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ESA ESTEC
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands

DESIGN FOR REMOVAL - INTERFACE REQUIREMENTS DOCUMENT FOR LEO AND GEO MISSIONS

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APPROVAL

Title	Design for Removal - Interface Requirements Document for LEO and GEO missions		
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	Head of Clean Space and Circular Economy Office (T. Soares)	Tiago Soares	Digitally signed by Tiago Soares Date: 2026.01.13 10:21:18 +01'00'

CHANGE LOG

Reason for change	Issue Nr	Revision Number	Date
First version of the document based on previous work on D4R interface requirements for High Priority Copernicus Missions	1	0	JAN 2023
Second version of the document, now applicable to any LEO mission, including the requirements and goals applicable for uncontrolled re-entry case and differentiating from the controlled re-entry case. Some changes to certain requirements applicable for controlled re-entry are detailed in the Change Record table	2	0	FEB 2024
Update for Copernicus Next Generation missions based on CAT lessons learned and addition of the GEO S/C requirements.	3	0	DEC 2025

CHANGE RECORD

Issue Number 3	Revision Number 0
Requirement / Figure	Change description
Introduction	Reference frames have been added
Requirements chapter	Reorganisation of the requirements sections resulting in the need for new numbering

New requirement added: D4R-IRD-0040	A requirement has been added to specify the relative clocking alignment of the 3D-marker with respect to the Mechanical capture interface.
Figure 2-3 in issue 2.0	Modification of the envelope below the LAR plane free of equipment to ensure chaser operations: measure 400 mm modified to 200 mm.
D4R-C-0160 in issue 2.0	Modification of the requirements on the interface loads: • torque value added; force value modified • deformations modified leading to 1e5 stiffness values • margin added to , given latest simulation results of GMV • analysis requested to check the impact of this load to the appendages
D4R-C-0160 in issue 2.0	Deleted: in favour of D4R-IRD-0290 which is the driving case and covers the load cases when decelerating.
D4R-C-0020 and D4R-C-0190 in issue 2.0	Requirement extended to include LAR-1666 and LAR-937.
D4R-C-0440 in issue 2.0	Goal values added for the 3D marker KoZ.
D4R-IRD-0050	Value added for coplanarity between MICE and LAR.
New requirement added: D4R-IRD-0090	Requirement added on the height of the MICE bolt heads.
D4R-IRD-0110	Larger flexibility added to the MSN 3D Marker positioning.
Requirements for uncontrolled re-entry	Only the differences between the D4R IRD requirements for satellites performing controlled re-entry have now been listed.
D4R-IRD-0110 and D4R-IRD-0120	3D marker alignment is now w.r.t. MICE frame
D4R-C-0271 and D4R-C-0410 in issue 2.0	Requirements on uniqueness of pattern on LAR and other S/C faces merged into 1 requirement with 20% deviation criteria
New requirement added: D4R-IRD-0412	In the cooperative scenario, the Spacecraft shall inhibit all AOCS commands moments prior to capture.
Operational requirements	Operation requirements have been removed from this IRD and are planned to be incorporated into the updated CPO guidelines (RD[01]). The IRD now focuses exclusively on defining the requirements and guidelines to ensure the spacecraft design is fully compliant and prepared for D4R implementation.
Goal requirements	Chapter has been removed, some of the requirements have been absorbed in the main requirements, some deleted.
Requirements numbering	Major changes made to requirements numbering and format with respect to issue 2.0.
Requirements for GEO Graveyard Orbit Relocation	Section 5 has been added for GEO satellites.
Applicability Matrix	Annex 2 has been added added to summarise the applicability of the requirements to each scenario.

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1. INTRODUCTION

1.1. Introduction

In the event that a spacecraft is unable to perform its end-of-life disposal operations (e.g. controlled re-entry or transfer to a disposal orbit), a dedicated removal service may be required to ensure compliance with space debris mitigation objectives. To enable such post-mission removal operations, spacecraft shall be designed to facilitate safe and reliable rendezvous and capture by a Servicer spacecraft. This design approach is referred to as Design for Removal (D4R).

The purpose of this document is to define the interface requirements applicable to spacecraft implementing the D4R concept. These requirements shall serve as the reference for the development of the mission-specific Interface Control Document (ICD), which shall provide the concrete interface definition to be used by the removal service provider.

There are two different scenarios where a removal service may be required:

1. **Uncooperative** – whereby the satellite is non-operational (either completely or with respect to attitude control) and tumbling.
2. **Cooperative** – whereby the satellite is operational but unable to perform the end-of-life functions with respect to removal from orbit.

The cooperative and uncooperative removal scenarios are described in ANNEX 1: Debris Removal Service Description. The scenario is not known upfront when designing the Client vehicle. The requirements in this document cover both scenarios.

Another distinction to be made is related to the type of disposal option, which can be a controlled or uncontrolled atmospheric re-entry for satellites in LEO, or a relocation to a graveyard orbit for satellites in GEO:

1. **Controlled re-entry** – whereby the de-orbit burn is actively commanded such that the break-up occurs over a remote, predefined area, thereby minimizing the casualty risk.
2. **Uncontrolled re-entry** – whereby the satellite is decaying naturally due to atmospheric drag, with no control over timing, location, or footprint.
3. **Graveyard orbit relocation** – whereby the satellite is actively relocated by the service vehicle to a disposal orbit, beyond the protected GEO region.

This type of deorbit is known upfront when designing the Client vehicle and affects the applicability of the requirements in this D4R IRD. The requirements for satellites performing a controlled re-entry are presented first, in Chapter 3, then the differences for satellites performing an uncontrolled re-entry are given, in Chapter 4, followed by the requirements for graveyard orbit relocation in Chapter 5. The differences come from the different loads that are involved for each case during disposal. For a controlled atmospheric re-entry, higher loads are involved and the solution proposed is to use the Launcher Adaptor Ring (LAR) to help sustaining them; while for an uncontrolled atmospheric re-entry the loads are much lower, therefore the use of a LAR is not needed.

It is important to note that this document is solution-biased, as it is based on technologies developed by ESA together with industry for the Copernicus Expansion Missions.

In some specific cases, requirements include a “Goal” performance of the related function/product, in addition to the “Threshold” . This means that the baseline concept shall be compliant with the threshold requirement, and the impact of achieving the goal performance shall be analysed with the intention of achieving the goal.

1.2. Scope

This document contains the relevant requirements and constraints for Design for Removal (D4R), including:

- Design requirements for D4R hardware
- Client satellite integration requirements for D4R hardware
- Client satellite requirements for cooperative debris removal service

The Guidelines on Safe Close Proximity Operations document, RD[01,] contains further operational requirements that are involved during the capture phase of an Active Debris Removal mission.

The requirements included in this document are applicable for all kind of satellites in LEO and GEO orbits.

Further work is needed to adapt the requirements to other orbital environments (MEO).

1.3. Definitions

Service vehicle – Service vehicle with the function of removing the Spacecraft from orbit after the end of life, either in a cooperative or uncooperative scenario.

Client vehicle – Vehicle being designed and prepared for capture in agreement with the current IRD

2D Navigation Aids – 2D markers, including:

1. Ground tracking aids: to support ground-tracking and attitude reconstruction, based on Laser Retro-Reflectors (LRRs) corner cubes.

2. Features to support rendezvous, with signature on visual and infrared wavelength, that can be used to improve pose and attitude determination

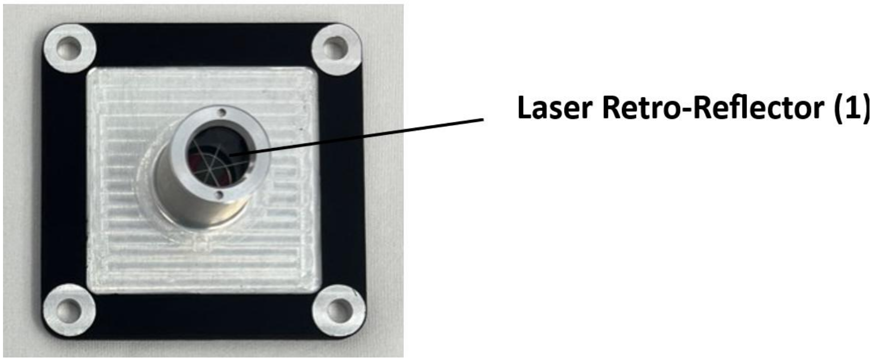

Figure 1: 2D marker (Credits: Admatis)

3D Navigation Aids – 3D shaped marker identifiable in the visible wavelength to support precise pose and attitude determination for the last phase of the capture, from 5m down to 0m distance between Spacecraft and removal vehicle.

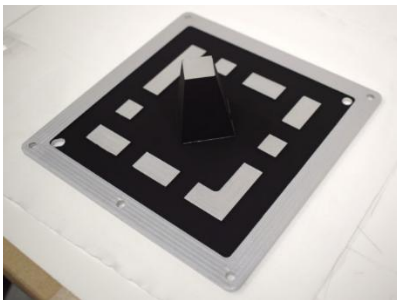

Figure 2: 3D marker (Credits: Admatis).

Mechanical Capture Interface – Passive metallic part mounted on Spacecraft's structure to allow its capture with a robotic gripper before rigidisation of the compound Spacecraft and removal vehicle.

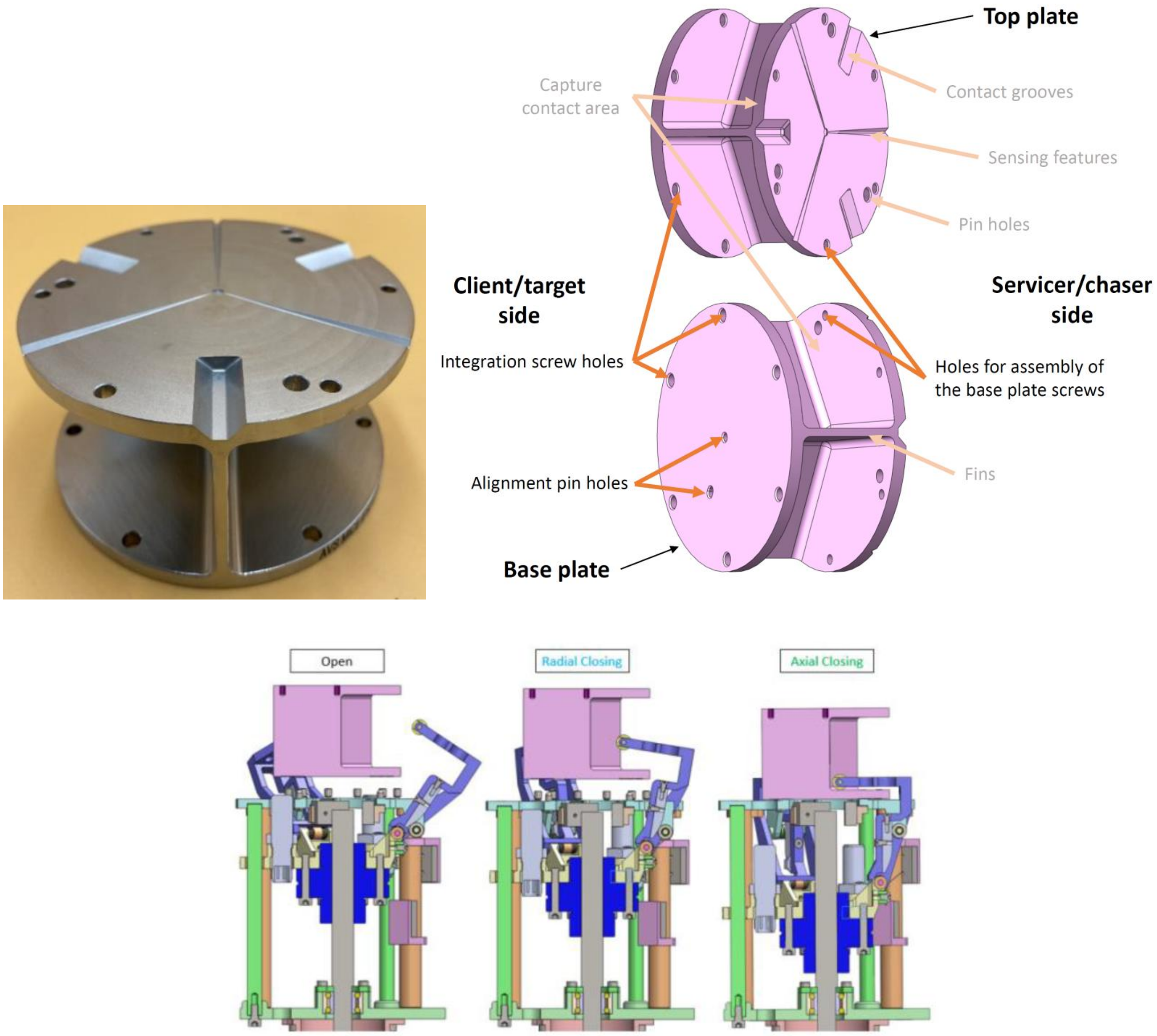

Figure 3: Passive capture interface and capture example (Credits: GMV).

1.4. Reference frames

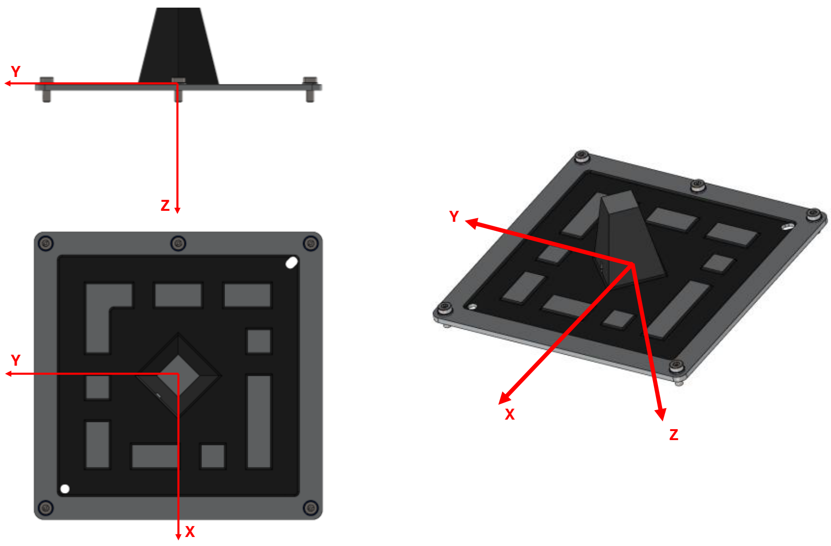

Figure 4: MSN 3D marker frame: on the pattern surface.

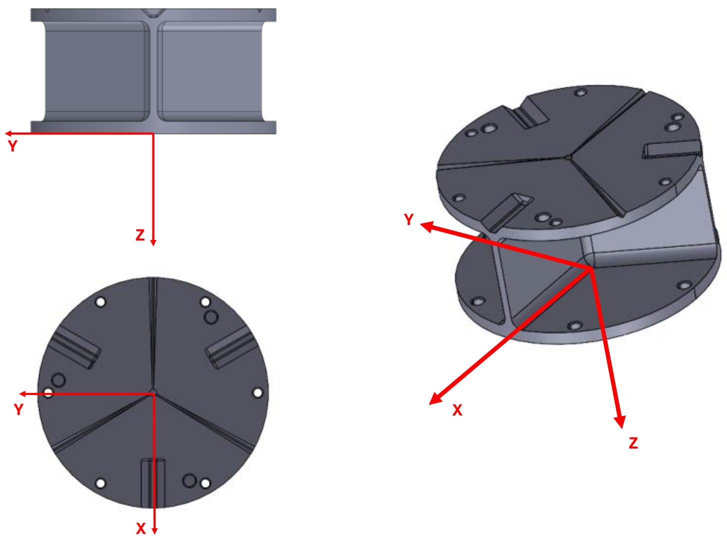

Figure 5: Mechanical Capture Interface frame: on the bottom surface.

1.5. Acronyms

Acronym	Definition
ADR	Active Debris Removal
AOCS	Attitude and Orbit Control System
CoG	Centre of Gravity
D4R	Design for Removal
EIRP	Effective Isotropically Radiated Power
EoL	End of Life
FDIR	Failure Detection, Isolation and Recovery
FoV	Field of View
FTP	File Transfer Protocol
GEO	Geostationary Orbit
GNSS	Global Navigation System
HKTM	HouseKeeping and TeleMetry
LAR	Launcher Adapter Ring
LEO	Low-Earth-Orbit
LRR	Laser Retroreflector
MCC	Mission Control Centre
MLI	Multi Layered Insulation
SA	Solar Array
SADM	Solar Array Deployment Mechanism
STR	Star Tracker

2. APPLICABLE AND REFERENCE DOCUMENTS

2.1. Applicable Documents

AD[01] Mechanical drawing of Mechanical Interface for Capture at End-Of-Life

AD[02] Mechanical drawing of Markers Supporting Navigation – 2D marker

AD[03] Mechanical drawing of Markers Supporting Navigation – 3D marker

Note: ADs will be provided upon request. Please contact cleanspace@esa.int.

2.2. Reference Documents

RD[01] ESA-TECSYE-TN-022522 Guidelines on Safe Close Proximity Operations Issue 3

3. REQUIREMENTS FOR CONTROLLED RE-ENTRY

3.1. D4R Hardware to be mounted

D4R-IRD-0010 The Client Satellite shall be equipped with:

- the following passive mechanical interfaces for rendezvous, capture and subsequent removal from orbit:
  - Mechanical Capture Interface (MICE)
  - Launcher Adaptor Ring (LAR diameter of 1194 mm or 1666 mm or 937 mm)
- The following navigation aids:
  - 2D markers
  - 3D marker.

Rationale: For a controlled re-entry, high loads are involved and the solution adopted is to use the Launcher Adaptor Ring (LAR) to help sustaining them.

3.1.1. Mechanical Capture Interface

D4R-IRD-0020 The Spacecraft shall accommodate a mechanical capture interface with 98 mm diameter and 50 mm height cylinder, at the centre of the LAR.
Note: For a S/C performing a controlled re-entry using the LAR, it is assumed that the centre of the Client Spacecraft Body Frame corresponds to the centre of the LAR, which is aligned with the Client S/C CoM.

D4R-IRD-0030 The Spacecraft shall allocate the corresponding mass for the mechanical capture interface as per AD[1].

D4R-IRD-0040 One of the three inner flanges (i.e. the vertical walls between the MICE lower and upper discs) of the MICE capture interface shall point towards the centre of the 3D marker, which location is defined in D4R-IRD-0100, as visualised in Figure 6.
Note 1: There are three possible alignments of MICE w.r.t. the 3D-marker possible: 0, 120 and 240 degrees.

Rationale: This configuration ensures alignment of the cameras on the Servicer vehicle and the 3D-marker on the Client vehicle.

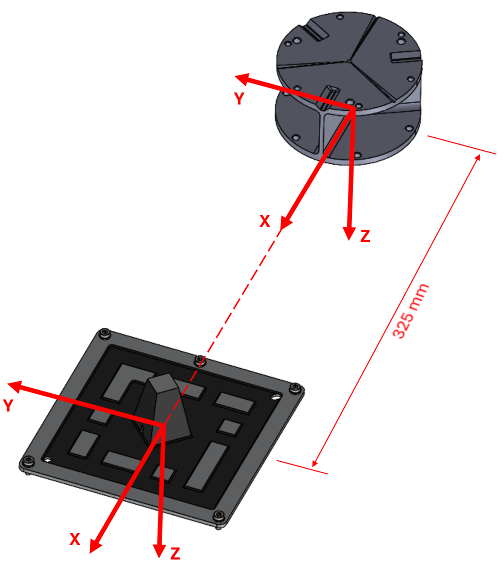

Figure 6: Relative nominal positioning of MSN 3D marker w.r.t. MICE.

D4R-IRD-0050 The Mechanical Capture interface shall be mounted such that its Top plate is coplanar with the launcher separation plane with an accuracy better than 1 mm.

D4R-IRD-0060 The mechanical capture interface in-plane mounting misalignment with respect to the nominal emplacement in Client Spacecraft body frame shall be lower than 1 mm and 0.25 deg along the MICE Z-axis.

D4R-IRD-0070 The position and alignment of the mechanical capture interface with respect to the nominal emplacement in Client Spacecraft body frame shall be known with a precision higher than 0.5 mm and 0.05 deg along the MICE Z-axis.

Note: Elements to support position and alignment knowledge can be added to the mechanical capture interface design.

D4R-IRD-0080 The mechanical capture interface shall be grounded to the Spacecraft structure.

Rationale: To allow both S/C to achieve to the same electrical potential.

D4R-IRD-0090 The height of the bolt heads for mounting MICE with respect to its mounting plane - dimension d in Figure 7- shall not be higher than 8 mm (TBC).

Rationale: To allow the gripper fingers to pass without obstruction.

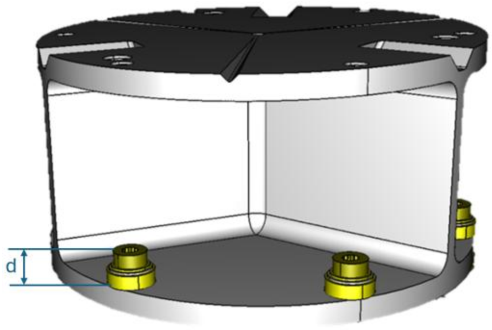

Figure 7: MICE maximum height of the mounting bolt heads.

3.1.2. 3D Markers

D4R-IRD-0100 The Spacecraft shall accommodate a 3D navigation aid for the mechanical capture interface with a 150x150 mm squared plate and 50mm height, at the following location:

- The base of the 3D marker shall be in the same plane as the Base plate of the Mechanical Capture interface, with the centre of the 3D marker at a distance of 325 mm from the centre of the Mechanical Capture Interface along the MICE frame X axis – as shown in Figure 6.
- with the MSN 3D marker frame Z axis parallel to the MICE frame Z axis.

D4R-IRD-0110 The 3D navigation aid mounting misalignment in the mechanical capture interface frame shall be according to Figure 8:

- lower than 1 mm ±10 mm along the MICE frame X and Y axis
- lower than ±10 mm along the MICE frame Z axis
- lower than ±5 deg around the 3D marker Z-axis.

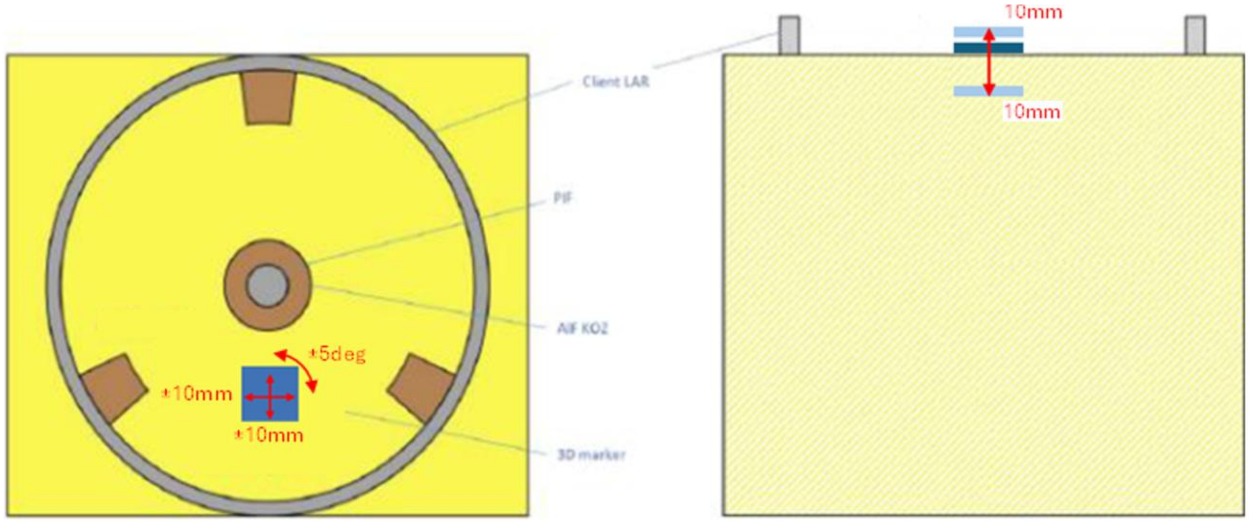

Figure 8: Flexibility in the MSN 3D Marker positioning.

D4R-IRD-0120 The position and alignment of the 3D navigation aid with respect to the mechanical capture interface frame shall be known with a precision better than 0.5 mm and 0.05 deg.

Note: Elements to support alignment knowledge can be added to the 3D markers design.

D4R-IRD-0130 The Spacecraft shall allocate the corresponding mass for the 3D navigation aid as per AD[3].

D4R-IRD-0140 The 3D navigation aids shall be grounded to the Spacecraft structure.

3.1.3. 2D Markers

D4R-IRD-0150 The Spacecraft shall include a pattern of 2D navigation aids on the LAR face and on all other faces except one, to support the Chaser's relative navigation.

Note-1: By navigation aids it is understood passive devices to support and improve the chaser relative navigation, in all illumination conditions (including eclipse).
Note-2: In the centre of the 2D navigation aid, a LRR is placed to support ground-tracking and attitude reconstruction (= the integrated ground tracking aids).

<u>Rationale</u>: Navigation aids aim at increasing the robustness of relative navigation using cameras in all phases of the approach, reducing the risk and simplifying the chaser design.

D4R-IRD-0160 The Spacecraft shall allocate 4 areas of 60 mm x 60 mm on the LAR face of the S/C, mounted outside the LAR - dimension c1 in Figure 9 - for the accommodation of these 2D navigation aids (including integrated ground tracking aids). For the patterns on the other S/C panels, the Spacecraft shall also allocate 4 areas of 60 mm x 60 mm for 2D navigation aids.

D4R-IRD-0170 The following rules shall be respected for the patterns on each face:

- Each of the areas allocated for 2D navigation aids on the LAR face (as specified in D4R-C-0260) are at least 1 meter apart from each other - dimension c2 in Figure 2 2, with a general recommendation to maximize the distance between aids on each surface. Final location of the markers is to be determined by the S/C integrator.
- On each face, the marker pattern shall not form a perfect square or rectangle: at least one marker shall be offset by ≥ 20% of the shorter side of the pattern from the position it would have in a perfect rectangular layout on that face.
- The marker pattern on each face shall not exhibit simple symmetry:
  - it shall not be possible to place all markers on, or within 20% of the shorter side from, a single straight line;
  - the pattern shall not be symmetric under 90°, 180°rotation or mirror symmetry within 20% of the shorter side.
- Marker patterns on different faces shall be uniquely identifiable: after any rotation/translation of one face with respect to another, at least one marker position shall differ by ≥ 20% of the shorter side of the corresponding pattern.

<u>Note</u>: a Matlab function can be made available to check the compliance of the panel coordinates (checkMarkers.m).

<u>Rationale</u>: Unequivocal identification of all faces (e.g. by creating different patterns with markers and retroreflector corner cubes on each face) is required for the determination from ground of the magnitude of the Spacecraft angular rate vector and to simplify the chaser's navigation.
Assuming that it will also be possible to identify from ground at most one face without ground-tracking aids, one of the faces besides the LAR can be left without 2D markers if necessary.

D4R-IRD-0180 The position and alignment of the 2D navigation aids with respect to the Client Spacecraft Body Frame shall be known with a precision better than 0.5 mm and 0.25 deg.

D4R-IRD-0190 The Spacecraft shall allocate the corresponding mass for all ground-tracking and 2D navigation aids as per AD[2].

D4R-IRD-0200 The 2D navigation aids shall be grounded to the Spacecraft structure.

3.2. Keep-out-Zones around the D4R hardware

Keep-out-zones in this chapter are referring to the area's necessary to avoid obstruction during last approach and capture between the capture payload and Client vehicle hardware. It is not referring to the operational KoZ which are defined in the Close-Proximity-Operations Guidelines (RD[01]).

This section starts with Figures summarizing the Koz's to be respected. Then the requirements are given for the specific D4R hardware items. KoZ requirements are given for the region above LAR plane, meaning according to the positive MICE Z-axis, and requirements are given for the region below LAR plane, meaning according to the negative MICE Z-axis.

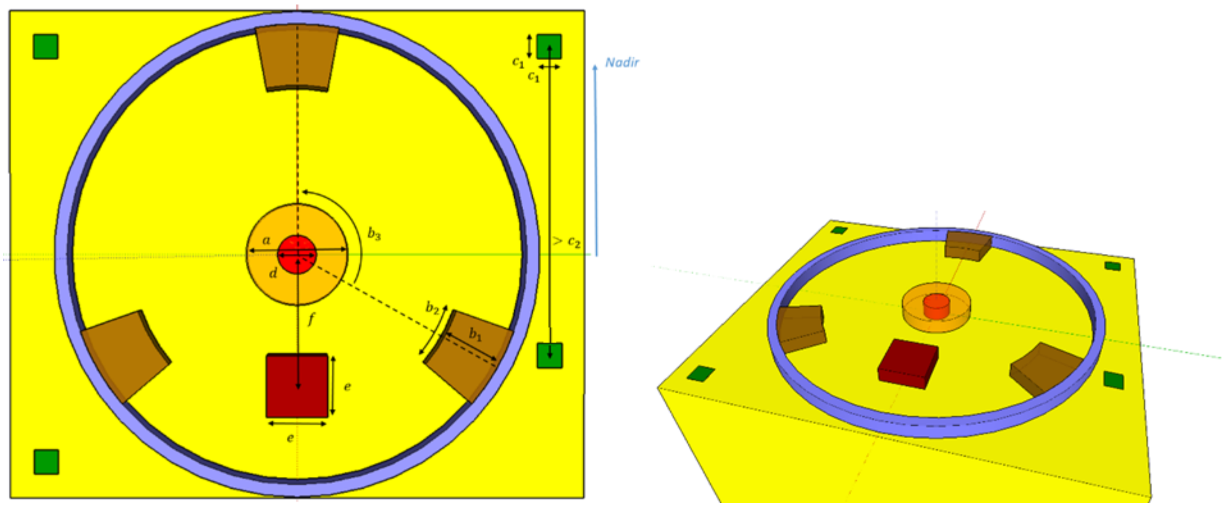

Figure 9: Representation of keep out zones above LAR surface for supporting capture (LAR diameter of 1194 mm and 50 mm height used as an example).

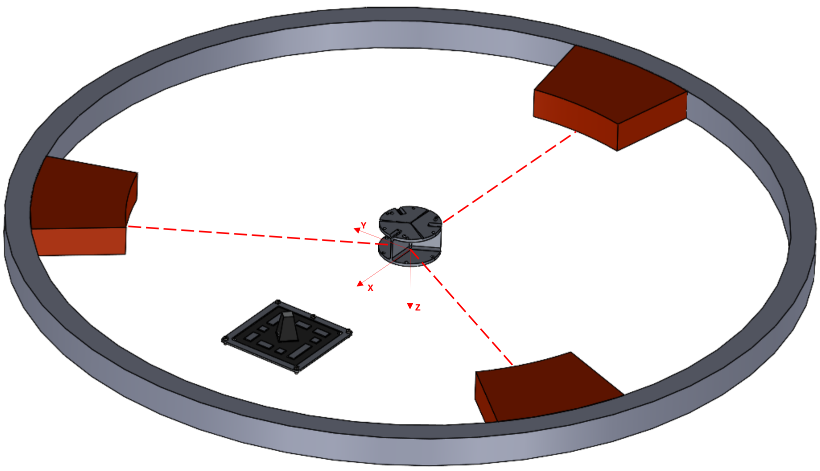

Figure 10: Relative orientation of the LAR KoZ's w.r.t. the MICE reference frame.

D4R-IRD-0210 The design of the Client Spacecraft shall ensure access to the Capture interfaces by the removal vehicle for capture operations, by ensuring that no equipment or appendages is inside the envelope represented in red in Figure 11.

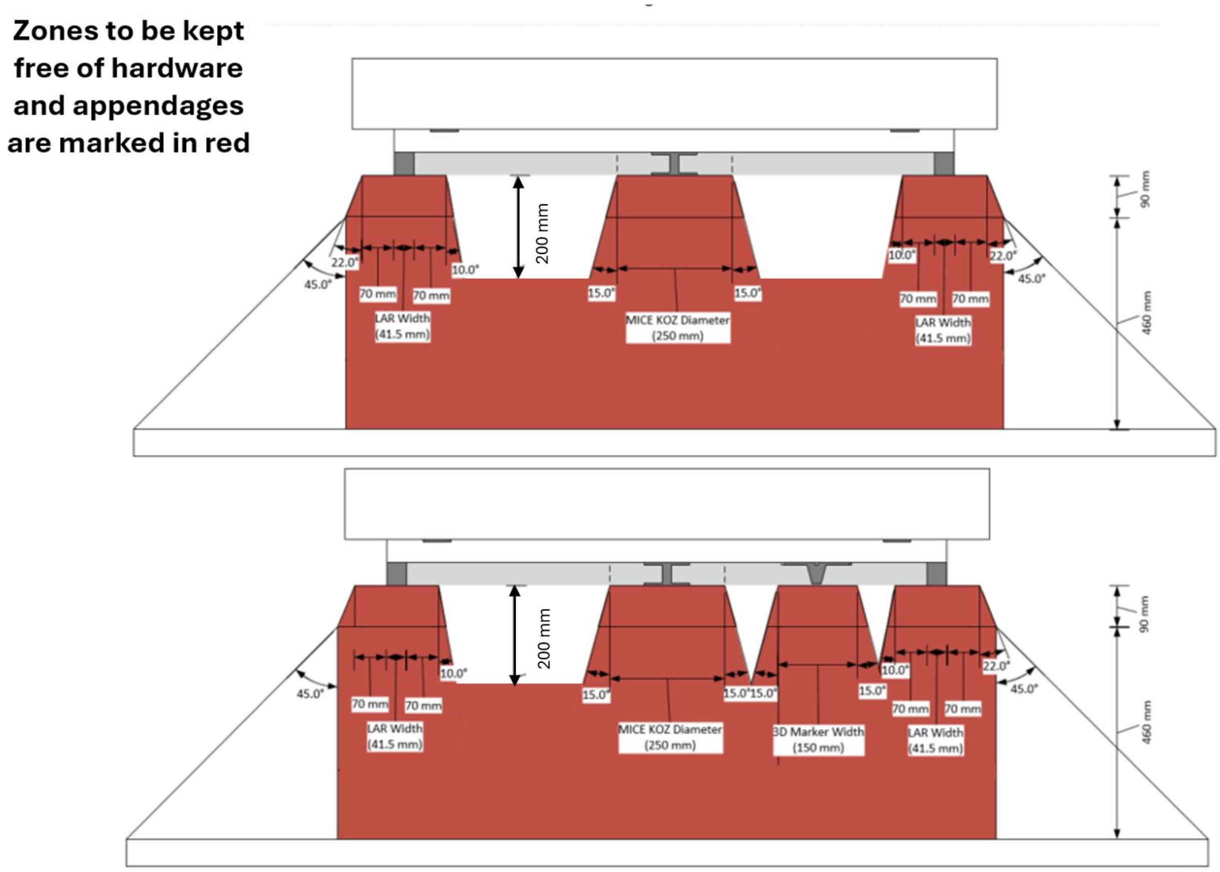

Figure 11: Representation of the envelope below the LAR plane free of equipment to ensure chaser operations, cross-sectional view (LAR diameter of 1194 mm)

3.2.1. Mechanical Capture Interface

D4R-IRD-0220 The Client Spacecraft shall ensure that a circular Keep-Out-Zone of 250 mm diameter - dimension a in Figure 9 – is available and free of any hardware at the geometrical centre of the Mechanical capture interface, up to 50 mm above the launcher separation plane (i.e. according to positive MICE Z-axis).

Rationale: To account for the width of the gripper assembly and the tracking inaccuracy of the active capture mechanism during capture operations.

3.2.2. LAR

D4R-IRD-0230 The Client Spacecraft shall ensure that 3 equally spaced Keep-Out Zones, axially separated by 120 deg – dimension b3 in Figure 9 – inside the Launch Adapter Ring (LAR) are available and free of any hardware up to 50 mm above the launcher separation plane, for the operation of the clamping system, with the following geometrical characteristics:

- Each of the 3 Keep-Out Zones has a thickness of 150 mm with respect to the LAR inner diameter – dimension b1 in Figure 9 – and has a width (dimension b2 in Figure 9) of:
  - 30 deg wide for 937 mm ring
  - 21 deg wide for 1194 mm ring
  - 14 deg wide for a 1666 mm ring.
- One of these KOZs shall be placed centered in the negative X axis in the MICE frame, and the others every 120 deg along the LAR, see Figure 10.

Note: Any rotation w.r.t. Nadir is possible, as long as the relative rotation of MICE, the clamp KOZs and the 3D marker around LAR center are respected.

Rationale: A clamping mechanism is required to rigidize the satellite mechanic capture and to enable removal from orbit. The 3 keep out zones are dimensioned to allow the actuation of the 3 clamping mechanisms accommodated in the removal vehicle.

D4R-IRD-0240 The design and operation of the Spacecraft appendages shall ensure visibility and access to the LAR face for the removal vehicle, by ensuring that no appendages project below the LAR plane.

Rationale: In the case of a failure in orbit, the removal vehicle needs to access and capture the Spacecraft even in an uncooperative scenario.

D4R-IRD-0250 In case the Spacecraft cannot be made compliant with D4R-IRD-0210, the Spacecraft shall be able to command and move the appendages that project below the LAR panel (e.g. Solar Array) to a fixed position that does not obstruct the access and visibility of the LAR face.

<u>Note</u>: It is assumed that the spacecraft before becoming uncooperative will pass by safe mode. While in Safe mode, moveable appendages positions that obstruct the access and visibility of the LAR face need to be prevented without ground commands.

<u>Rationale</u>: In the case of a failure in orbit the removal vehicle needs to access and capture the Spacecraft, even in an uncooperative scenario where there was no time to send a command from ground to move appendages.

3.2.3. 3D Markers

D4R-IRD-0260 Centered around the 3D marker a pyramidical Keep-out-zone shall be foreseen as shown in the bottom part of Figure 11, with a basis of 150x150mm (Threshold) and 250x250mm (Goal), and with outward angles of at least 30 deg (± 15 deg) (Threshold) and 50 deg (± 25 deg) (Goal). The Spacecraft hardware, in its deployed configuration, shall not enter this Keep-out-Zone.

<u>Rationale</u>: KoZ defined based on a worst-case geometric analysis of the approach conditions.

3.2.4. 2D Markers

D4R-IRD-0270 The Spacecraft shall ensure that no appendages in the deployed configuration are blocking the visibility of the 2D navigation aids on each face including the LAR face with an angular clearance of at least 30 deg (± 15 deg) (Goal) and 50 deg (± 25 deg) (Threshold).

<u>Note</u>: The general recommendation is to maximize the angular clearance for each 2D navigation aid. Final location of the markers is to be determined by the S/C integrator.

<u>Rationale</u>: It is assumed that the spacecraft will be tumbling in the uncooperative scenario. The clearance will allow the proper characterization of the attitude motion from ground and from a chaser spacecraft to support the rendezvous operations.

3.3. Thermal and optical properties around the D4R hardware

3.3.1. Mechanical Capture Interface and LAR

D4R-IRD-0280 The passive mechanical capture interface and the LAR shall be free of thermal hardware susceptible to detach. Also, the keep-out zones described in D4R-IRD-0220, D4R-IRD-0230 and D4R-IRD-0260 are assumed to be free of thermal hardware, except for the structural panels behind these KOZs, if any, they are not considered part of the KOZ itself and can have, for example, MLI as depicted in Figure 12. Figure 13 depicts the same for the clamping mechanism KOZ on the LAR.

Rationale: To avoid interference with the capture and clamping mechanisms operations.

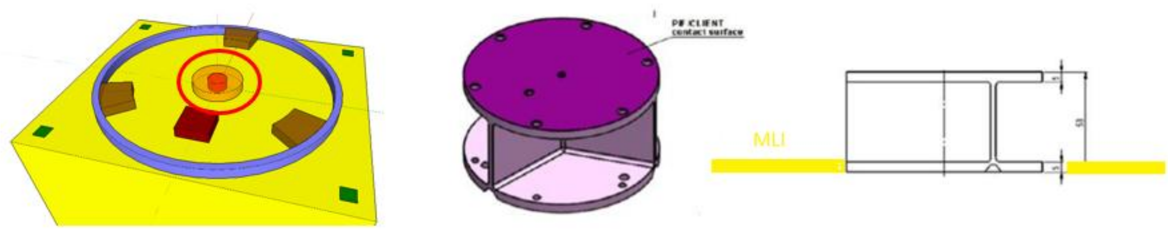

Figure 12: Thermal hardware allowed around the passive capture interface.

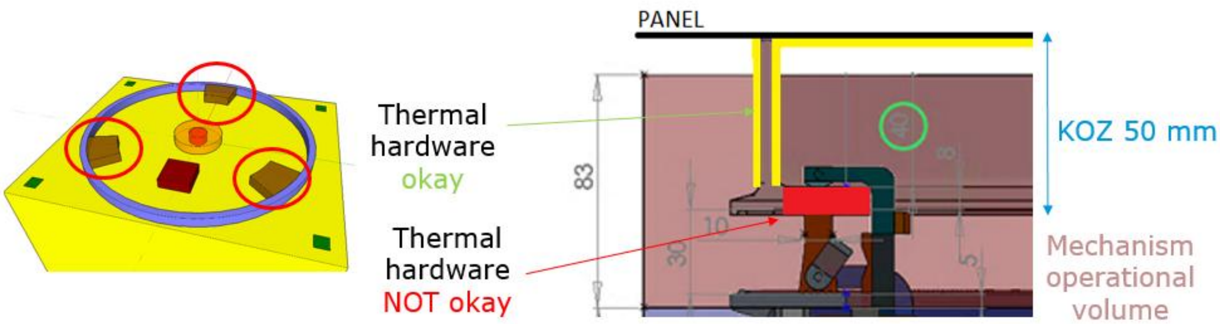

Figure 13: Thermal hardware allowed around the clamping mechanism KOZ on the LAR.

3.3.2. 3D Markers

D4R-IRD-0290 The Client spacecraft shall ensure that the solar absorptivity of the materials in the area of 250 mm by 250 mm centered around the 3D marker is higher than 0.9 in the visible spectrum. Exceptions are to be agreed with ESA.

Note-1: This requirement could be verified by inspecting the materials datasheet.
Note-2: If there are grounding straps, their effect can be considered as a focalized effect and not an issue.

Rationale: It is necessary to constrain the solar absorptivity of the surface surrounding the 3D marker, to limit the unwanted optical reflections from surfaces / materials on the chaser's sensors (which will be using active illumination in the visible spectrum). Unwanted reflections are for example glares which blind the sensors and prevent detection of the 3D marker.

3.4. Structural requirements

D4R-IRD-0300 The Client satellite shall support a 250 N axial load with a maximum deformation of 2.5 mm and 50 Nm torque load around all 3 axes at the capture interface, with a maximum deformation of 0.5 mrad. Analysis shall be performed to verify the structural integrity of at least the following interfaces under these loads: (1) the structural connection of the mechanical capture interface to the S/C and (2) mechanical limits of mechanisms (e.g. SADM), the interface to the deployed appendages and the appendages itself.

Rationale: These are the maximum loads exerted on the mechanical capture interface during all phases of operations, driven by the capture operations. The deformations lead to 1e5 stiffness values.

D4R-IRD-0310 The Client Spacecraft shall be capable of sustaining disposal acceleration forces through the Centre of Mass of 0.015 g (Threshold), 0.004 g (Goal) for at least 8 min.

Note: Disposal acceleration forces are to be considered perpendicular to the LAR separation plane.

Rationale: The acceleration limit aims to avoid that deployed appendages break or release debris. Besides the spacecraft structural design, also mechanical limits of mechanisms (e.g. SADM) shall be considered. The *chaser vehicle maximum thrust used for deorbiting will be limited accordingly to this requirement.*

3.5. AOCS requirements

D4R-IRD-0320 The Spacecraft, when in cooperative scenario, shall be able to acquire and maintain a three-axis stabilised attitude.

For LEO missions, the spacecraft shall align the LAR reference axis with the Spacecraft velocity vector in the Flight Path Frame. Deviations are to be agreed with ESA.

<u>Note</u>: The LAR reference axis is defined as the axis perpendicular to the LAR separation plane (also called launcher separation plane or LAR plane) passing by the centre of the LAR circumference (see Figure 14). The LAR face can be pointing to the velocity or anti-velocity direction.

<u>Rationale</u>: This requirement comes from the Servicer for the RdV/Capture operations. Approaching from V-bar is safer than from R-bar, as it allows to hold at any point in time.

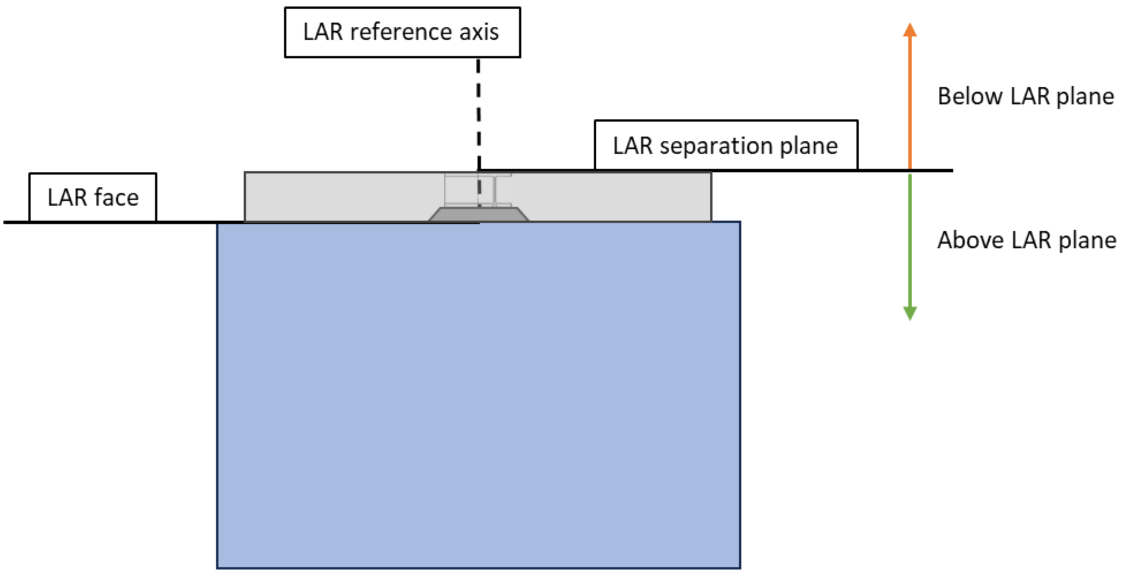

Figure 14: Representation of the LAR plane and LAR reference axis.

D4R-IRD-0330 The Spacecraft, when in cooperative scenario, shall maintain the required attitude defined in D4R-IRD-0320 for 3 orbits. Deviations are to be agreed with ESA.

Rationale: To allow sufficient time for rendezvous and capture operations (2 orbits nominal + 1 orbit margin).

D4R-IRD-0340 The Spacecraft, when in cooperative scenario, and while in the required attitude defined in D4R-IRD-0320, shall be capable of maintaining the attitude control without relying on thrusters that project below the LAR panel.

D4R-IRD-0350 The Spacecraft, when in cooperative scenario, and while in the required attitude defined in D4R-IRD-0320, shall be capable of maintaining the attitude control without relying on sensors for which the Field of View projects below the LAR panel.

Rationale: The required attitude shall be maintained by the spacecraft down to capture. Hence, the necessary equipment to maintain this attitude, e.g. AOCS sensors and actuators, shall not interfere with the removal vehicle approaching from the LAR face direction (e.g. thrusters plumes impingement, D4R-IRD-0340) nor be affected by its proximity (e.g. sensors fields of view, D4R-IRD-0350).

D4R-IRD-0360 The Client Spacecraft, when in cooperative scenario, and while in the required attitude defined in D4R-IRD-0320, shall ensure the pointing Absolute Performance Error is better than 1 deg (3-sigma) in any direction.

Rationale: This requirement comes from the Servicer for the RdV/Capture operations and the LAR design.

D4R-IRD-0370 The Client Spacecraft, when in cooperative scenario, and while in the required attitude defined in D4R-IRD-0320, shall ensure the spacecraft angular rates are less than 0.1 deg/s (3-sigma) in any direction.

Rationale: This requirement comes from the service vehicle for the RdV/Capture operations and it is normally within the capabilities of AOCS for LEO and GEO missions.

D4R-IRD-0380 The Client Spacecraft shall include a passive detumbling system which shall guarantee satellite angular rate reduction from up to 3 deg/s down to 0.75 deg/s in less than one year.

Note-1: Potential sources of angular rate increase are fatal failure mode (thrusters, momentum stored in reaction wheels), propellant system leakage, collision, Solar Radiation Pressure, …

Note-2: The impact of precession and nutation on the time for the reduction of the magnitude of the angular rates vector shall also be considered in the analysis.
Note-3: This shall be achieved without AOCS actuation.

Note-4: The detumbling system shall be verified under orbital environmental conditions considering that the satellite is not operational, assuming a failure in the nominal orbit.

Rationale: The magnitude of the Spacecraft's angular rate is a major design driver for chaser GNC, propulsion and telecommunications subsystems design and should be kept as low as possible. However, when the Spacecraft is uncontrolled the angular rates cannot be easily controlled and on-ground observations have shown that sudden increases of their magnitude are possible. Therefore, the damping of the tumbling motion rates is essential to make the removal feasible.
The rationale behind the duration of the angular rates damping is to allow the replacement in orbit of the non-operational satellite by the new operational one within one year.

D4R-IRD-0390 The detumbling system shall be able to automatically perform detumbling in case of mission loss without ground command. If activation is required, the activation criterium is to be agreed with the Agency.

Note: If the detumbling system is permanently active it can be considered already compliant with this requirement. Performances of the operational satellite shall be verified and met taking in consideration the potential perturbations created by the detumbling system.

Rationale: The angular rate damping shall be achieved passively as the Spacecraft can be considered uncontrolled and non-operational in the uncooperative scenario.

D4R-IRD-0400 The activation of the detumbling system, if an activation is required, shall be one fault tolerant to prevent an unintentional activation.

D4R-IRD-0410 The detumbling system, if an activation is required and when the satellite is in cooperative scenario, shall allow its activation or deactivation under ground command.

D4R-IRD-0420 In case of unforeseen end-of-life requiring a service mission for the disposal, the spacecraft shall enter a (sub)mode compatible with rendezvous and capture.

<u>Note</u>: Once the capture is done, when the spacecraft is in safe mode, the AOCS shall be inhibited from ground.

D4R-IRD-0422 In the cooperative scenario, the Spacecraft shall inhibit all AOCS commands moments prior to capture.

<u>Note</u>: The AOCS is inhibited so that the Servicer can perform the AOCS takeover. The command may be given through a ground command.

3.6. Operational requirements

D4R-IRD-0424 Following completion of nominal operations, when in cooperative scenario, the Spacecraft shall be manoeuvred by ground command from the operational orbit by at least 3 km in altitude, below the operational orbit.

<u>Note</u>: Other orbiting spacecraft below the operational orbit are to be considered when determining the reduction of altitude at the time of EOL approval.

<u>Rationale</u>: To prevent debris generation in the Spacecraft's operational orbit. Lower orbit is preferred as in the event of debris generation these would decay faster.

3.7. Documentation and models

D4R-IRD-0430 The documentation listed in Table-1 for a future removal mission shall be provided:

- Dedicated D4R requirements compliance matrix, indicating documents and sections with the justification for the compliance with each requirement included in this document.
- Dedicated D4R verification matrix, verification control to be included as part of the system level verification control document and respective work.
- Interface Control Document for Removal Servicer. The final version of this document shall be free of proprietary information in a format to be agreed by the Agency, so that it can be provided to a removal service provider. It shall include:
    - Detailed CAD or virtual 3D model updated with detailed final configuration mapped prior to launch.
    - Detailed MCI properties of the Spacecraft.
    - Detailed vibration modes of all deployable.

- Geometry of the docking surface to be provided with detailed description of the LAR including position, structural properties, materials, thermal hardware, etc. Detailed description of equipment accommodated inside the LAR (e.g. thrusters, antennas, umbilicals).
- Detailed information on the Keep Out Zones clearance for clamping mechanism and mechanical capture interface, 2D markers and 3D marker.
- Detailed information on all marker's positions, misalignments, clearance and surrounding materials, i.e. For each marker, document the background surface material, including AIT pictures, up do 10 cm surrounding it.

- Documentation of the LAR face when it is in final flight configuration. The pictures shall be free of proprietary information. The following pictures shall be taken:
  - LAR-Camera distance: several, from 5 m to 0.5 m, with a step 0.5 m (10 points), and from 0.4 m and 0.2 m, with a step 0.1 m (3 points), the angle between the normal to LAR plane and Camera line of sight shall be zero (0 deg).
  - For the pictures at 5, 4, 3, and 1 meter, the angle between the normal to LAR plane and Camera line of sight shall be varied: -15, -10, -5, +5, +10, +15 deg (4x6 = 24 pictures)
  - For the pictures at 0.8 and 0.5, the angle between the normal to LAR plane and Camera line of sight shall be varied: -5, -3,-1, +1,+3,+5 deg (2x6 = 12 pictures)
  - The pictures shall be taken with the 3D marker centred, in focus and properly exposed with an illumination unit.

Table 1: ADR documentation to be delivered per review

Document	PDR	CDR	QAR/FAR
ADR requirements compliance matrix	X	X	
ADR verification matrix	X (include compliance status)	X (as part of the system VCD)	X (as part of the system VCD)
ADR verification plan		X (as part of the system verification plan)	
ADR design justification file		X	X

Document	PDR	CDR	QAR/FAR
		(may be provided as part of the system DJF)	(may be provided as part of the system DJF)
Interface Control Document for Removal Servicer		X	X (updated identifying the modification since CDR)

Note 1: These photos can be taken only of the propulsion module bottom panel, before assembly into the SC, if no changes are expected to the configuration inside the LAR plane between assembly and flight. Thruster covers shall be removed for the pictures.

Note 2: Camera to be used characteristics: VNIR spectrum, 2048 x 2048 pixels, Focal Length 12 mm, assumed pixel size 5 micrometer.

Note 3: Information on illumination unit to be used: LED Stripes, Color 6000K, Luminous Flux 3000 lm. Illumination is to be placed 3 cm below and above the camera.

4. REQUIREMENTS FOR UNCONTROLLED RE-ENTRY

The differences compared to controlled re-entry come from the different loads that are involved for each case during the de-orbiting. For a controlled re-entry, high loads are involved and the solution adopted is to use the Launcher Adaptor Ring (LAR) to help sustaining them; while for an uncontrolled re-entry the loads are much lower and the use of a LAR is not needed.
Only the differences between the D4R IRD requirements for satellites performing an uncontrolled re-entry are listed below.

In the requirements for controlled re-entry, there are many references to the *LAR face*, which have to be replaced by the *capture face* for the case of uncontrolled re-entry. These requirements are not included in the change list below.

The following three requirements are different in case of an uncontrolled re-entry:

D4R-IRD-0010 The Client Satellite shall be equipped with:

- the following passive mechanical interfaces for rendezvous, capture and subsequent removal from orbit:
  - Mechanical Capture Interface (MICE)
  - ~~Launcher Adaptor Ring (LAR diameter of 1194 mm or 1666 mm 0r 937 mm)~~
- The following navigation aids:
  - 2D markers
  - 3D marker.

<u>Rationale</u>*: For an uncontrolled re-entry, the loads can be sustained by the MICE interface.*

D4R-IRD-0020 The Spacecraft shall accommodate a mechanical capture interface with 98 mm diameter and 50 mm height cylinder, aligned with the Client S/C CoM.

D4R-IRD-0210 The KoZ's in Figure 9 around the LAR are not applicable.

The following requirements are not applicable in case of an uncontrolled re-entry:

- D4R-IRD-0230
- D4R-IRD-0240
- D4R-IRD-0250

The following additional requirements shall be complied to in case of an uncontrolled re-entry, in addition to the requirements in chapter 3:

D4R-IRD-0440 The maximum misalignment between the centre of the mechanical capture interface and the projection of the Spacecraft's CoG on the capture face, d_{cog}, shall be lower than the value given by Figure 16, depending on the perpendicular distance from the capture face to the Spacecraft's CoG, $d_{v_{cog}}$.

Note 1: The centre of gravity of the servicer is assumed to be at 0.5 m along the capture interface reference axis (defined in Figure 14) with respect to the top of the mechanical capture interface after capture.

Note 2: A force of 20 N thrust applied perpendicular to the centre of the mechanical capture interface has been assumed.

Note 3: d_{cog} and $d_{v_{cog}}$ are represented in Figure 15.

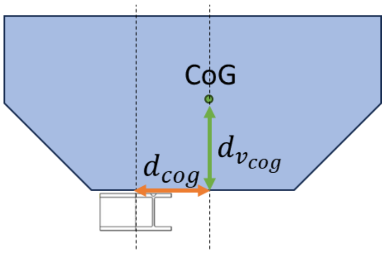

Figure 15: Definition of distance d_{cog} and $d_{v_{cog}}$.

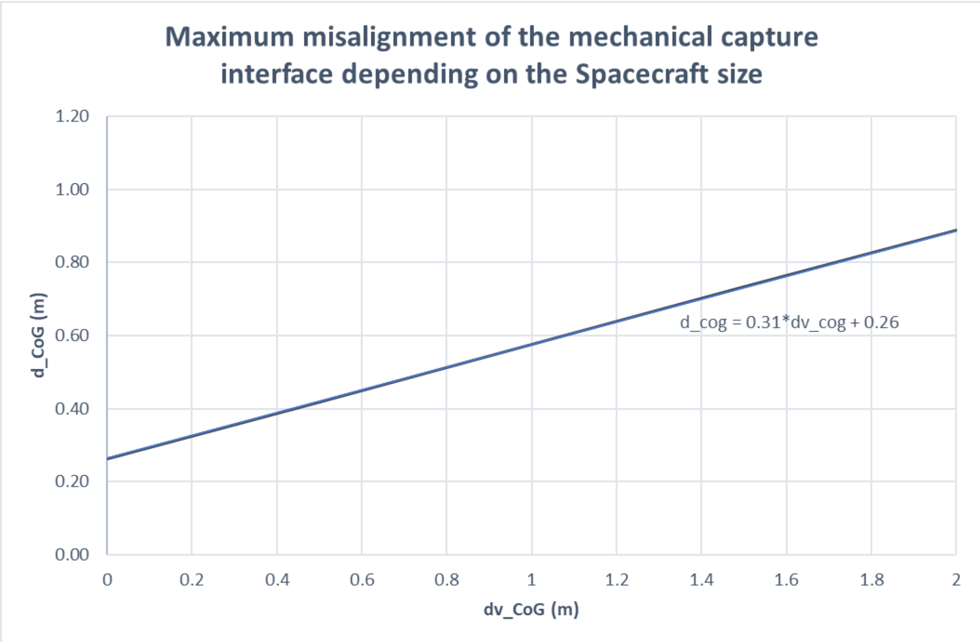

Figure 16: Maximum misalignment between the centre of the mechanical capture interface and the projection of the Spacecraft's cog on the capture face, d_{cog}, with respect to the perpendicular distance from the capture face to the Spacecraft's cog, and $d_{v_{cog}}$

5. REQUIREMENTS FOR GEO GRAVEYARD ORBIT RELOCATION

Graveyard orbit relocation typically involves loads comparable to those sutained during an uncontrolled re-entry. However, depending on the mission profile and removal startegy, these loads can exceed the nominal range. In such cases, the mechanical capture interface alone may not be sufficient to sustain the forces involved (see D4R-IRD-0290). Therefore, the use of the LAR, or other attachment points, might be required.

In GEO, active attitude control is necessary since passive detumbling cannot be achieved with the same systems used in LEO. Further work is needed to understand the performance of this feature for GEO orbits. Therefore, a cooperative scenario is mandatory when considering graveyard orbit relocation as disposal option.

The specific requirements applicable to graveyard orbit relocation in GEO, and the differences with respect to the uncontrolled re-entry scenario requirements, are detailed in this section.

The following requirements differ in case of a graveyard orbit relocation:

D4R-IRD-0010 The Client Satellite shall be equipped with:

- the following passive mechanical interfaces for rendezvous, capture and subsequent removal from orbit:
  - Mechanical Capture Interface (MICE)
  - To be analysed if additional interfaces are needed that can sustain disposal loads. The spacecraft ICD shall provide the possible mechanical attachment points for the Servicer, together with the tolerable forces and torques of those mechanical interfaces.
- The following navigation aids:
  - 2D markers*
  - 3D marker.

** The functionality of 2D markers to support ground-tracking and attitude reconstruction are to be confirmed for GEO (further work on ESA side is needed to understand the performance of these features for GEO orbits), and thus the retro-reflector element of the 2D markers are not imposed by the requirements at this stage.*

D4R-IRD-0210 The KoZ's in Figure 9 around the LAR are not applicable, in case the LAR is not used as a capture interface.

D4R-IRD-0330 The Spacecraft, when in cooperative scenario, shall maintain the required attitude defined in D4R-IRD-0320 for at least 5 hours. Deviations are to be agreed with ESA.

Rationale: To allow sufficient time for rendezvous and capture operations.

The following requirements are not applicable in case of a graveyard orbit relocation:

- D4R-IRD-0150
- D4R-IRD-0160
- D4R-IRD-0170
- D4R-IRD-0180
- D4R-IRD-0190
- D4R-IRD-0200
- D4R-IRD-0230
- D4R-IRD-0240
- D4R-IRD-0250
- D4R-IRD-0380
- D4R-IRD-0390
- D4R-IRD-0400
- D4R-IRD-0410
- D4R-IRD-0424

ANNEX 1: DEBRIS REMOVAL SERVICE DESCRIPTION

This annex describes the steps to be followed by a debris removal for both a cooperative and uncooperative removal.

The descriptions are particularised for a Sentinel satellite as a target, but they would be the same for any other satellite.

Cooperative Removal

The currently assessed cooperative case mission architecture is described in the following points:

1. **Launch** Phase: the Servicer is launched to an orbit TBD km below the operational one.
2. Launch **Separation**: the Servicer separates from the launcher and performs a launch injection correction manoeuvre to acquire the capture orbit.
3. **Commissioning** Phase: the Servicer is commissioned, and all payload and platform functions are verified before proceeding with the mission. Main implications for CAT payload may include: health checks for CAT and potential mechanical release of robotic actuator, calibration of nav. system, etc…).
4. **LTAN Correction** Phase. This manoeuvre is required in order to compensate for Sentinel satellite orbit plane drift (along 1 year after failure as a mean).
5. **Rendezvous** phase: Rendezvous Phase. This phase involves relative navigation between the Servicer and the Sentinel satellite once line-of-sight is acquired. The baseline includes at least the following sub-phases (with several hold points):
    - Far rendezvous phase = start of relative navigation by servicer -> boundary of the approach ellipsoid
    - Close rendezvous = inside the approach ellipsoid. It includes the final approach up to capture
6. Inspection phase = inside the approach ellipsoid, outside the keep-out-zone, at a distance including safety margins in case of anomaly during inspection. Recommendation to place it as far as the inspection resolution permits. **Capture** and **Stabilisation** phase: from an operations point of view, constant visibility from ground is required and the confirmation of capture on-board by the Servicer. The Capture/Stabilisation is split into the following sub-phases:

- Last approach up to capture distance (from 5m to capture distance). It includes the close rendezvous phase with target tracking up to capture triggering distance.
- Soft (topological) capture. It lasts from the Gripper closing command issue up to the moment in which the MICE can no longer escape from the End-effector.
- Hard capture. In this phase, final gripping is performed, for what misalignments compensation and contact preload takes place via end-effector and robotic platform.
- Relocation of stack. This is the phase in which the Client is already linked to the Servicer satellite by means of the End-effector fully closed over the MICE or passive interface. The robotic platform performs the required actuation as to bring together both Client and Servicer LARs so that Clamping can be performed to form a rigid link between both spacecrafts.
- Clamping. In this sub-phase the three clamping devices are commanded at the same time to actuate and clamp over the Client LAR and conform at the end of the actuation a rigid stack (Client + Servicer) linked at their LARs.
- Braking (stabilisation), for uncontrolled capture only. Is the removal of the rotational velocities w.r.t. the orbital frame remaining after capture.
- End-effector release. After clamping, the End-effector is released from the MICE and the robotic platform retreats up to its resting state to avoid loads.
- Stack re-orientation. The Servicer GNC re-orients the stack (considered as a rigid single body) so that it is aligned with the de-orbiting delta-V vector before de-orbiting or disposal manoeuvre.

7. **Disposal** phase: in this phase the stack is already stabilised (rotation rate close to 0 deg/s) and the Servicer performs the required attitude and delta-V manoeuvres as to de-orbit the stack.

For **cooperative** and prepared targets, it is assumed the satellite:

- Is prepared for capture (e.g. dedicated mechanical capture interface, rendezvous markers / navigation supports implemented)
- Can provide telemetry to the mission control centre of the debris removal service provider

- Capable to perform attitude control
- Will not hinder the capture process (e.g. thrust during the final moment before capture).

For **uncooperative** and prepared targets, it is assumed the satellite is:

- Prepared for capture (e.g. dedicated mechanical capture interface, rendezvous markers / navigation supports implemented)
- Unable to provide telemetry on the status, all information on target status based on observations from ground
- Unable to perform attitude control:
- Tumbling motion shall be assumed around any axis
- Characterisation of tumbling motion shall be done in orbit by the Chaser.

ANNEX 2: APPLICABILITY MATRIX

Table 2: Applicability Matrix

Requirement	Controlled	Uncontrolled	Graveyard
D4R-IRD-0010	X	X*	X**
D4R-IRD-0020	X	X*	X*
D4R-IRD-0030	X	X	X
D4R-IRD-0040	X	X	X
D4R-IRD-0050	X	X	X
D4R-IRD-0060	X	X	X
D4R-IRD-0070	X	X	X
D4R-IRD-0080	X	X	X
D4R-IRD-0090	X	X	X
D4R-IRD-0100	X	X	X
D4R-IRD-0110	X	X	X
D4R-IRD-0120	X	X	X
D4R-IRD-0130	X	X	X
D4R-IRD-0140	X	X	X
D4R-IRD-0150	X	X	
D4R-IRD-0160	X	X	
D4R-IRD-0170	X	X	
D4R-IRD-0180	X	X	
D4R-IRD-0190	X	X	
D4R-IRD-0200	X	X	
D4R-IRD-0210	X	X*	X**
D4R-IRD-0220	X	X	X
D4R-IRD-0230	X		
D4R-IRD-0240	X		
D4R-IRD-0250	X		
D4R-IRD-0260	X	X	X
D4R-IRD-0270	X	X	X
D4R-IRD-0280	X	X	X
D4R-IRD-0290	X	X	X
D4R-IRD-0300	X	X	X
D4R-IRD-0310	X	X	X
D4R-IRD-0320	X	X	X
D4R-IRD-0330	X	X	X**
D4R-IRD-0340	X	X	X
D4R-IRD-0350	X	X	X
D4R-IRD-0360	X	X	X
D4R-IRD-0370	X	X	X

Requirement	Controlled	Uncontrolled	Graveyard
D4R-IRD-0380	X	X	
D4R-IRD-0390	X	X	
D4R-IRD-0400	X	X	
D4R-IRD-0410	X	X	
D4R-IRD-0420	X	X	X
D4R-IRD-0422	X	X	X
D4R-IRD-0424	X	X	
D4R-IRD-0430	X	X	X
D4R-IRD-0440		X	X

X: Requirement is applicable, see requirement definition in section 3.

X*: Modified requirement with respect to controlled scenario is applicable, see requirement definition in section 4.

X**: Modified requirement with respect to uncontrolled scenario is applicable, see requirement definition in section 5.