

Design for Removal

Executive Summary Report

ESA STUDY CONTRACT REPORT		
ESA Contract No: 4000116081/15/NL/GL C/as	SUBJECT: Design for Removal	CONTRACTOR: Thales Alenia Space
NAME OF ESA STUDY MANAGER: Andrew Wolahan DIV: Directorate of Technical and Quality Management. Clean Space Section DIRECTORATE: D/TEC	ESA BUDGET HEADING: ESA's General Studies Programme	

Approval evidence is kept within the documentation management system.

1. INTRODUCTION AND SUMMARY.....	3
2. STUDY LOGIC AND COMPLETED ACTIVITIES.....	5
3. MAIN SYSTEM REQUIREMENTS.....	8
4. TRADE-OFFS OVERVIEW	10
5. SDRS TECHNIQUES SELECTION.....	12
6. CONCLUSION.....	15

1. INTRODUCTION AND SUMMARY

The current study D4R (“Design For Removal”) proposes an assessment of the potential added value to implement additional mechanisms or tools on future satellites or launcher upper stage to ease their removal. This study is an opportunity to address the duality in between “easing ADR mission” / “minimizing impact on space bodies”.

With Cleanspace initiative, ESA gives a pro-active answer to the environmental challenges both on Earth and in Space. Space Debris Mitigation and Space Debris Remediation are two branches of these Clean Technologies which need to be conducted in parallel to face the risk of losing mission through the impact of space debris.

While Active Debris Removal missions and technology building blocks are currently supported by on-going analysis, this study proposes an assessment of the potential added value to implement additional mechanisms or tools on future satellites or launcher upper stage to ease their removal.

In the future, satellites will have to demonstrate compliance with debris mitigation requirements, covering re-entry or parking graveyard orbits and passivation. Nevertheless, during the mission, a failure could occur without any possibility to manoeuvre the satellite and achieving its compliance to the Space Debris Mitigation requirements. Therefore to anticipate the need to use ADR for deorbiting (or reorbiting) the satellite, it is interesting to evaluate the implication of adapting the satellites and launcher upper stage to support a future ADR mission.

The main challenge was to find new solutions for assisting future removal missions and to analyse the impacts from system point of view. Indeed, those solutions include SDRS (Situational Awareness, Active Debris Removal and On-orbit Servicing) aspects and cover the different segments:

- *Situational awareness*; Europe relies on the European Space Situational Awareness Program, where ESA is designing a system to track debris and alert satellite operators when evasive action may be necessary. Those observations detect, catalogue and predict position and velocity of the pieces. For future ADR mission, in addition to those 2 parameters, motion of the satellite or launcher stage at EOL in orbit is necessary to prepare efficiently the ADR capture. This has been clearly demonstrated during e.Deorbit phase A study, with the impact of the satellite tumbling rate on the design of the capture system mechanism itself or of the capture strategy and rendezvous
- *Rendezvous & Inspection*; to estimate target motion, 3D model salient edges extraction and projection onto image is one option which would be improved by differentiated patches on target.
- *Stabilization before capture*; It has been demonstrated that with a tumbling rate higher than few dozen degree per seconds, robotic arm capture mechanism will not offer the capacity to catch in a safe manner.
- *Capture*; Different appendages could ease target grasping and capture.

Implementation of those devices is qualitatively compared on 3 types of satellites and one launcher upper stage

- GEO satellite
- LEO satellite
- Constellation satellite
- AVUM

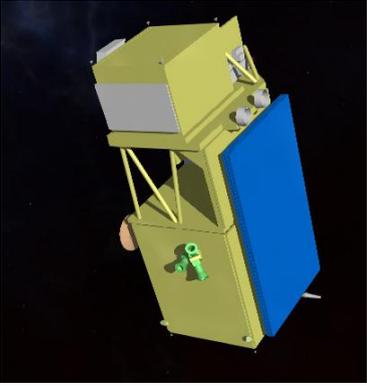
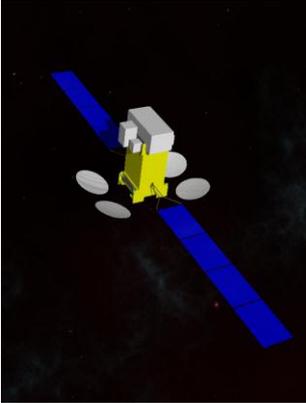
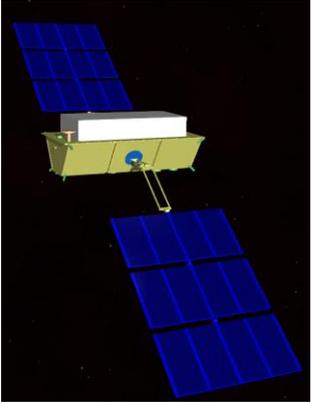
			
<p>"LEO-like" satellite</p>	<p>"GEO-like" satellite</p>	<p>"Constellation-like" satellite</p>	<p>AVUM Upper Stage</p>

Figure 1-1: D4R Study cases

After trade-off analyses, 4 study cases designs have been selected to implement proposed SDRS techniques to support ADR mission. Those design cases were considered for system and programmatic analysis of the potential added devices.

To build a methodology enabling comparison, high level criteria were proposed to support grading with four major axis:

1. Cost : covers development cost, manufacturing cost, integration cost, validation cost, development duration, integration impact on programmatic
2. Technical feasibility: covers design criticality, TRL & maturity
3. Performances : covers mass, consumption, geometry, inertia, mechanical behaviour
4. Risk: covers risks & interference with nominal operation, risk during device deployment (if any), risk during capture, risk of additional debris creation, reliability

The heritage and TRL of the proposed devices has led to identify the early development tasks needed and to propose a technology development roadmap.

2. STUDY LOGIC AND COMPLETED ACTIVITIES

The study activities were kicked-off on December 15st, 2015. The study logic has been shaped by the need for identification of SDRS possible concept and associated. This Concept Design step included four work packages run essentially in series:

Task 1 – State of the Art

Task 2 – Preliminary Evaluation

Task 3 – System trade-off

Task 4 – Road map

The overall work logic is sketched in Figure 2-1. It consists into four phases lasting a total of 15 months.

During the first phase, the first task aimed at performing a comprehensive SDRS background analysis, for each segment, and addressed all the specific points detailed in the SOW. It was the occasion to gather the background of each company part of the consortium, and completed it with the survey of the European and non-European industry advances in the SDRS field. The satellite primes, TAS F and TAS I, closely followed this state-of-the-art review to identify devices possibly implemented on spacecraft under development.

The PM#1 was held on February 25th, 2016 and dedicated to a shared ESA/TAS creativity session.

This high level screening of the available technologies, assessing the most promising ones, support mapping of SDRS segments with SDRS technologies. Very simplified graphical representation of each proposed concept gather identification of problematic areas.

A progress meeting, held in April, 21st, 2016 validated the work performed during task 1.

Task 2 consisted in the definition a set of criteria. During this task, elementary evaluation methods among partners' experiences has been discussed, and integrated into an overall system assessment methodology. This task out came into an objective procedure, allowing the comparison of various types of impacts, such as mass, power consumption, development duration, cost, risks.... criteria allowing the consortium to evaluate and compare the system level impacts the concept applications.

This evaluation has been applied on 4 examples (LEO satellite, GEO satellite, constellation and upper stage) chosen properly and rationally to support sufficient detailed analysis. Selection has been agreed by ESA during MTR on July, 12th, 2016.

The third phase consisted in the redesign of the non-functional space system focusing among passive stabilization, solutions to assist rendezvous, and capture, facilitating safe structural attachment, reflectors to assist tracking. The methodology derived in task 2 is used to assess precisely the system impacts of the re-design solutions. Preliminary design has been defined depth enough to support performance analysis.

Final Presentation was held on March, 15th, 2017 highlighting the most promising applications and the further development steps to mature SDRS technologies to an acceptable qualification level.

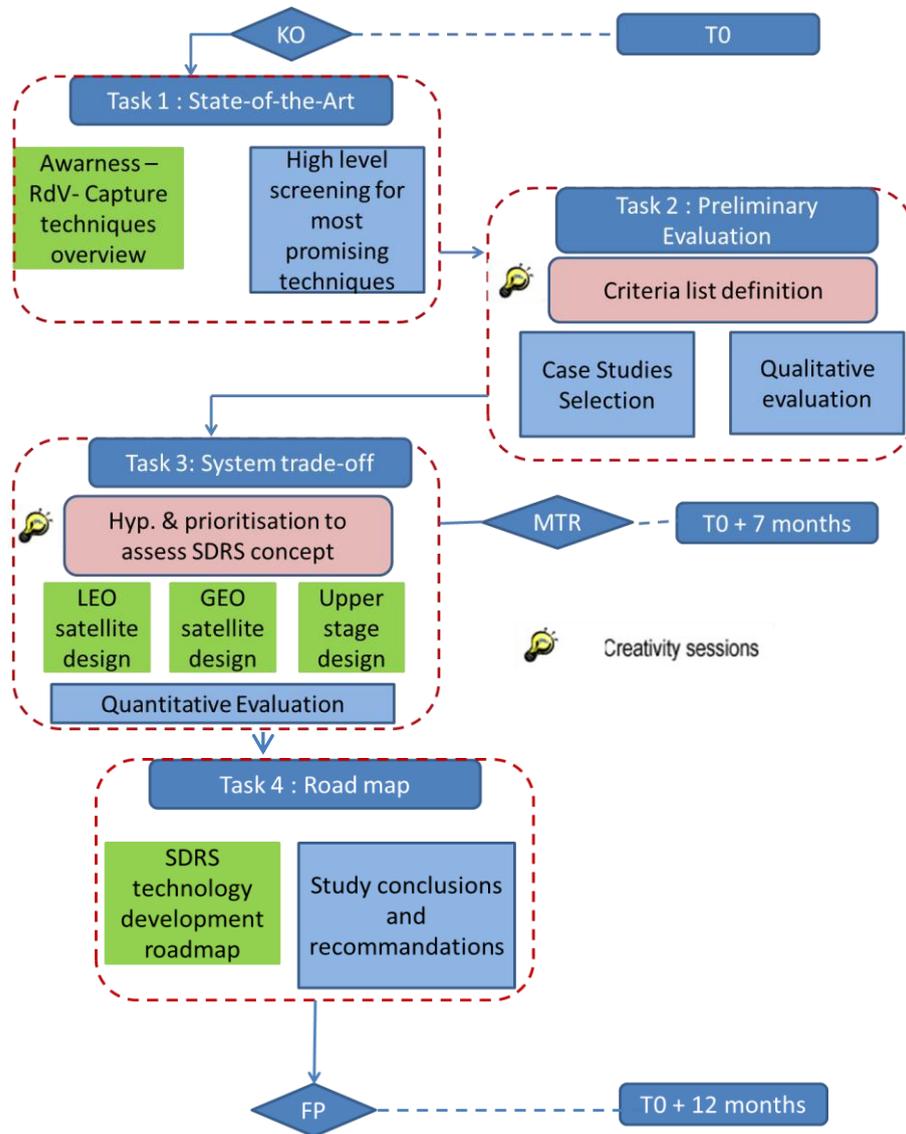


Figure 2-1: Study logic

The consortium was built to provide the system understanding through two experienced satellite primes, and entities acknowledged for their capability to manage complex sub-systems, with distribution of WP as per Figure 2-2, with the header colour indicating:

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

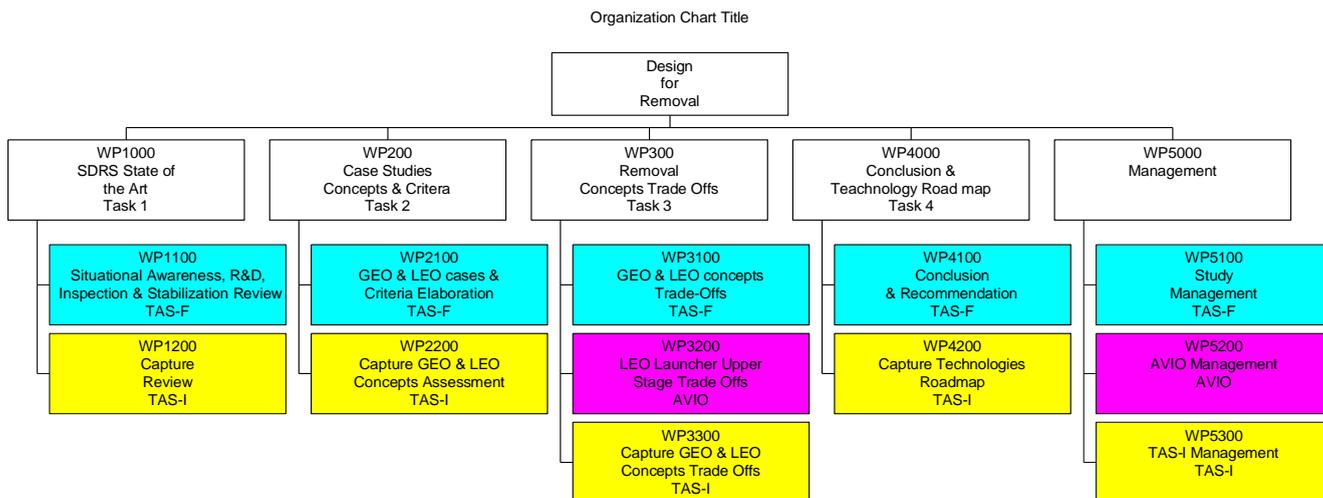


Figure 2-2: D4R study WBS

3. MAIN SYSTEM REQUIREMENTS

In first step, high level screening of the most interesting SDRS techniques has been set with focus on TRL and reflecting advantages for ADR applications. Those SDRS techniques address each domain:

- Space Surveillance and Tracking
- Rendezvous & Inspection
- Stabilization before capture
- Capture and Further stabilization before de-orbiting initiation

D4R addresses debris after EOL or after major failure during mission. The major assumption is there is no on-board capacity to react or to use on-board equipment to ease ADR capture.

For ADR mission, 4 main risks were identified during previous ADR studies:

1. Risk of collision between chaser and debris target
2. Risk of debris generation
3. Risk of unsuccessful capture
4. Risk of casualty on ground.

The last risk is out of scope of the current study, which addresses the devices to support ADR mission up to capture.

Therefore, several technologies have been identified as promising to support each risk identified for an ADR mission and relying on a dedicated SDRS domain:

Ref	Failure Mode ADR	Effect	SDRS Domain	Proposed Mitigation on D4R
C1	Unknown debris motion	<p>Would imply additional propellant budget and approach mode definition update in-flight for ADR</p> <p>Would increase ADR mission time to consider a first phase of determination of attitude motion vector and evolution to build the capture strategy</p>	SST device	<p>To support detection, location and attitude motion evaluation from ground or from orbit</p> <ul style="list-style-type: none"> • LRR • Radar corner reflector
C2	Error in the relative pose	<p>Could lead to a collision or could induce additional in-orbit loop to support close range RdV and to secure capture process definition</p>	RdV device	<p>To support relative navigation and fine pose determination</p> <ul style="list-style-type: none"> • Retro-reflector • 2D-3D markers

Ref	Failure Mode ADR	Effect	SDRS Domain	Proposed Mitigation on D4R
C3	Non-sufficient lighting condition for capture due to eclipse	Could lead to loss of vision system with no possibility to track and capture	Vision device	To support illumination during capture <ul style="list-style-type: none"> • LED
C4	High tumbling rate	Every capture technique (tentacle, net, harpoon, robotic arm) present a physical limit in the relative angular momentum between ADR and target. Would induce possible non capture feasibility or additional risk	Stabilization device	To support detumbling before capture or to stabilize at EOL <ul style="list-style-type: none"> • Dedicated AOCS stack-mode (servicing solution) • Passive transferred AOCS • Fluid damper
C5	Rigid Capture slippery	Could result a non-correct grasping or inadvertent contact with the satellite Stiffness of the capture point on debris could not be sufficient to handle deorbiting process	Capture device	To support easier capture by robotic arm If LAR capture not possible, <ul style="list-style-type: none"> • FGFR • Drogue for servicing option
C5	Flexible capture with harpoon in bad location	Would possibly create additional debris Could result a non-correct harpooning (on pressurized vessels for example)	Capture device Stabilization device	To support harpooning process <ul style="list-style-type: none"> • Harpoon canister

4. TRADE-OFFS OVERVIEW

The Trade-offs work conducted during the study has been performed in accordance with the following criteria:

Programmatic

- development cost
- recurrent cost which includes manufacturing cost and AIT/AIV

Technical

- Power
- Mass
- Dimensions/ accomodation
- TRL
- Inertia (through Impact on mass properties, hence required modifications to AOCS/GNC modes)

Performance

- Reduction in Mission Risk. This covers collision risk, debris generation risk, unsuccessful detumbling, controlled re-entry, flexibility to SDRS segments)
- Increase in complexity to chaser (approach complexity, detumbling, ..)
- Synergy with in-orbit servicing

Those trade-offs allowed to select SDRS techniques, based on

- Timeline scenario for a future ADR mission

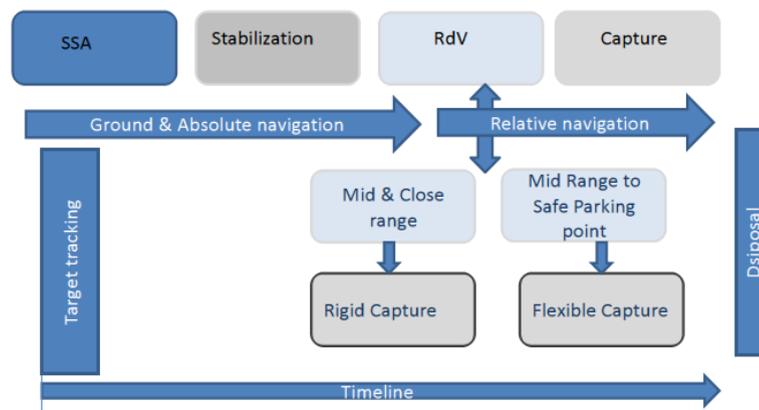


Figure 4-1 : SDRS technique introduction in the ADR mission timeline

- Mapping of the techniques with the domain

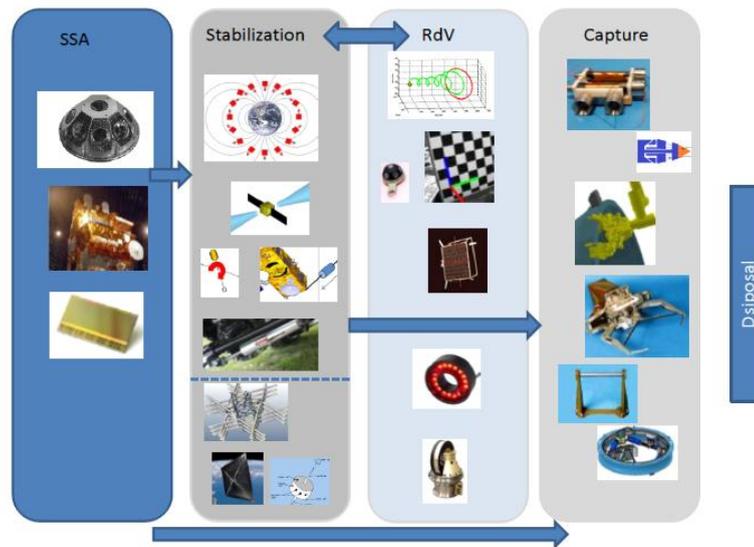


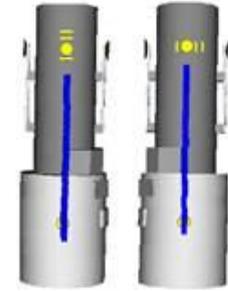
Figure 4-2 : SDRS technique mapping

- Qualitative evaluation of the SDRS technique on each study case

5. SDRS TECHNIQUES SELECTION

For each of the selected SDRS techniques, the system activity has been supported by:

- a functional description
- a baseline design supported by a IDM model
- preliminary definition of requirements for the concept that can be used as a starting point in a potential follow-up phase

		<p>Adequate retro reflectors on the corners of the satellite will support improvement of motion characterization.</p> <p>Satellite Laser Ranging (SLR) measures distances to the satellites with a laser and is improved with corner cubes (right picture) that reflect the laser beam.</p>
		<p>Radar corner reflector or material with higher reflectivity for radar waves will improve radar imagery.</p> <p>Use of contrasted colors on the spacecraft with black, gold or stripped MLI vision (right picture) will improve the imagery interpretation and camera capacity for far range rendezvous based on image recognition.</p>
		<p>Embedded marks, patterns are a possible solution to increase effectiveness and efficiency of unmanned sensors.</p> <p>Those marks maximize the ability to process sensor imagery and detect and identify, supporting pose estimation algorithms.</p>

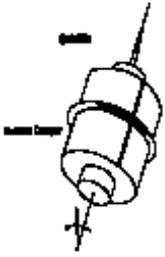
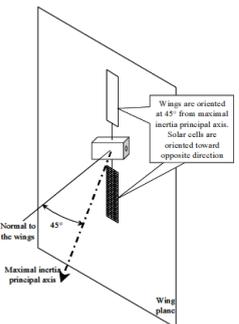
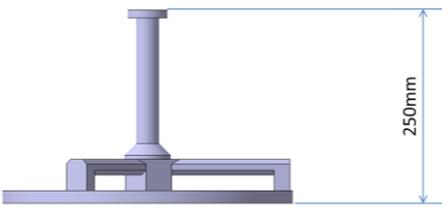
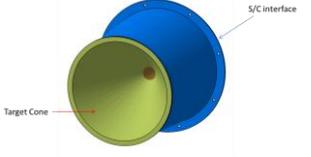
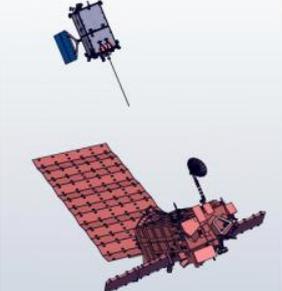
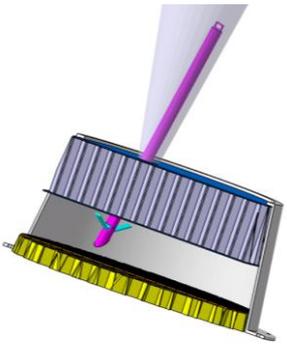
 <p>(credit Nathaz Modelling Laboratory)</p>	 <p>Wings are oriented at 45° from maximal inertia principal axis. Solar cells are oriented toward opposite direction.</p> <p>Normal to the wings 45° Maximal inertia principal axis Wing plane</p>	<p>Passive dampers increase the energy dissipation within the debris (viscous friction, flexible appendage, moving mass). The aim is to reach a pure rotation along the debris main inertia axis.</p> <p>Stabilization by Solar Array windmill is already used as active process for stabilization and could also improve passively long term stabilization.</p>
 <p>250mm</p>	 <p>S/C interface Target Cone</p>	<p>For rigid capture, end deflector could be specifically designed for grasping outside from the satellite adapter ring.</p> <p>Probe and drogue docking system is one possible docking system which is in-flight demonstrated.</p>
		<p>For flexible capture, harpoon anchorage can be considered as a critical operation.</p> <p>Dedicated appendage to safely harpooning would insure no critical part perforation and no further debris production.</p>

Figure 5-1 : SDRS solutions

Main impacts at satellite system level are identified:

- Small increase of satellite dry mass, and consequently on launch mass thanks to snow ball effect
- Limited impact at system level for validation (inside AOCS databank, no power...)
- No major impact on integration time and satellite AIT/V process
- Requests some specific technologic activities to mature the technology

OPEN



REFERENCE : CS-D4R-ESR

DATE : 12/04/2017

ISSUE : 1

Page : 14/15

It is noted that in the future, spacecraft will be designed to achieve the EOL compliance to Space Debris Mitigation requirements. Nevertheless, any failure could endanger this status with a non-controlled spacecraft in the protected region. The proposed SDRS solutions to improve future ADR mission should be balanced with additional mass and cost for satellite, only devoted to a failure case.

Furthermore, definition of future ADR servicing is not off the shelf and the design of the ADR vehicle itself will impact the choice of SDRS devices to promote.

THALES

100181547K-EN-3

OPEN

6. CONCLUSION

A set of trade-offs has been conducted during the D4R phase 0 study. With a first focus on existing concepts, it has been highlighted that the proposed additional devices to support ADR mission relies on some well-known technologies having a high TRL, already all equal or above 6. For the units having a lower TRL, pre-development activities are requested:

- Improvement of situational awareness for measurement from ground radar
- Fluid damping stabilization
- Several devices for Rendezvous depending on ADR sensors definition
- Device for capture depending on ADR capture method

Several techniques have been selected as promising and those which need to go to additional technology development are identified, through preliminary TDA.

The development road map has to be built in coherence with ESA Cleanspace roadmap and ADR technology and definition.