOSAT MPD-SYLDA5 MPD-ASAP-S MPD-VESPA GEO-EUROSTAR3000 MC-SC
Structural fixtures	Robotic arm grappling fixture	MPD-SYLDA5 MPD-ASAP-S MPD-VESPA MC-SC
	Robotic arm grappling fixture + Reinforcement (support of clamping mechanism)	LEO-SEOSAT GEO-EUROSTAR3000

8. SYSTEM IMPACT ANALYSIS OF D4R AIDING DEVICES

This section provides the results of the system impact analysis for the selected aiding devices based on the design and integration of the ADR Aiding Devices Subsystem on the selected case studies.

A set of guidelines to design and integrate the ADR Aiding Devices Subsystem, ADR-ADS, i.e. the selected aiding concepts to support the future ADR missions are followed in order to define the role of the ADR support engineers along the nominal project life cycle.

The designs proposed here should be considered as an application exercise of the proposed guidelines in order to assess system impact. The design in a space project would require the use of more detailed tools e.g. Monte Carlo campaigns, CAD drawings and detailed part models, structural and electromagnetic FEM models…

The proposed steps are the following ones:

- End-of-life characterisation: The estimation of the EOL state shall be used to design the different ADR aiding elements. During a spacecraft design, it would be useful to define an envelope of the possible EOL states and their probability, to obtain:
  - End-of-life rotational state.
  - Identification of possible rendezvous strategies, based on the EOL rotational state.
  - Estimation of disposal strategies.
- Design and integration of ADR aiding devices: The inputs generated in the EOL characterization, plus the available S/C data like MCI properties and platform layout, are used to dimension and integrate the different ADR aiding devices. The considerations to introduce the different elements are:
  - State estimation enhancement elements: Their design is based on EOL state and rendezvous strategies, aiming to optimize their utility for as many mission phases as possible. Large retroreflectors shall be located in the face expected to point towards the Earth with more frequency, while small RR and visual markers should support navigation for the expected approaching strategies, also in conjunction with the location of structural interfaces.
  - Detumbling devices: Their design is based on EOL rate, spacecraft orbit and MCI properties. It is also a trade-off between mass impact on operational life and detumbling time, meaning that usually larger devices can stop high spins faster, at the cost of increasing the mass budget. The design can undergo an optimization process based on the maximum expected spacecraft rate and the time required to launch an ADR mission.
  - Structural interfaces: Their design is based on EOL state, approach strategies, disposal strategies and MCI properties, the different grasping points are distributed considering the best capture directions. The dimensioning process takes into account the loads induced during the disposal manoeuvres. The following disposal strategies are considered for the different selected case studies:

Table 8-1 Disposal Strategies and Case Studies

Scenario	Case Study	Orbit	Disposal Strategy	Comments
LEO	SEOSAT	SSO at 670 km	Controlled re-entry	Use of robotic arm and clamping mechanism
MPD	SYLDA5	GTO at 200/700 x 20000/36000 km	Uncontrolled re-entry	Robotic arm
	ASAP-S	SSO at 620 km	Uncontrolled re-entry	Robotic arm
	VESPA	SSO at 675 km	Uncontrolled re-entry	Robotic arm
GEO	EUROSTAR 3000	GEO	Graveyard orbit	Robotic arm and clamping mechanism
MC	MC-SC	LEO at 1200 km	Uncontrolled re-entry	Robotic arm

8.1. FUNCTIONAL DESCRIPTION AND APPLICABILITY

This section introduces the assumptions and models used to analyse the different ADR aiding elements.

8.1.1. STATE ESTIMATION ENHANCEMENT DEVICES

The different devices considered for this purpose, as well as their dimensions and uses, are:

- Retroreflector arrays: These devices are used to enhance the satellite laser ranging campaigns and precisely determine the trajectory, helping possible CAM of other vehicles and the mission analysis of the future ADR mission. Two different kinds of arrays are considered:
  - Pyramidal RRA, used for low orbit satellites, which should support the orbit and state estimation from multiple ground locations. The baseline size considered is 5 cm.
  - Planar RRA, used for high orbit satellites, maximizing the reflected energy to enhance the detection at long distances. The baseline size is a rectangle of 300x260 mm^2.

  It is important to highlight the support that can be provided by these elements to SLR campaigns to be used in combination with other ground measurements to improve the estimation of the rotational state, as defined by [RD.9].
- Single retroreflectors: These devices are used to maximize the light reflected by laser-based sensors, increasing the range and offering a set of mark points that help attitude determination. The size considered is a square of 5x5 cm^2.
- Optical markers: These devices help camera navigation algorithms at close distances. The different navigation characteristics depend on the size and pattern of the markers, but are closely related to the properties of the cameras on the chaser. The space allocated is a square of 5x5 cm^2, although the characteristics could change to account for different chaser designs.

8.1.2. DETUMBLING DEVICES

The effects considered in this section are applicable to LEO spacecraft. At this altitude, the main perturbative torques are the gravity gradient and the Earth's magnetic field.

- The gravity gradient torque can be used to stabilize the spacecraft attitude around stable points. In a general case, high spin motions produce unbounded rotations, and the effect of this torque is to re-orient the angular rate vector due to gyroscopic precession. After an analysis of the gravity gradient potential, there are a set of possible stable rotations. The characteristics of the stable configurations are:
  - Angular rate parallel to axis of largest inertia in body frame.
  - Angular rate parallel to orbital angular momentum, with axis of maximum inertia pointing perpendicular to the orbital plane.

  These configurations are asymptotic. With said assumptions, under the presence of a dissipative torque the tendency of the system should be towards these stable points. However, this is an extremely simplified model and the evolution can be affected by multiple other factors. This tendency will be used to generate an estimation of the target state, but the design process during a space project should incorporate a more precise model of the torques.
- The magnetic field torque acts as a dissipative torque. It is produced by the currents induced within a conductor inside a varying magnetic field, which dissipate the spacecraft rotational energy by means of Joule effect. It can be enhanced by increasing the S/C conductivity, which is the purpose of the introduction of eddy current enhancers. In the current study, they have been modelled using [RD.7], based on an electromagnetic finite element model to determine the "magnetic matrix" which models the effect produced on a rotating spacecraft. The magnetic field used is obtained with a dipole model of the Earth's magnetic field, integrating the field in body axis along the operational spacecraft orbit to obtain mean values. The combination of magnetic matrix and magnetic field can be used to obtain an estimation of the angular rate decay time, which behaves as an exponential decay. The design of the eddy current enhancer has some degrees of freedom, like the cross sectional area, which can be used to modify the additional mass of these devices and the parameter of the exponential decay. This can be used, in combination with the expected angular rate at the EOL and the time required to launch an ADR mission, to dimension the eddy current enhancers.

8.1.3. STRUCTURAL FIXTURES

Two main strategies from the design and implementation point of view can be considered:

- The use of existing elements of the spacecraft designed for other functions, with the possibility of introducing minor modifications.
- Design new grasping features or devices to be added to the vehicle structure.

The first strategy could be applied to existing missions, while the second one can only be applied to future missions and would increase their cost. Two different strategies are considered, robotic arm and robotic arm plus clamping mechanism. It is necessary to consider the interaction between the robotic arm and the attachment point, assessing the risk of generating new debris due to mechanical shocks, but it could be possible to use multiple structural elements that are already installed in different vehicles. Adding a clamping mechanism might require reinforcing different points or areas, but it is assumed that these areas would be part of the primary structure.

8.1.4. DESIGN RULES

The following design rules are considered in the design and integration of ADR-ADS:

- Detailed S/C documentation: The availability of detailed documentation to support the ADR mission design and development plays a key role. For this reason in the design and development of the ADR Aiding Devices Subsystem, the effort devoted to the documentation activities shall be considered in order to ensure that the proper information related to this subsystem is available to ADR mission developers.
- Inertia matrix constraint: The impact of the design recommendations or constraints to the S/C inertia matrix are shown in several sections of the ADR-ADS design and integration. During the characterization of the end-of-life state the S/C inertia matrix characterises the impact of the gravity gradient on the attitude evolution. The design and integration of structural fixtures to support capture and disposal should also take into account the S/C inertia matrix and could introduce some recommendations or requirements to payload and equipment distribution during the S/C design and development.
- Reduction of vibrations: The design and integration of structural fixtures to support capture and disposal shall take into account this recommendation in order to avoid unintended breakups during capture, stack stabilization and disposal activities.

8.2. DESIGN AND INTEGRATION

8.2.1. LEO SCENARIO

The operational orbit of SEOSAT is a Sun-synchronous orbit of around 670 km of altitude. At this altitude, the orbital period is approximately 98 minutes. The two main disturbing torques that affect the attitude of the spacecraft are the Earth magnetic field and the gravity gradient torque.

The initial angular rate at the EOL proposed for this study is 0.25°/s which is based on its operational attitude profile. Considering additional factors could produce different values and rotation axes. Considering factors like discharge of control wheels would require a thorough study of all the possible contingencies, so the number provided for this document should be considered as a simple proof of concept. The rotational state is shown in the left image of Figure 8-1. The spacecraft would be rotating around one of the largest moments of inertia, with the angular rate pointing perpendicular to the orbital plane.

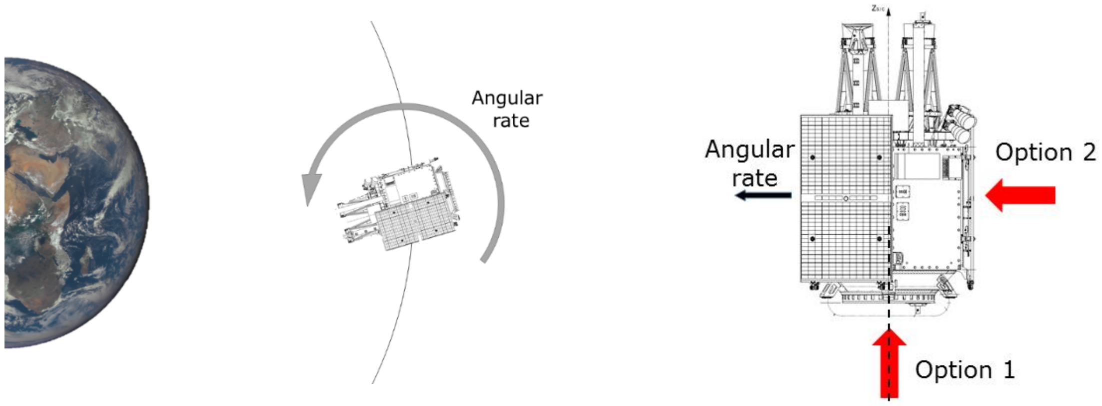


Figure 8-1 SEOSAT Expected Rotational State (Left) and Proposed Capture Axes (Right)

The right image of Figure 8-1 shows the two considered rendezvous strategies.

- Option 1 would be an approach through the orbital plane. The spacecraft would be captured using the I/F ring at the bottom of the platform, which is a fairly resistant interface. The downside of this strategy is that under the angular rate assumptions mentioned, the interface point would be moving due to the target rotation, increasing the capture complexity.
- Option 2 would be an out of plane approach. The chaser spacecraft would only need to synchronize its rotation with the target to perform the capture, but this strategy would require additional hardware on the target to be captured.

With these two mentioned strategies, the proposed state estimation enhancement devices are shown in Figure 8-2. The proposed distribution locates the elements close to the edges, to minimise the possible impact on radiators or insulation on the surface of the spacecraft. It could be also possible to incorporate elements in the faces supporting the solar panels, although the content of said faces is unknown and have not been considered in the current study.

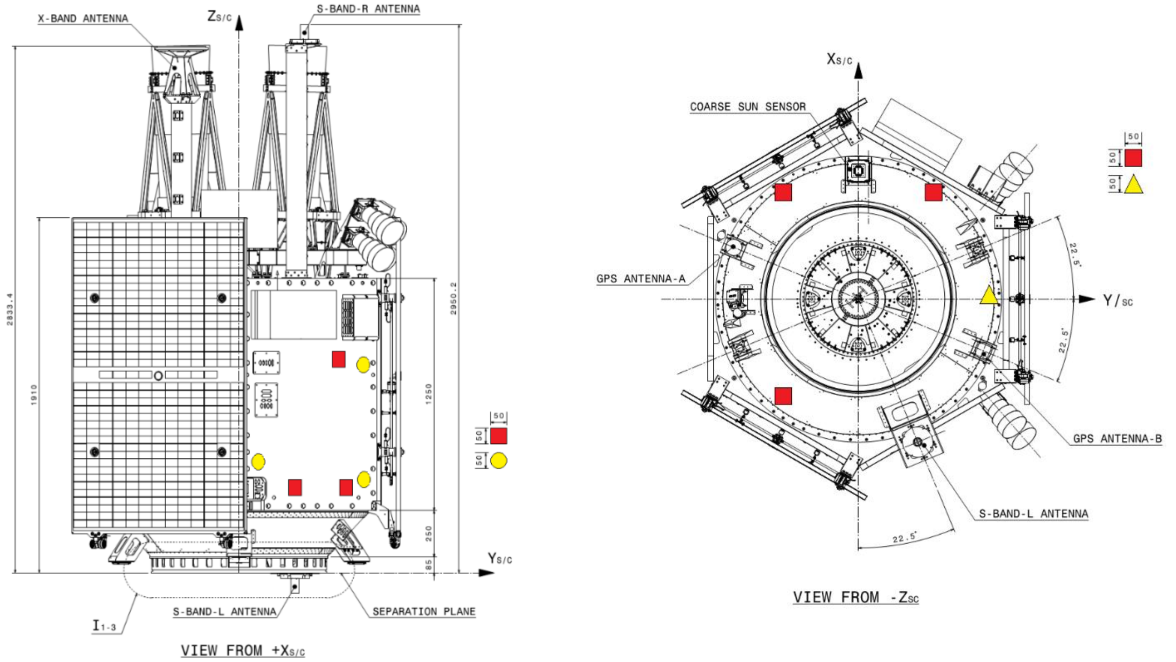


Figure 8-2 Optical Markers and Retroreflector Distribution, Optical Markers in Red, Yellow Squares for Single RR, and Yellow Triangles for RRA

The RR located on the lateral faces would support navigation in the orbital plane, while the optical markers would help navigation for the two proposed approaching strategies. The RRA located at the bottom of the spacecraft can be used to support SLR campaigns.

The detumbling devices considered are eddy current enhancers because the magnetic field is fairly strong at this 670 km altitude. The proposed approach to design the eddy current enhancer is shown in the technical note "D4R Aiding Concepts: System Impact Analyses", see [RD.4].

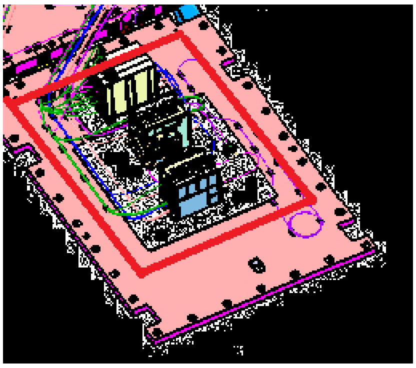


Figure 8-3 Possible Location of Coils as Detumbling Device

The approximate shape of the platform is a hexagonal prism with 1.2x0.9 m^2 faces. This element could be attached to each internal face of the spacecraft, both lateral and top/bottom faces. This solution represents a preliminary design that can be modified based on future technology assessments. Using a set of coils as described before, with a wire diameter of 15 mm would increase the mass by approximately 3.3 kg, which is roughly 0.5% of the 720 kg spacecraft mass. This addition would reduce the initial angular rate of 0.25°/s to 0.06°/s, approximately the angular rate of the orbital frame, in 5 and a half years. The addition of these devices would have a slight impact on the AOCS, due to the increased mass (translated into more propellant and thrust/control authority required) and the additional torques produced (also translated into more propellant). However, the first contribution should be small because the mass increase is small, while the second contribution is small because the angular rate during operations is also small. To obtain an estimate value of the effect of this cost, it should necessary to use detailed information regarding the AOCS of the platform, information that is available during the mission design phases.

8.2.2. MPD SCENARIO

8.2.2.1. Sylda

This MPD is used in high eccentricity GTO. This study uses mean values to estimate the behaviour of this dispenser, considering that the gravity gradient and magnetic torque values change depending on the orbital anomaly. The angular rate at the EOL considered is 1.12°/s, which was obtained assuming maximum errors after ejection from the launcher, and rotating the angular momentum vector towards the axis of maximum inertia, for simplicity of the study. The angular rate has been pointed perpendicular to the orbital angular momentum, also to reduce the complexity of the study. In a more detailed analysis, it could be interesting to perform a statistical approach to the EOL state, to dimension the detumbling devices.

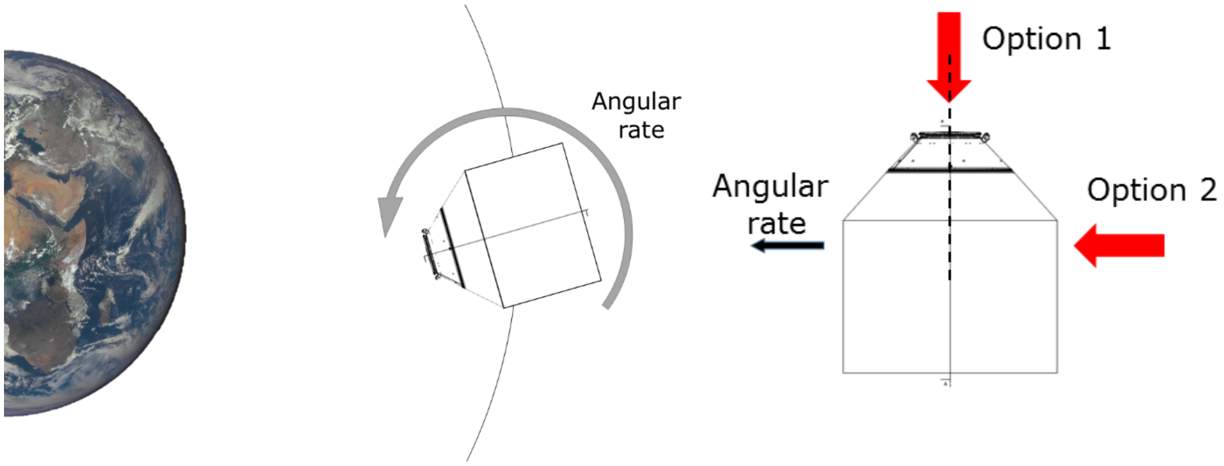


Figure 8-4 Sylda Expected Rotational State (Left) and Proposed Capture Axes (Right)

The right image of Figure 8-4 shows the two considered rendezvous strategies.

- Option 1 would be an approach through the orbital plane. The dispenser would be captured using the I/F ring at the top of the platform, which is a fairly resistant interface. The downside of this strategy is that under the angular rate assumptions mentioned, the interface point would be moving due to the target rotation, increasing the capture complexity.
- Option 2 would be an out of plane approach. The chaser spacecraft would only need to synchronize its rotation with the target to perform the capture, but this strategy would require additional hardware on the target to be captured.

With these two mentioned strategies, the proposed state estimation enhancement devices are shown in Figure 8-5. The proposed distribution locates the elements as far and equally distributed as possible to maximise the accuracy of the navigation algorithms, although different sets of elements could be used for different distances, considering the amount of free surface available. The RR located on the lateral faces would support navigation in the orbital plane, while the optical markers would help navigation for the two proposed approaching strategies. The RRA located at the top of the spacecraft can be used to support SLR campaigns.

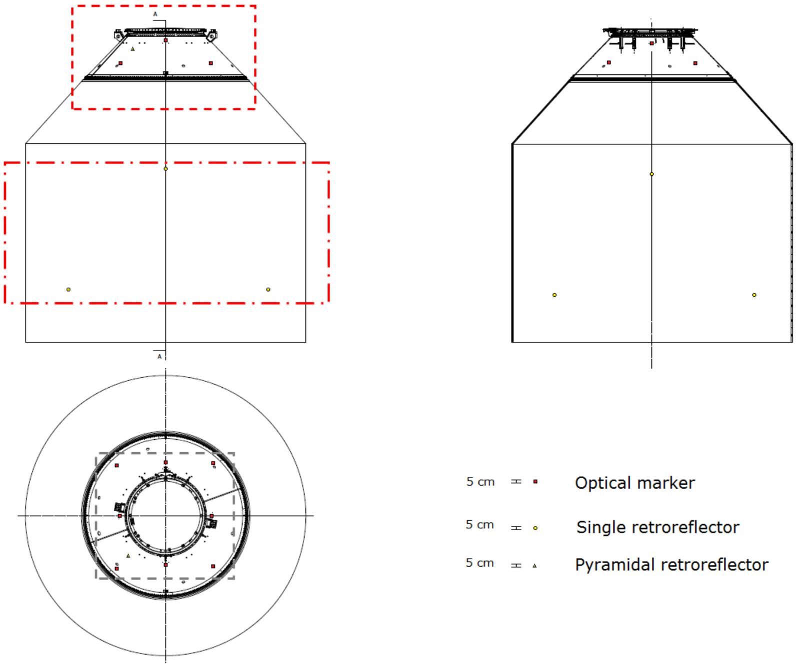


Figure 8-5 Proposed Navigation Aiding Elements for SYLDA

Eddy current enhancers are considered as an option for this MPD, even with the lower mean magnetic field due to the highly eccentric orbit. The proposed distribution, used to estimate the magnetic properties of these aiding devices, is shown in Figure 8-6.

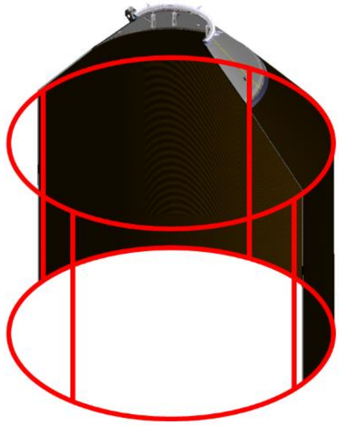


Figure 8-6 Detumbling Device Proposed for SYLDA

A device with that shape, made of aluminium and with cross section of 9 mm, produces a mass increase of 12.7 kg, which is a 2.7 % of the total mass of SYLDA. This device is not capable of damping the proposed angular rate, due to a combination of high inertia with lower mean magnetic field. This additional mass has been selected to compare the results with the other MPDs, even if it is not capable of performing the stabilization.

8.2.2.2. ASAP-S

The two main torques that appear in this scenario are the magnetic field of the Earth and the gravity gradient. The angular rate at the EOL considered is 1.45°/s, which was obtained assuming maximum errors after ejection from the launcher, and rotating the angular momentum vector towards the axis of maximum inertia, for simplicity of the study. The angular rate has been pointed perpendicular to the orbital angular momentum, also to reduce the complexity of the study. In a more detailed analysis, it could be interesting to perform a statistical approach to the EOL state, to dimension the detumbling devices.

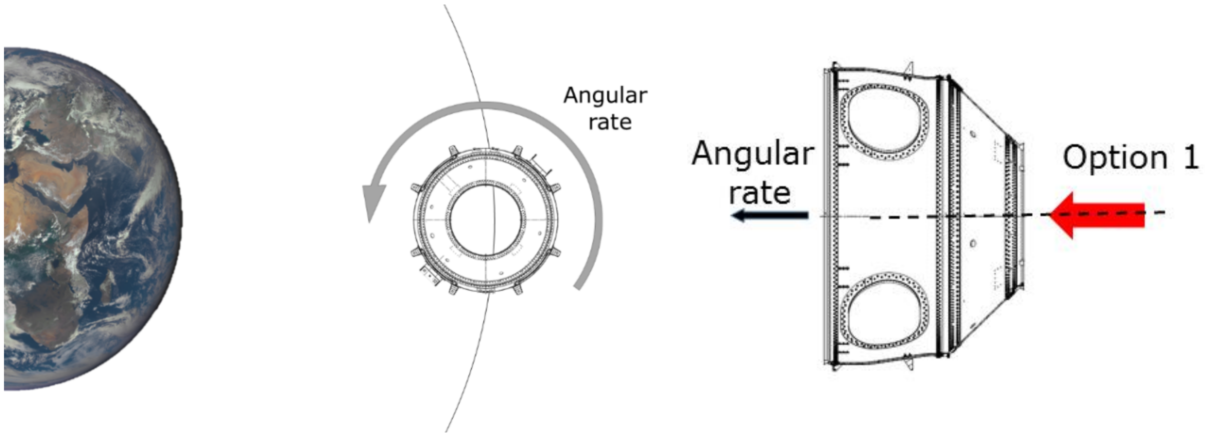


Figure 8-7 ASAP-S Expected Rotational State (Left) and Proposed Capture Axes (Right)

The right image of Figure 8-7 shows the considered rendezvous strategy. The capture axis, the symmetry axis and the rotation axis of the spacecraft are aligned, so that should be the easiest option to capture this element. The lateral holes are also viable option, in case the actual rotational state of the vehicle differs too much from this configuration.

With this mentioned strategies, the proposed state estimation enhancement devices are shown in Figure 8-8. The proposed distribution locates the elements as far and equally distributed as possible to maximise the accuracy of the navigation algorithms, although different sets of elements could be used for different relative distances, considering the amount of free surface available. The RR located on the lateral faces would support navigation in the orbital plane, while the optical markers would help navigation for the two proposed approaching strategies. The RRA located on the lateral face of the platform can be used to support SLR campaigns.

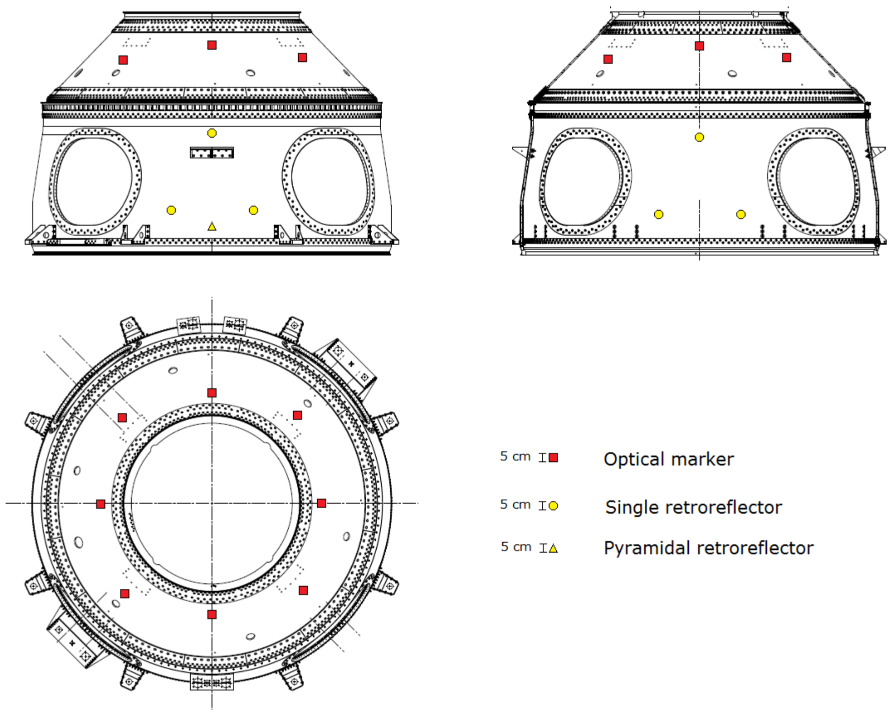


Figure 8-8 Proposed Navigation Aiding Elements for ASAP-S

Eddy current enhancers are considered as an option for this MPD. The proposed distribution used to estimate the magnetic properties of the eddy current enhancers is shown in Figure 8-9.

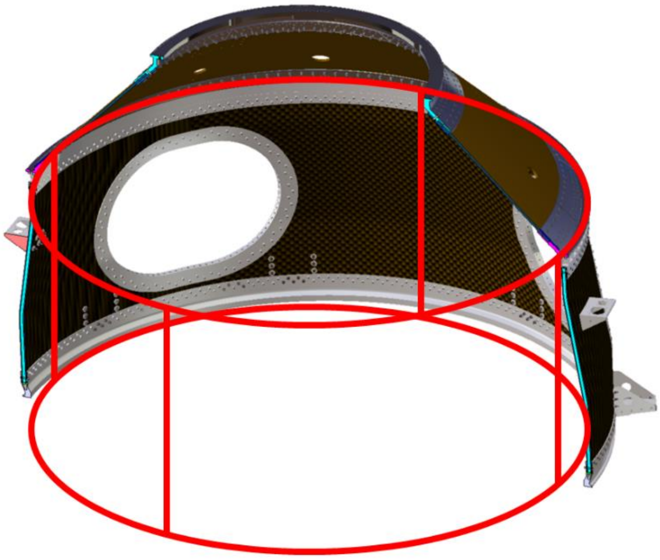


Figure 8-9 Detumbling Device Proposed for ASAP-S

A device with that shape, made of aluminium and with cross section of 9 mm, increases the mass by 3.3 kg, which is a 2.6 % of the initial 125.9 kg. This device could reduce the initial angular rate of 1.45 °/s to 0.06 °/s in about 5 years, with the preliminary study performed.

8.2.2.3. Vespa

The two main torques that appear in this scenario are the magnetic field of the Earth and the gravity gradient. The angular rate at the EOL considered is 1.85°/s, which was obtained assuming maximum errors after ejection from the launcher, and rotating the angular momentum vector towards the axis of maximum inertia, for simplicity of the study. The angular rate has been pointed perpendicular to the orbital angular momentum, also to reduce the complexity of the study. In a more detailed analysis, it could be interesting to perform a statistical approach to the EOL state, to dimension the detumbling devices.

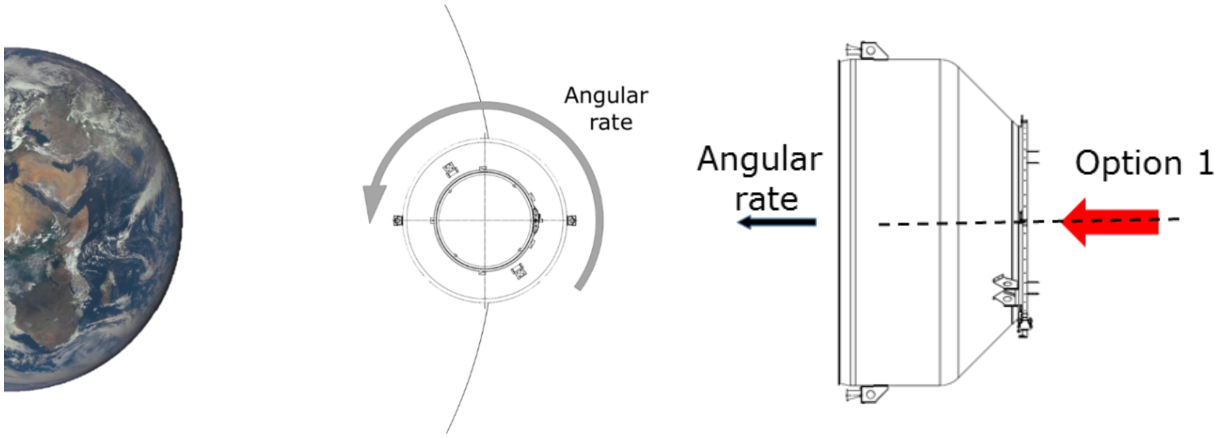


Figure 8-10 Vespa Expected Rotational State (Left) and Proposed Capture Axes (Right)

The right image of Figure 8-10 shows the considered rendezvous strategy. The capture axis, the symmetry axis and the rotation axis of the spacecraft are aligned, so that should be the easiest option to capture this element. The lateral holes are also viable option, in case the actual rotational state of the vehicle differs too much from this configuration.

With this mentioned strategies, the proposed state estimation enhancement devices are shown in Figure 8-11. The proposed distribution locates the elements as far and equally distributed as possible to maximise the accuracy of the navigation algorithms, although different sets of elements could be used for different relative distances, considering the amount of free surface available. The RR located on the lateral faces would support navigation in the orbital plane, while the optical markers would help navigation for the two proposed approaching strategies. The RRA located on the lateral face of the platform can be used to support SLR campaigns.

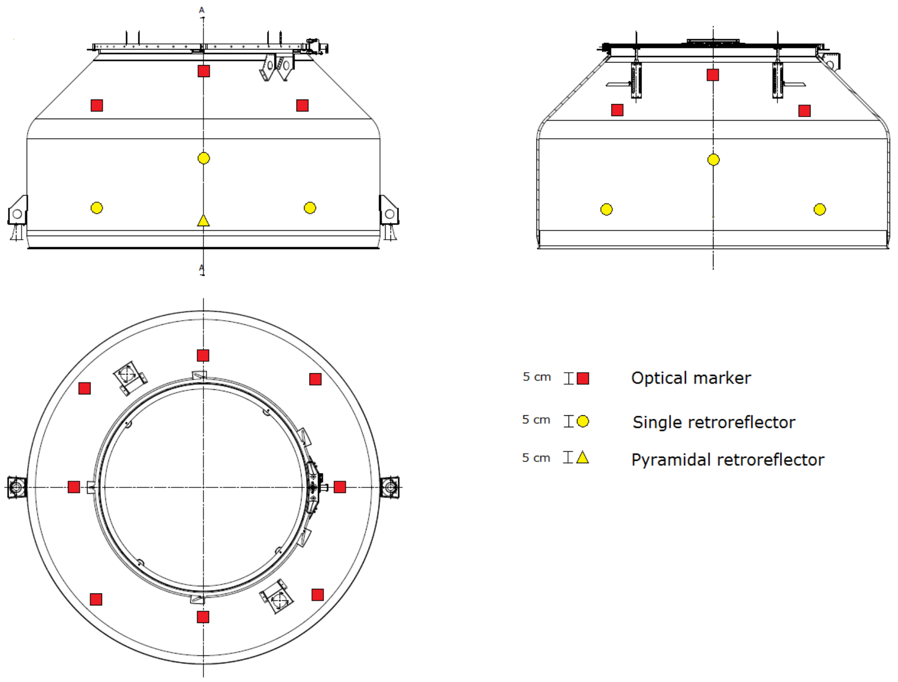


Figure 8-11 Proposed Navigation Aiding Elements for Vespa

Eddy current enhancers are considered as an option for this MPD. The proposed distribution, used to estimate the magnetic properties of the eddy current enhancers is shown in Figure 8-12.

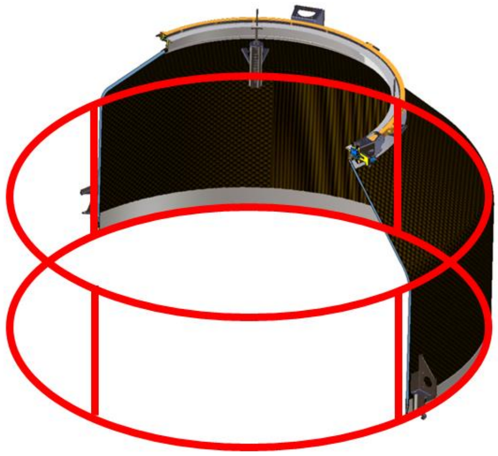


Figure 8-12 Detumbling Device Proposed for Vespa

A device with that shape, made of aluminium and with cross section of 7 mm, increases the mass by 2.2 kg, which is a 2.9 % of the initial 76.3 kg. This device could reduce the initial angular rate of 1.45 °/s to 0.06 °/s in about 6 and a half years, with the preliminary study performed.

8.2.3. GEO SCENARIO

The GEO environment has relatively low perturbing torques. Also, this platform operational attitude has only its antennae pointing towards the Earth. It is difficult to obtain an estimation of the spin rate that the spacecraft could experience, but a survey on multiple defunct super-GEO vehicles [RD.8] shows that, in most of the cases, the angular rate is low enough to perform a capture, which is the assumption used for this design process based on a nominal end of operational life. Nevertheless, it is true that other tumbling rates can appear depending on the events that cause the expiration of the nominal operations. The characterisation of these end-of-life events should be considered in the frame of a contingency analysis in order to identify those rotational states that could be managed by the ADR aiding devices.

The rotation axis considered is around the axis of maximum inertia as shown by the arrow in Figure 8-13, for stability considerations, and the gravity gradient does not produce enough torque to have an impact on the angular rate, so the inertial direction of the angular rate vector is not determined.

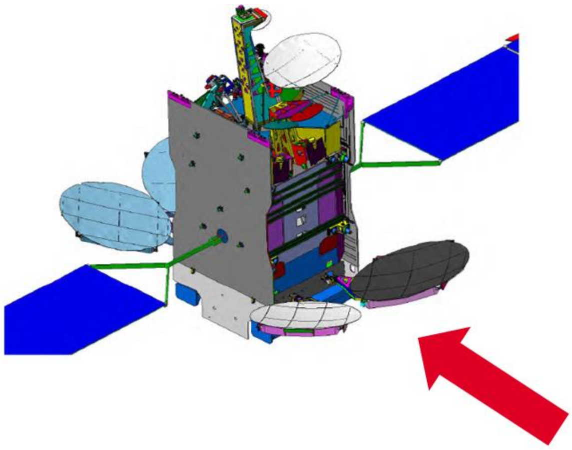


Figure 8-13 Eurostar Assumed Angular Rate and Proposed Approach Direction (Option 1)

This would also be the preferred direction of capture for this spacecraft (option 1). This strategy avoids problems with the large solar panels, which would vastly increase the risk of collision in a rotating spacecraft. In case that locating the navigation enhancement devices and the capture mechanisms was problematic in that face, it could be possible to place them and perform the approach through the faces holding the solar panels (option 2). The combination of these two strategies is shown in Figure 8-14, Figure 8-15, Figure 8-16 and Figure 8-17.

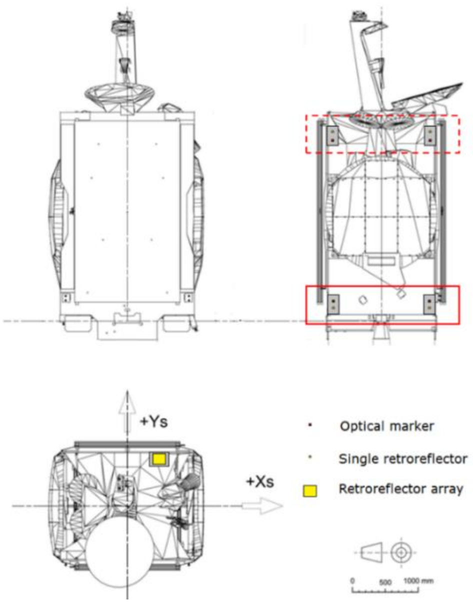


Figure 8-14 Close-up View of the Proposed Option 1

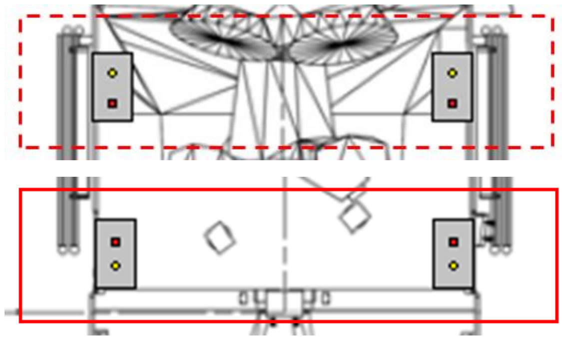


Figure 8-15: Close-up View of the Proposed Option 1

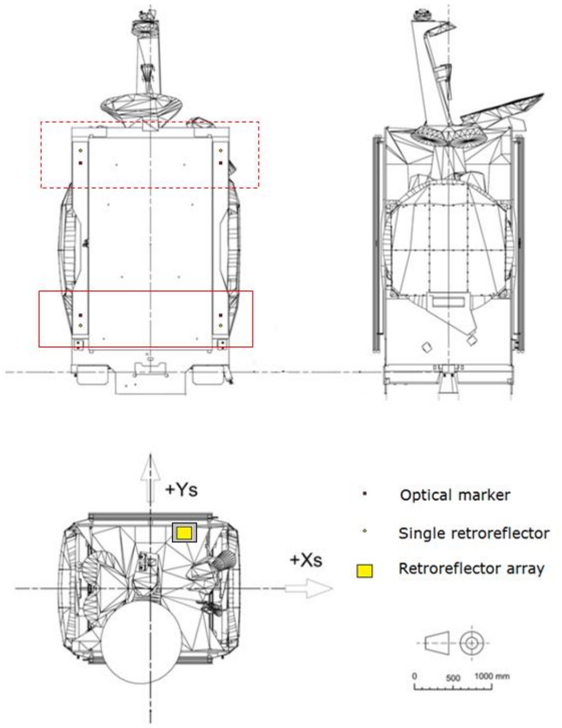


Figure 8-16: Global View of the Proposed Option 2

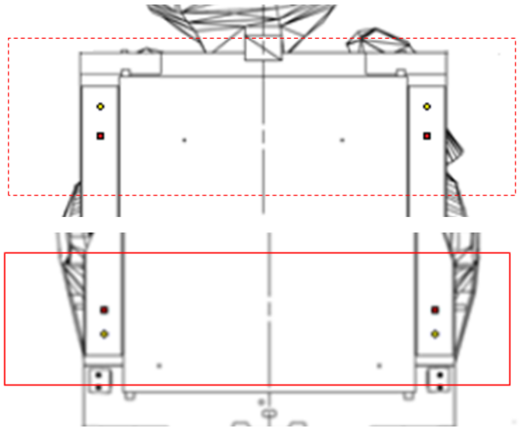


Figure 8-17: Close-up View of the Proposed Option 2

The distribution would be optimized depending on the selected approach. As mentioned before, the first option is safer considering the expected direction of the angular rate, although a thorough study could determine a more precise EOL state, changing the strategy. The top face should be pointing periodically to the Earth, so this is the selected face to host the large retroreflector for laser-ranging campaigns.

8.2.4. MC SCENARIO

At this altitude, the main disturbing torques are gravity gradient and Earth magnetic field. During an initial analysis, no direct causes of high spin were identified, although the information available about the operational orbit and the studied platform is relatively scarce. Following the design philosophy of the previous cases, an EOL state was estimated using a passive end of operations as a baseline. Assuming that the spacecraft is oriented in a gravity gradient unstable attitude, pointing with its antennae to ground, the satellite would start to slowly rotate due to the effect of said torque. There could be many other causes of end-of-life which would end in a high spin, like reaction wheels discharge or impact with a micrometeoroid, but the information available is not enough to obtain realistic values. The angular rate vector considered to perform the design is pointing in the direction of maximum inertia, and perpendicular to the orbital plane.

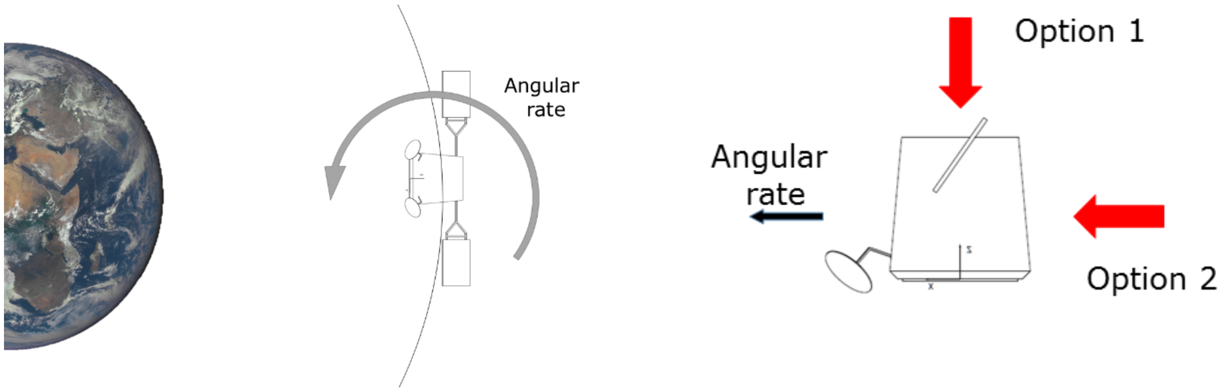


Figure 8-18 MC Expected Rotational State (Left) Rendezvous and Capture Strategies (Right)

The directions of capture proposed are two:

- Option 1 would be an approach through the orbital plane. The downside of this strategy is that under the angular rate assumptions mentioned, the face would be moving due to the target rotation, increasing the capture complexity.
- Option 2 would be an out of plane approach. The chaser spacecraft would only need to synchronize its rotation with the target to perform the capture.

However, in this small platform the limiting factor to distribute the state estimation enhancement devices is the available surfaces. There is not much information about either the free space or the expected location of elements to perform the capture, so the proposed distribution is used to determine the space required, rather than a feasible option in terms of mission analysis, as shown in Figure 8-19.

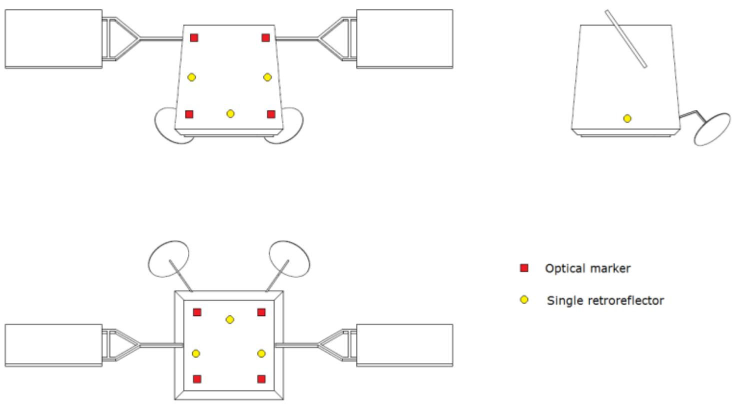


Figure 8-19: Proposed Navigation Aiding Elements for the MC

The distribution in the two large faces would support capture from the two proposed approaches, while the single retroreflector located in the lateral face could be used for long range phases of the retrieval mission, allowing detection for a wider variety of orbital plane approaches and distances.

The eddy current enhancer used here have a weaker effect than in the LEO satellites due to the lower magnetic field value. The distribution proposed has a weight of 4.5 kg, which is a 3% of the initial platform mass, to be comparable to the devices selected for the MPDs.

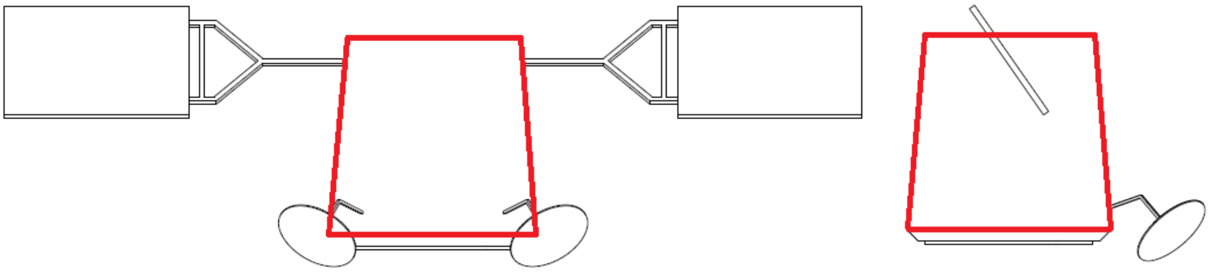


Figure 8-20: Detumbling Device Proposed for the MC

A detailed study of the possible EOL scenarios would allow to dimension the eddy current enhancer with more justification, but it would be necessary to have more information about the selected platform.

8.3. IMPACT AT SYSTEM LEVEL

This section contains the results of the ADR-ADS impact at system level. The approach followed is to consider the ADR aiding elements as an additional spacecraft subsystem which is designed at the same time as the rest of the spacecraft. This would allow to estimate the effort devoted to this subsystem and characterise the impact on other subsystems.

The effort estimation for ADR-ADS for each scenario or study case has been addressed for the different project phases and taking into account the core activities for each phase:

- Mission preparation activities during Phases 0 and Phase A
- Design activities performed during Phase B and Phase C.
- Manufacturing, assembly, integration and testing activities during Phase D.

8.3.1. PHASE 0

During this phase the following tasks and activities are addressed:

- Contribution to Mission Statement: ADR support needs and aiding devices are identified.
- Contribution to Preliminary Technical Requirement Specification: Requirement definition based on identified ADR support needs and potential candidates for the ADR-ADS.

The estimated effort for the ADR-ADS during this phase is based on the conceptual design performed in the frame of D4R study and taking into account a high reuse of D4R outcomes.

The following figure provides the estimated effort for the different activities and for the different scenarios:

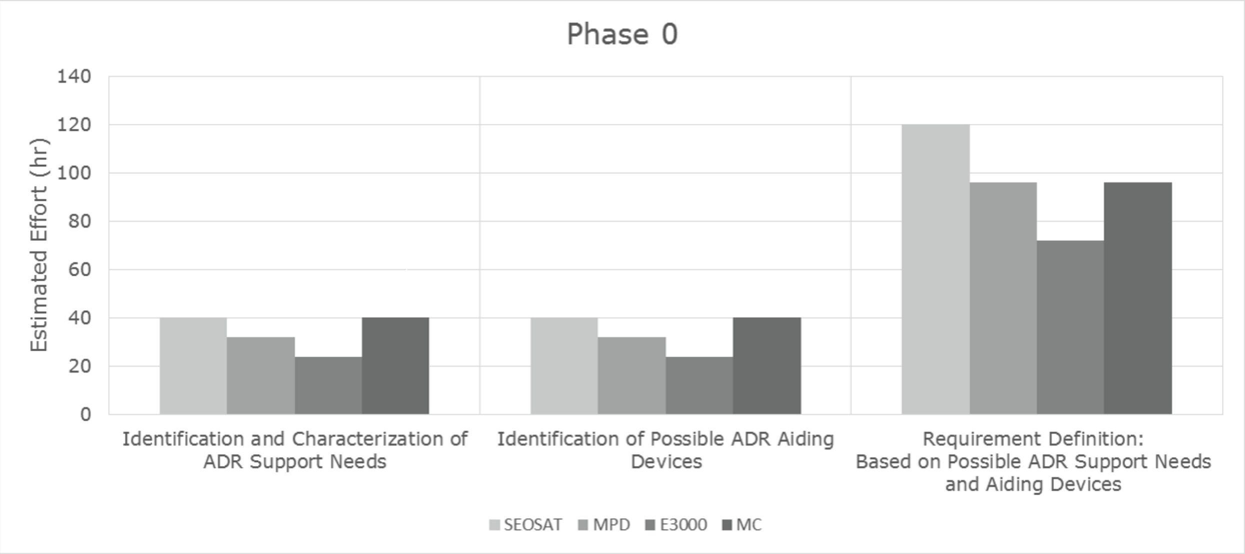


Figure 8-21 Estimated Effort for ADS-ARD Activities in Phase 0

The effort during this phase is driven by the number of aiding devices to be included in the ADR-ADS.

8.3.2. PHASE A

During this phase the following tasks and activities are addressed:

- Contribution to Technical Requirement Specification
  - Conceptual design of ADR aiding devices in order to support the requirement definition.
  - Requirement definition for ADR Aiding Devices Subsystem.

The following figure provides the estimated effort for the different activities and for the different scenarios:

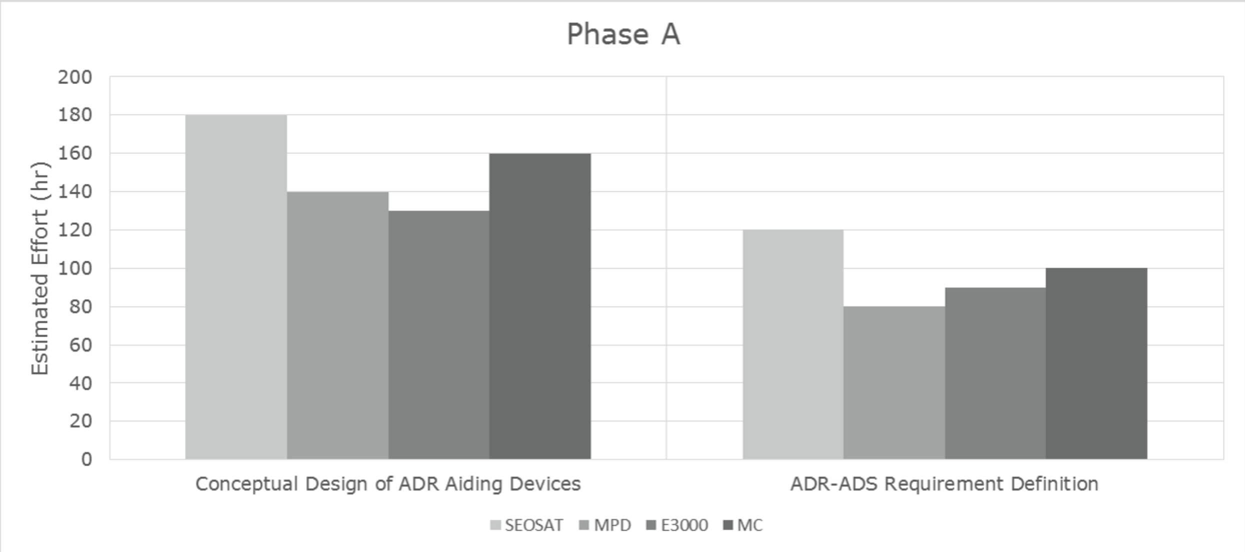


Figure 8-22 Estimated Effort for ADS-ARD Activities in Phase A

The effort during this phase is driven by:

- Number of aiding devices in the ADR-ADS: Defining requirements for more elements is assumed to require more time.
- Payload constraints: Mission and S/C payload define important constraints to be considered in the conceptual design and in the requirement definition.
- Platform size: ADR-ADS shall be compliant with platform size and then it represents an important driver to the conceptual design and requirement definition.

8.3.3. PHASE B

During this phase the following tasks and activities are addressed:

- Definition of the Technical Requirement Specification:
  - End-Of-Life characterization to support the ADR-ADS requirement definition for System PDR, EOL-B1.
  - Definition of ADR-ADS requirements.
- Preliminary Design Definition
  - End-Of-Life characterization to support the ADR-ADS PDR, EOL-B2.
  - Conceptual design considering sizing and accommodation of the different elements.
  - Impact on other Subsystems (MCI, AOCS, Structural, TCS).
- Verification Plan Definition. Model philosophy shall be defined and shall be compliant with System approach.
- Contribution to System Plans:
  - Engineering Plan
  - Space Debris Mitigation Plan
  - Disposal Plan

The following figure provides the estimated effort for the different activities and for the different scenarios:

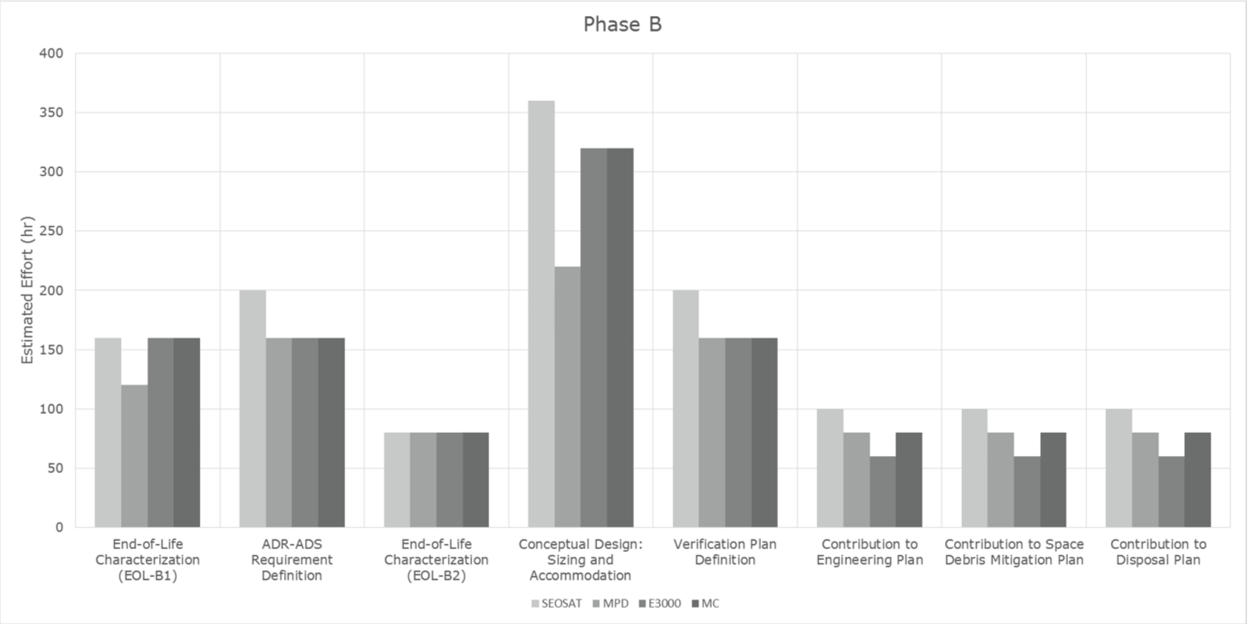


Figure 8-23 Estimated Effort for ADS-ARD Activities in Phase B

The effort of this phase is similar for all the scenarios, depending on the mission complexity, constraints, and number of elements.

8.3.4. PHASE C

During this phase the following tasks and activities are addressed:

- Detailed Design Definition for ADR-ADS CDR:
  - End-Of-Life characterization to support the ADR-ADS CDR, EOL-C1.
  - Detailed design considering sizing and accommodation of the different elements.
- Detailed Design Definition for System CDR:
  - End-Of-Life characterization to support the System CDR, EOL-C2.
  - Updated detailed design considering sizing and accommodation.
  - Analysis of impact on other Subsystems, MCI, AOCS, Structural, TCS.
- Assembly, Integration and Testing Definition:
  - Definition of AIT Plan.
  - Definition of Test Specification.

The following figure provides the estimated effort for the different activities and for the different scenarios:

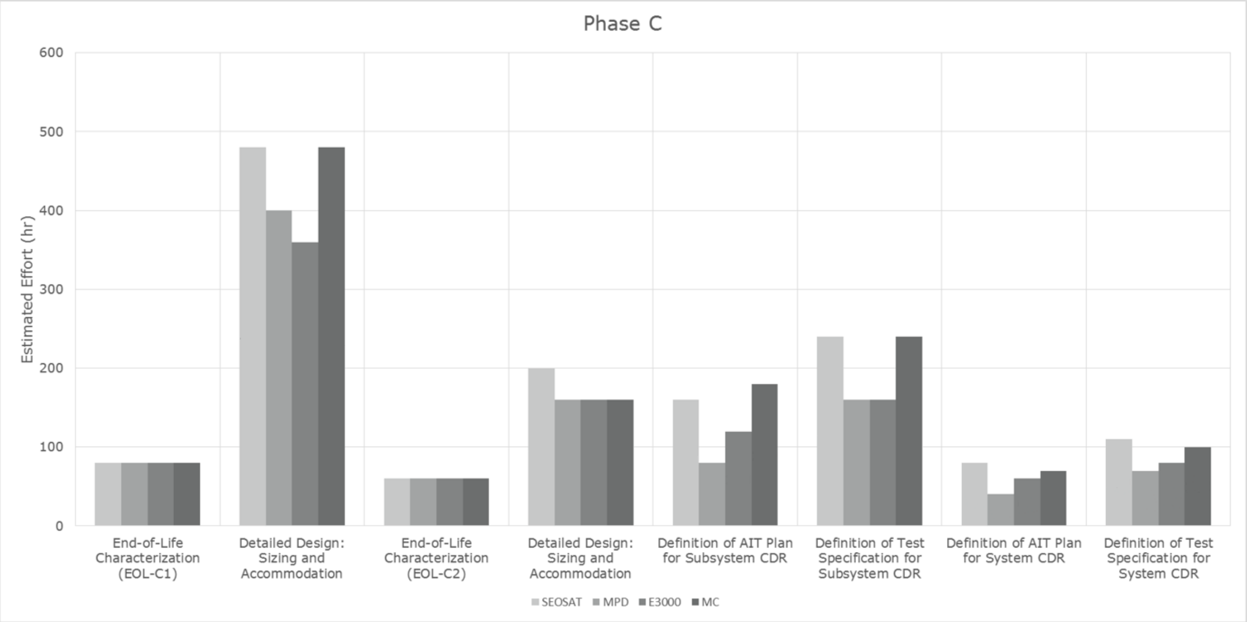


Figure 8-24 Estimated Effort for ADS-ARD Activities in Phase C

The effort of this phase is driven by the number of elements to be considered in the ADR-ADS.

8.3.5. PHASE D

During this phase the following tasks and activities are addressed:

- Manufacturing or procurement of the different ADR-ADS elements.
- Assembly and integration of the elements and ADR-ADS in the S/C.
- Testing:
  - Definition of Test Procedures.
  - Unit level, qualification, and integration level tests.

The following figure provides the estimated effort for the different activities and for the different scenarios:

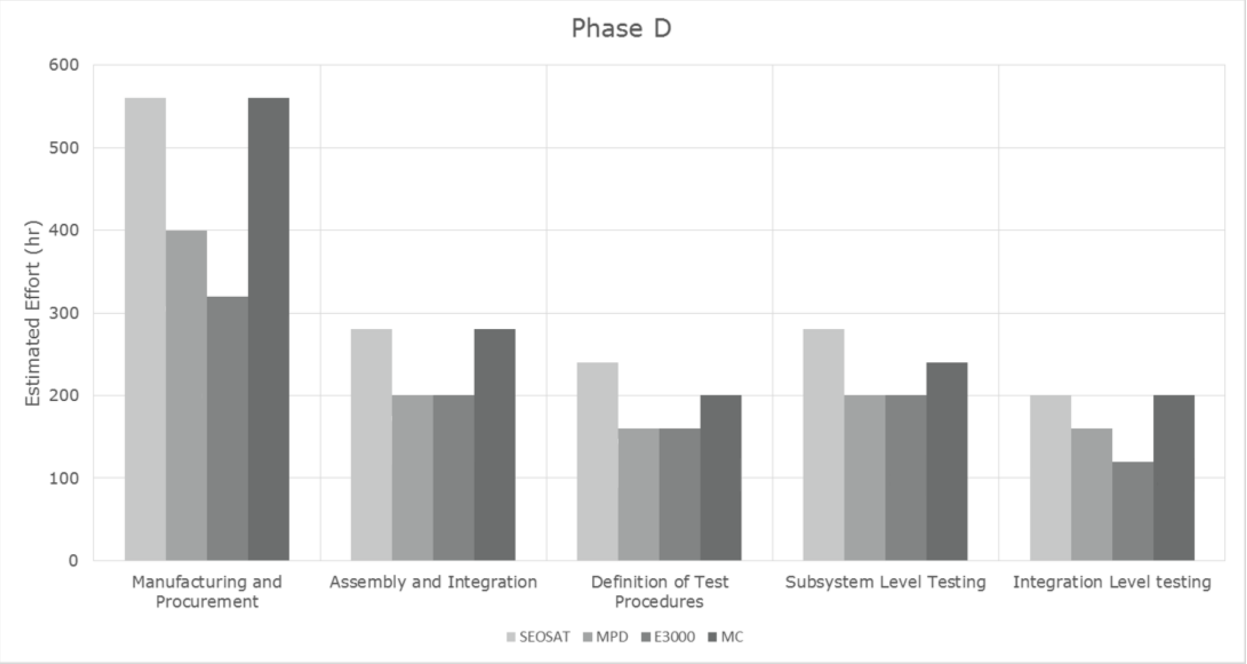


Figure 8-25 Estimated Effort for ADS-ARD Activities in Phase D

The effort estimation for the activities of this phase contains high uncertainties. The effort is mostly driven by the number of elements, but it is also necessary to consider that the model philosophy has an effect on the testing activities.

It is important to highlight that an optimization of the effort is expected in case of platform reuse, like mass-produced units or standardized platforms.

8.4. CONCLUSIONS

The following points have been identified during the design and integration process for the different case studies:

- Retroreflectors, single and arrays, have a high TRL and they do not increase the mass and cost budget noticeably. Expected relatively low impact on other subsystems.
- Optical markers represent low mass and cost solution for the State Estimation Enhancement devices. They provide an interesting and low cost solution for chaser design in terms of close rendezvous sensors, i.e. use of a camera instead of a LIDAR.
- Eddy current enhancers are useful in LEO for vehicles with compact shapes and low inertias (i.e. no large extended solar panels). Low TRL and specific design required for each platform, but promising performance and small impact expected on AOCS.
- Structural fixtures. The most promising candidates are the launcher interface rings in order to minimise the modifications. The use of handle devices has been also considered for LEO, GEO and MC cases, which would have a standard design compliant to end effector.

The following conclusions are derived from the effort estimation to characterize the impact of ADR-ADS in the project cycle for each considered scenario:

- Considering the ADR Aiding Device Subsystem from the beginning of the project introduces the following advantages:
  - Availability of S/C detailed documentation. Easier access to the right documentation and data to be used during the design, development, validation and integration in the S/C.
  - Impact on the rest of S/C subsystems is constrained by assigning proper requirements and margins.
  - Easier EOL characterization thanks to the fluid information exchange and possible reuse of models required to design other subsystems.
  - The analysis of the contingency cases could be managed at project level in order to define requirements applicable to ADR-ADS. This would define the boundary conditions of operation after the operational life.
- Recommended development of "chaser design guidelines" to define requirements for the different ADR-ADS elements that directly interact with a chaser spacecraft. These guidelines could be used to optimize the ADR elements. For instance:
  - Relationship between state estimation enhancement devices design and relative navigation sensors on the chaser.
  - Relationship between mechanical interfaces design, both shape and resistance, with robotic arm end effector and clamping devices.

The following points are proposed in order to allow the adoption of the proposed technologies or ADR aiding concepts on future missions:

- Retroreflectors and optical markers. These devices have a high TRL because both can be considered as flight proven devices. Nevertheless, it is important to highlight that they should be qualified for longer operational lifetimes because they have been selected as aiding concepts to support the SST and RdV once the spacecraft is not operational and in the frame of ADR mission design and operations. For this reason the definition and application of a qualification test programme that takes into account the extended operational lifetime shall be considered. Afterwards, the design, development and qualification of flight models to be integrated in a space demonstrator for these two technologies/devices shall be considered to reach the "flight proven" level.
- Eddy current enhancers. These are the aiding devices with the lower TRL, but they are also the most promising ones in the frame of attitude stabilisation. The activities to be considered in order to incorporate them in future missions start with breadboard models in order to characterise and validate their functional performance. The next step shall be the incorporation of these aiding elements to cubesats in order to validate the application in a relevant and operational environment. Finally the application to LEO spacecraft could be promoted in commercial missions to support ADR missions and reach the "flight proven" level.
- Interface ring as capture, stabilisation and disposal supporting elements. These devices are already available in spacecraft, but we have to validate additional requirements put on them to support the capture, stabilisation and disposal load transfer. Then, the proposed steps or activities to follow go from the structural analysis of these elements in order to verify the compatibility with the new requirements, including also as an outcome of these analyses the definition of the qualification test cases; manufacturing of qualification models in order to perform a qualification campaign; to finally include them in a space demonstration mission to reach the "flight qualified" and "flight proven" levels.
- Grapple fixtures. The first steps for these elements shall be the design and structural analyses of the platform in order to identify the reinforcement to be introduced in the S/C primary structure. Afterwards the compatibility with ADR loads for capture, stabilisation and disposal segments shall be performed, first by simulations in order to redesign, if needed, and after by dedicated test campaigns to be able to manufacture qualification models that finally, after qualification and acceptance campaigns, allow integrating them in space demonstrators to reach the "flight qualified" and "flight proven" levels.

9. D4R AIDING DEVICES: CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are derived from the D4R activities:

- Active Debris Removal Aiding Devices Subsystem has been defined based on a methodical approach with the following stages:
  - Review of SDRS technologies to identify potential enhancements that have been translated into aiding devices/concepts, proto-elements of the ADR-ADS.
  - Assessment of the impact on ADR mission of the proto-elements in order to define a preliminary set of ADR aiding devices/concepts. This assessment has been performed based on the impact of each proto-element on the ADR mission considering three different categories:
    - Performance category to assess the reduction in mission risk, the complexity and the flexibility of the element.
    - Technical category to assess the element needs in terms of power, impact on S/C mass and inertia, complexity of accommodation and TRL.
    - Programmatic category to assess the impact on design, manufacturing and AIT activities and also the impact on development and recurrent costs.
  - Conceptual design of the preliminary set of ADR aiding devices/concepts in the representative scenarios in order to propose the elements to be integrated in the ADR-ADS.
- The impact of the ADR-ADS on the different selected platforms at system level has been assessed based on:
  - A set of proposed guidelines to design and integrate the different aiding devices of the ADR-ADS.
  - Application of the design and integration guidelines for the selected case studies in order to validate the proposed approach.
- The activities related to the ADR-ADS design, development and integration in the frame of a project lifecycle has been identified.
- The benefits of considering the ADR-ADS from the beginning of the project has been identified, i.e. availability of S/C documentation and models, possibility to address the impact on the rest of S/C subsystem from earlier stages, better characterization of EOL and contingency cases to be managed by ADR-ADS elements.

The definition of space demonstrators to qualify the different elements of the ADR-ADS is the next challenge with the purpose of pushing the proposed technologies and being capable of supporting future ADR missions to tackle the space debris problem.

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