ZERO DEBRIS TECHNICAL BOOKLET

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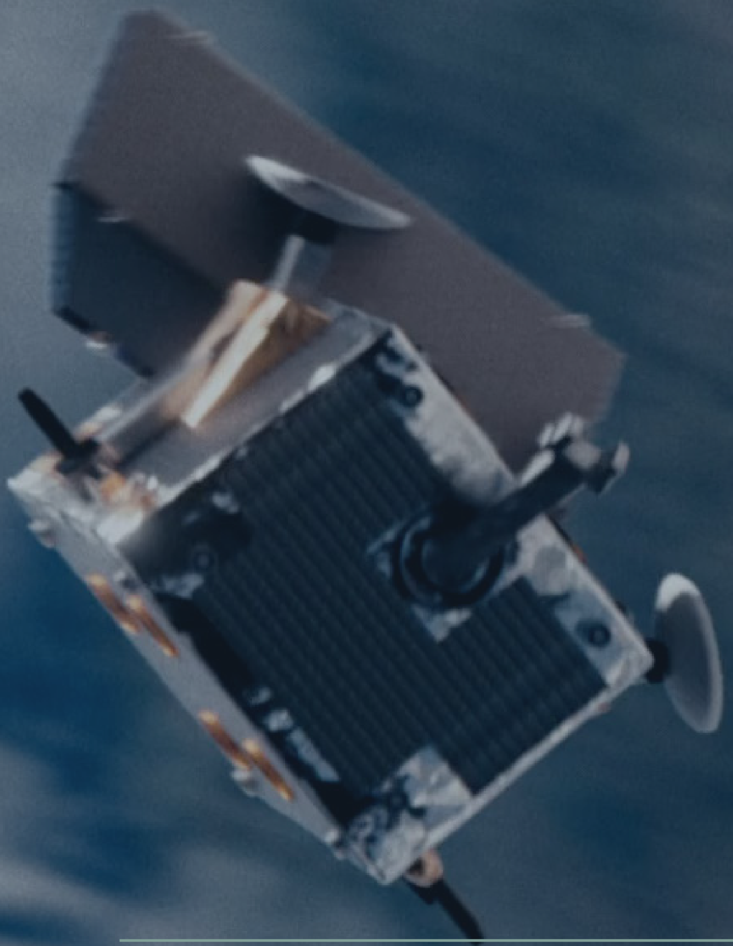
1.
INTRODUCTION

1.1. BACKGROUND

The orbital environment is a limited natural resource. Due to the ever-increasing number of space activities and the democratisation of access to space, the growing population of space objects and associated debris in Earth and cislunar orbits is putting an increasing strain on this limited resource. Despite several initiatives for space debris mitigation in recent years and modest improvements in public awareness, there is a general consensus that more ambitious actions are urgently needed from all space stakeholders to prevent, mitigate, and remediate debris. This is essential for ensuring the long-term Sustainability of outer space activities as defined by the Guidelines for the Long-term Sustainability of Outer Space Activities of the United Nations Committee on the Peaceful Uses of Outer Space, enabling future missions, preserving existing assets in space, and protecting human populations and infrastructure on the ground. To this end, a group of stakeholders, facilitated by the European Space Agency, co-developed the Zero Debris Charter[1]: a statement for space Sustainability that outlines a set of guiding principles and jointly agreed targets for 2030.

The principles underpinning the Charter are, in brief: to minimise the unintentional release of debris; to avoid the intentional release of debris; to anticipate and mitigate the impact of debris on human populations, infrastructure, and Earth's environment; and to encourage constant and collaborative efforts to improve awareness and understanding of the debris population.

Accompanying these principles is a set of quantifiable, jointly defined targets that establish the metrics for assessing the efforts of the Zero Debris community. This Booklet presents a selection of technical needs, solutions and key enablers that collectively provide the means to achieve the targets of the Zero Debris Charter.



[1] The Zero Debris Charter is available at the following link:
https://esoc.esa.int/sites/default/files/Zero_Debris_Charter_EN.pdf

1.2. SCOPE OF DOCUMENT

The Zero Debris Technical Booklet (the Booklet) provides a non-exhaustive list of technical needs, proposed solutions, and key-enablers considered and identified by the Zero Debris community as essential to achieve the targets set out in the Zero Debris Charter. The Booklet is a living document, intended to be periodically updated by the Zero Debris community, ensuring that it remains aligned with emerging solutions and evolving space Sustainability challenges. The needs, solutions, and key enablers are not arranged in order or priority or importance and should not be interpreted as highlighting any particular enablers or key needs over any other.

Technically-Focused:
This Booklet focuses on technological developments and activities only. It is not meant to cover legal, regulatory, political, or financial aspects.

Non-Binding:
This Booklet does not constitute a binding agreement or commitment on the part of any party. It is meant to provide general guidance and should not be interpreted as a formal statement of intent or obligation.

Cross-Cutting:
This Booklet is organised into chapters. Some key enablers apply to multiple chapters or require context from other sections and are identified as such [like this].

Collaborative:
This Booklet was voluntarily developed by stakeholders of the Zero Debris community in an open and collaborative process.

Complementary:
This Booklet does not impose any additional expectations on the signatories of the Zero Debris Charter.

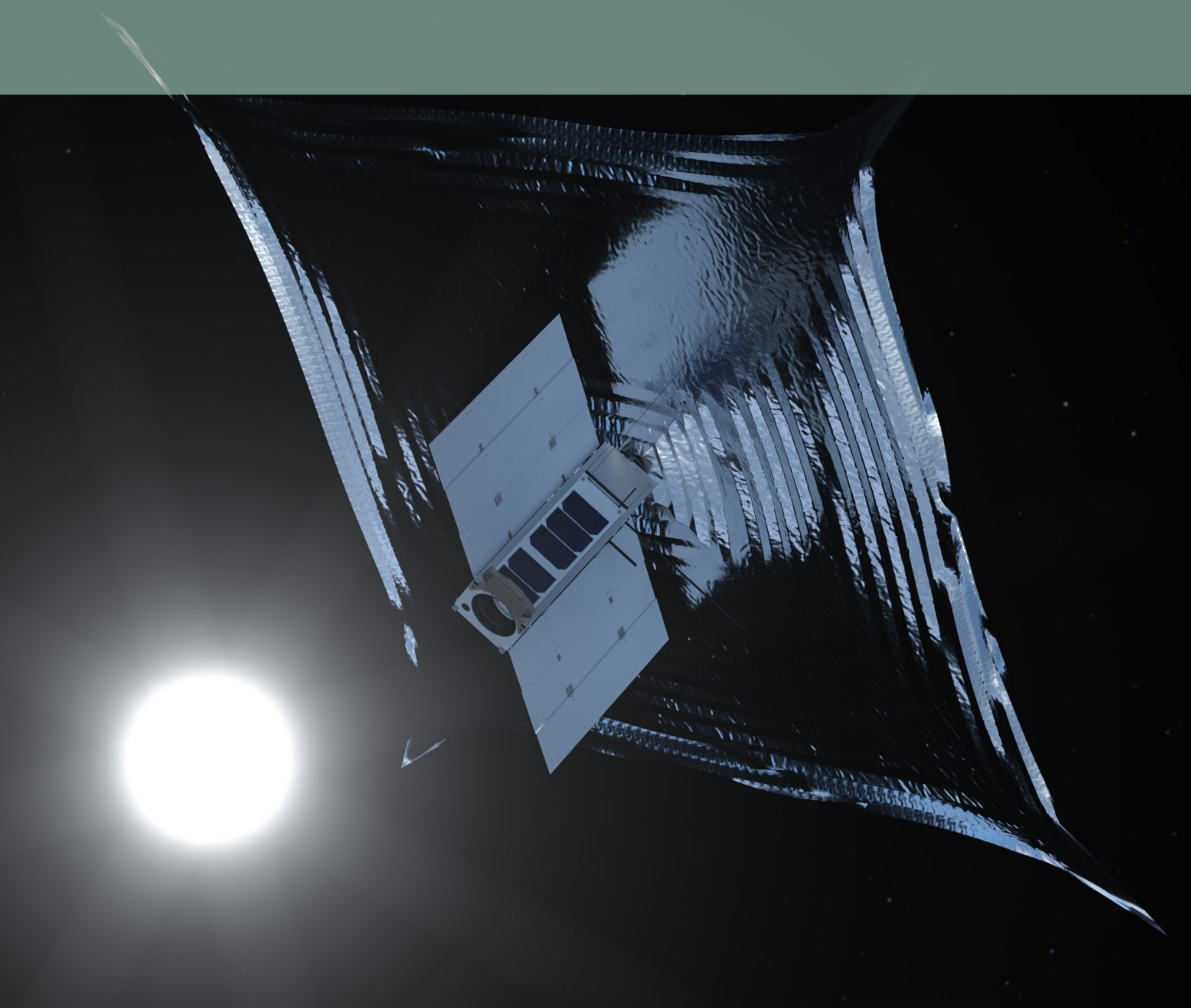
Glossary

This glossary provides descriptions of the terms used throughout this booklet. Instead of offering rigid definitions, it provides specific descriptions of how these terms should be understood within the context of this document. This approach ensures that users of the Zero Debris Booklet share a consistent understanding, helping to facilitate clear communication and minimise potential misunderstandings. Capitalised terms throughout the document are described below.

Term	*Description*
Close Proximity Operations	A series of orbital manoeuvres executed to place and maintain a spacecraft in the vicinity of another space object and which intentionally affect their relative separation and orientation during normal operations (including debris removal and in-orbit servicing).
Conjunction	A detected potential collision between two space objects, such as spacecraft or debris.
Covariance Realism	How well predicted covariances represent the actual distribution of the propagated trajectories of a space object.
Cumulative Probability of Collision	The total Probability of Collision experienced by a given object summed over a specified period of time.
Dead-On-Arrival	A spacecraft that fails to become operational after insertion into its operational orbit. This can occur due to technical failures during launch, deployment, or initial operations.
Debris	All non-functional, human-made objects, including fragments and elements thereof, in orbit or re-entering into Earth's atmosphere.
Demisability	The ability of a spacecraft or its elements to Demise.
Demise	Burn-up and disintegration of a space object or its component parts during re-entry into Earth's atmosphere, usually due to intense heat and aerodynamic forces.
Disposal	Actions performed to permanently reduce the spacecraft's or launch vehicle's chance of accidental break-up and to achieve its needed long-term clearance. This can be achieved for example by depletion of on-board stored sources of energy and deorbiting to limit interference with other space objects.

End of Life	The instant when a spacecraft or launcher is permanently turned off or can no longer be controlled by its operator, normally when it completes its Disposal operations.
End of Mission	The instant when a spacecraft or launcher completes its mission, becomes incapable of accomplishing its mission, or has its mission permanently halted through a voluntary decision.
Key Enabler	An essential asset required to implement a solution effectively. Key enablers provide the necessary technologies, support, or conditions that make a solution feasible.
Mission-Related Object	Objects released during the course of a mission including, but not limited to nozzle closures, lens caps, cooler covers, tethers, dummy masses, dual launch structures, yo-yo weights and lines, and burst disks.
Probability of Collision	The likelihood that two objects in space will collide with each other.
Removal Services	Missions designed to remove space objects from orbit.
Retention	The retention of un-demisable spacecraft elements, which has evolved from the principles of design for containment.
Spacecraft State(s)	The condition of a space object, including its position, velocity, attitude, and operational status.
Small Particles	Debris fragments, usually considered to be between 1 millimetre and 1 centimetre in diameter.
Small Spacecraft	A spacecraft with low mass and or size, usually considered be less than 500 kilograms wet mass.
Space Debris Indices	Measures that reflect the current and future debris generation and risk profile of a particular orbital scenario.
Sustainability	Responsible behaviour in space activities, minimizing the creation of space debris, and ensuring that outer space remains safe, secure, and accessible for current and future generations.
Untrackable	Space objects and any fragments thereof which cannot be tracked by current means, typically considered smaller than 10 centimetres (LEO) or 50 centimetres (GEO) from ground, depending on the objects' characteristics.

2.
NEEDS, SOLUTIONS, AND ENABLERS TOWARDS 2030



1. PREVENT RELEASE OF DEBRIS

1.1. AVOID UNINTENTIONAL RELEASE OF DEBRIS IN ORBIT

All space stakeholders need to avoid the unintentional release of any debris.

Exposure to the space environment, with altitude-dependent characteristics such as radiation in high orbits or atomic oxygen in low orbits, can lead to structural failure of exposed spacecraft materials, releasing hazardous and potentially long-lived debris in orbit.

Solutions to address this issue include:

A. Characterisation of the degradation of materials caused by exposure to the space environment both during and beyond expected mission lifetime

Key Enablers:

- I *Qualification procedure to avoid flaking in orbit*
- II *Improved models to simulate exposure to space environment (e.g. chemistry understanding to extrapolate results, TGA analysis*[2] *to simulate extreme sun exposure)*
- III *Development of multi-layer insulation and coating technologies preventing long-term degradation of materials*
- IV *Identification of technologies enabling in-orbit monitoring of material degradation*
- V *In-flight demonstration of material degradation (e.g. ISS*[3] *experiments, LDEF*[4]*, EURECA*[5]*, etc.)*

B. Development and use of technologies that minimise the release of debris from impacts and collisions

Key Enablers:

- I *Development of specific materials that are resistant to collisions (e.g. solar array cover glass, aerogel materials), technologies to absorb impact (e.g. layered shielding), and materials minimising the ejecta in case of high-energy impacts*
- II *Characterisation and development of technologies to prevent the release of particles during CPO operations, including contingency cases, with dedicated contact interfaces (e.g. interface protection during CPO*[6] *and capture; coatings for interfaces between modules during separation)*
- III *Development of testing guidelines to verify the minimisation of Small Particle release*

The use of propulsive technologies in space missions is essential for manoeuvring, station-keeping, and deorbiting operations. However, traditional propulsion systems, especially those using solid propellants, can generate Small Particles that pose a risk of collision and contribute to the growing issue of debris. Solutions to address this issue include:

C. Use of propulsive and pyrotechnic technologies that avoid the release of Small Particles

[2] Thermogravimetric analysis
[3] International Space Station
[4] Long Duration Exposure Facility
[5] European Retrievable Carrier (EURECA)
[6] Close Proximity Operations

Key Enablers:

I *Qualified Small Particle-free solid propulsion (especially metal-free propellant)*

II *Use of pyrotechnics in-orbit that do not release Small Particles*

III *Development of propellant-free propulsive technologies (e.g. using magnetic forces such as electromagnetic tethers, momentum transfer tethers, drag or solar radiation pressure augmentation devices)*

IV *Replacement of particle-emitting propulsion with alternative propulsive technologies that do not release Small Particles if applicable*

V *Development of slag-free solid propulsion (e.g. non-metallised fuel, external throat)*

VI *Development of rocket engine throat materials limiting the release of Small Particles due to erosion*

1.2. DO NOT INTENTIONALLY RELEASE DEBRIS

To achieve Zero Debris, all space stakeholders should refrain from intentionally releasing debris that jeopardises space safety and has an impact on the Sustainability of space operations.

The release of structural elements from launcher upper stages poses a significant risk to the space environment. These elements, if not properly contained, can become long-lived debris, increasing the likelihood of collisions with operational spacecraft. Solutions include:

A. Launchers designed to contain Mission-Related Objects, including dual launch structures, dummy masses, adapters

Key Enablers:

I. *Upper stage structural elements designed to prevent the release of any unintended debris*

Mission-Related Objects that are intentionally released can remain in orbit for extended periods. Particularly concerning are objects that are intentionally released during launch, as these can often be avoided with improved design and operational practices. Solutions include:

B. Design or develop and adopt de-orbiting systems for Mission-Related Objects

Key Enablers:

I. *Demonstration and qualification of de-orbiting kits for intentionally released elements (e.g. dual launch structures, dispensers)*

2. GUARANTEE TIMELY AND SUCCESSFUL CLEARANCE

All space stakeholders need to ensure that space objects are successfully disposed of in a timely manner to mitigate the risk of debris generation and disturbance to operational missions. Further efforts to develop technical and operational solutions are needed to improve the probability of successfully de-orbiting space objects at the End of Mission.

Achieving a timely and successful orbital clearance after the End of Mission is fundamental to avoid the accumulation of debris. Reaching a success rate for orbital clearance of at least 99% requires improvements at various levels, including but not limited to:

- Increasing the probability for an object to de-orbit itself after End of Mission
- Designing more reliable spacecraft architectures
- Complementing these capabilities with external means such as Removal Services, when necessary
- Ensuring space objects are prepared for removal

The following needs, solutions, and key enablers were identified:

2.1. IMPROVE ORBITAL CLEARANCE WITH HIGH PROBABILITY OF SUCCESSFUL DE-ORBITING

De-orbiting systems and architectures that enable an object to de-orbit itself at End of Mission currently exist for some use cases (e.g. *de-orbit systems for spacecraft in LEO*) but need to be made affordable and more reliable in order to reach high clearance success rates and widespread adoption. In addition, other solutions could be explored for different orbital regions and use cases (e.g. *Disposal from MEO, mission extension, etc.*) Solutions to address this issue include:

A. Development /and adoption of safe and reliable de-orbiting systems and operations for different orbital regions and object characteristics

Key Enablers:

I *Affordable Disposal solutions for Small Spacecraft (e.g. propulsion systems, drag-sails, aerobrakes, tethers, plug and play Disposal subsystem for CubeSats, based on COTS*[7] *technology)*

II *Evaluation and use of alternative strategies for orbital clearance and backup options for objects in Earth orbit (e.g. technical implications of Disposal strategies for MEO, GEO, GTO, HEO, etc.)*

III *Spacecraft architectures which increase the probability of successful Disposal by accounting for possible mission extensions, failures and external factors (e.g. redundancy for Disposal capabilities, back-up deorbiting systems, incorporating margins)*

IV *Technologies enabling safe autonomous and/or independent de-orbiting that can be integrated before launch or in-orbit (e.g. autonomous activation of de-orbiting devices, etc.)*

V *Improved understanding of operational practices for de-orbiting (e.g. sharing of best practices, operational procedures, de-orbiting in degraded/safe mode, high-drag attitude control)*

[7] Commercial Off the Shelf

VI *Operational practices and technologies for Dead-On-Arrival spacecraft (e.g. smart deployer/upper stage performing health check, low-altitude injection, time-tagged de-orbiting systems)*

Improving health monitoring will require coordination between developers and operators, and integration of lessons learned through experience that contribute to the development of robust failure detection and prediction methods and algorithms, as well as clear decision-making criteria. Solutions to address this issue include:

B. Development, validation and adoption of improved Health Monitoring systems and methods **[see section 4]**

Key Enablers:

I *Technologies for in-situ spacecraft health monitoring (e.g. vibro-acoustics sensors, fibre sensors embedded in CFRPs, accelerometers, temperature, radiation, accurate propellant gauging)*

II *Anomaly detection and prognostic methods for failure prediction (e.g. AI for failure prediction, digital twins, improved feedback loops between operators and spacecraft developers)*

III *Systematic monitoring of in-flight data (e.g. monitoring failures, anomalies, performance degradation, resources management, updating probability of successful Disposal)*

Effective verification methods are essential/critical to ensure the timely and successful clearance of debris and other space objects from orbit, so that objects do not remain in orbit longer than planned and pose risks to active missions. Solutions to address this issue include:

C. Verification methods for timely and successful clearance

Key Enablers:

I *Standard methodology for residual orbit lifetime calculation (e.g. drag coefficient, atmospheric models, solar models, tumbling predictions)* **[see sections 4 and 5]**

II *Standard methodology for assessing the probability of successful Disposal, including impacts with debris or other objects in orbit, and periodically re-assessing until End of Life*

2.2. PREPARE SPACE OBJECTS FOR REMOVAL

For space objects which fail to de-orbit themselves for whatever reason, external means can be used to remove these objects from orbit. To this end, removal interfaces and aids are required to facilitate Close Proximity Operations, capture and removal. Solutions to meet this need include:

A. Development of interoperable interfaces and requirements that facilitate removal for different types and sizes of objects (e.g. large/Small Spacecraft, launcher stages and elements, constellation spacecraft), adapted for different orbital regions (e.g. LEO, MEO, GEO), for different Disposal strategies (e.g. controlled, uncontrolled re-entry, orbital transfer to graveyard orbit), and with easy adoption in mind.

Key Enablers:

- I *Standardisation of requirements related to removal interfaces (e.g. enabling interoperability)*
- II *Aids for precise attitude reconstruction and orbit positioning of un-cooperative objects from ground or in space (e.g. laser, retroreflectors, beacons)* **[see section 4.2]**
- III *Relative navigation aids for Close Proximity and capture Operations, compatible with different rendezvous sensors (e.g. fiducial markers, laser retroreflectors, plates with different optical properties)*
- IV *Capture interfaces (e.g. mechanic interfaces, magnetic interfaces) adapted to different user needs (e.g. controlled/uncontrolled re-entry, cooperative/un-cooperative capture, attaching de-orbit kit etc.)*
- V *Capture interfaces with minimised form factor, mass, and cost*
- VI *Detumbling solutions (e.g. energy dissipation, de-tumbling kit)*

2.3. DEMONSTRATE REMOVAL SERVICES

Even with highly reliable Disposal systems, spacecraft may still fail to de-orbit at the end of their operational lives. To ensure at least a 99% success rate in clearing orbits, especially in congested areas, external Removal Services can complement self-de-orbiting capabilities. For widespread adoption, it is essential to demonstrate the feasibility and effectiveness of these services. Solutions to meet this need include:

A. Improved characterisation of objects to be removed, including improved knowledge of Spacecraft States, and structural integrity of space objects and debris to assess risks and feasibility of Removal Services

Key Enablers:

- I *Technologies or systems to characterise state of objects from ground and/or from space (e.g. in-situ inspections, dedicated observation campaigns, from telemetry, etc.)*
- II *Technologies or systems to characterise structural integrity of object from ground and/or from space (e.g. in-situ inspections, dedicated observation campaigns, predictive modelling of aging)*

B. Development of technologies for rendezvous and capture required to enable approach, capture and removal by an external servicer, in particular taking advantage of removal interfaces.

Key Enablers:

- I *Qualified sensors and cameras for Close Proximity Operations (e.g. lidar, radar, high-resolution cameras, wireless communication devices)*
- II *Developed and qualified robotics and capture mechanisms (e.g. electromagnetic compatibility, end-effectors)*
- III *Developed and qualified servicer GNC subsystem (e.g. close-approach algorithms, capability to control un-cooperative tumbling targets, control during stack configuration)*

A demonstrated interoperable ecosystem of Removal Services will help meet demand for Removal Services for 2030 in addition to being fundamental for the long-term Sustainability of outer space activities. Solutions to address this issue include:

C. Mature Removal Services ecosystem

Key Enablers:

I Continued demonstration missions of Removal Services (e.g. adapt upper stages to remove debris after placing payloads into orbit, systems to retrieve Dead-On-Arrival payloads, extending the ability of servicers to remove multiple debris)

II Standardised and improved Close Proximity Operations safety (e.g. improved models for characterisation of risks during capture phase, lessons learned)

III Guidelines and standard for operators and developers to share information for facilitation of future removal operations (e.g. challenges surrounding imaging targets, inertia tensor, surface material properties, uncontrolled attitude motions, possible interface or capture points, logistical chains)

IV Demonstration of robotic subsystems for Removal Services

3. PREVENT DEBRIS GENERATION THROUGH BREAK-UPS OR COLLISIONS

Keeping the probability of debris generation through collisions and break-ups below 1 in 1000 per object requires a combination of minimising the risk of internal break-ups and minimising the probability of debris generation through collisions with both trackable and Untrackable objects. This chapter addresses enablers for the design stage, whereas Chapter 4 addresses enablers for the operational stage.

The following needs and solutions were identified:

3.1. IMPROVE COLLISION RISK ASSESSMENT

The increasing number of debris and the risk associated with collisions in orbit lead to an ever-increasing need for operators to carry out collision avoidance manoeuvres. During the design phase, calculating the Cumulative Probability of Collision over the total orbital lifetime of a spacecraft can be used to select safer orbital operations and Disposal strategies.
Solutions to address this need include:

A. A standardised methodology for assessing collision probability during the design phase, which involves formalising input conditions for analysis, such as space objects population models, spacecraft properties and characteristics, as well as how uncertainties are handled

Key Enablers:

- I *Accurate estimation of debris hard body radius (e.g. measured by laser ranging)*
- II *Improved open reference space objects population models for predicting the future position of space objects and their interactions*
- III *More frequent and accessible predictions of the evolving debris environment*
- IV *Improved estimation of impact areas for objects under design, considering the actual shape of the object*[8]
- V *Enhanced collision risk assessment algorithms for large deployable appendages (e.g. drag-sails, tethers)*
- VI *Guidelines and methodologies for Cumulative Probability of Collision assessment tailored to mission phases and relevant debris population, including reassessment during operations*
- VII *Improved atmospheric density, space weather and propagation models*
- VIII *Standardised set of guidelines and improved technical approaches for pre-launch and post-deployment collision assessments*
- IX *Methods to integrate collision risk assessments from multiple providers and tools for more accurate collision risk estimation*
- X *Machine learning algorithms to predict collision probabilities more accurately by leveraging historical collision data, spacecraft behaviour models, and predictive maintenance indicators*
- XI *Development and uptake of optical and radio tracking aids (retroreflectors, beam locators, etc.)* **[see section 4.2.b)]**

[8] The attitude of an object with a known shape can potentially be estimated from ground

Understanding the consequences of collisions and break-ups is essential for effective debris mitigation. Accurate modelling of fragmentation events is necessary to accurately predict and reduce collisions risks. Solutions to address this issue include:

B. Methodology for assessing consequences of collisions and break-up modelling

Key Enablers:

- I *Development of fragmentation models, including addressing their impacts on the orbital environment.*
- II *Development of ejecta cloud models through experimental and numerical testing*
- III *Enhanced understanding of collision consequences (through modelling and testing) for large deployable appendages (e.g. dragsails, tethers, etc.)*
- IV *Increased confidence in ballistic limit equations, including correlation with existing test data to enable shielding solutions* **[see section 3.4.b)]**

3.2. STANDARDISED EVALUATION OF IMPLIED AND ENCOUNTERED RISKS

Existing debris mitigation guidelines are commonly based on approximations (e.g. lifetime limitations) rather than focusing on the risk of debris generation. This can result in designs and operational concepts that meet guidelines but still negatively impact the space environment. To address this, metrics and methodologies need to be developed to directly quantify the risk of debris generation. Solutions to address this need include:

A. Development of standardised, internationally recognised methods for assessing the likelihood and severity of debris generation events, to enable consistent and reliable risk evaluation across space missions, ensuring that the impacts of debris are accurately analysed and managed.

Key Enablers:

- I *Establishment of standardised Space Debris Indices to measure the impact of space debris generation* **[see section 4.1]**
- II *Agreed-upon metric(s) to evaluate the debris-generation impact of missions including all mission elements*
- III *Different risk evaluation methods based on orbital characteristics and object population*
- IV *Risk assessments that include factors beyond debris risk (e.g. spectrum, Life Cycle Assessment, etc)* **[see section 6]**

Existing debris mitigation guidelines generally do not account for changing space traffic or the success of post-mission Disposal manoeuvres. Solutions to address this issue include:

B. Development of a robust system to optimise the space environment

Key Enablers:

- I *Development of forecasting models of future space traffic and interactions*
- II *Methods to assess the impact of debris risk on the usability and safety of the space environment*
- III *Metrics and methods that ensure safe and reliable access to all orbital regions*

3.3. IMPROVE COLLISION AVOIDANCE CAPABILITIES DURING DESIGN STAGE

As orbits become more congested, collision avoidance becomes increasingly challenging for operators. To address this, there is a need to improve both manoeuvring capabilities and autonomous systems for collision avoidance during design. Solutions to address this need include:

A. Improving the ability of spacecraft to perform manoeuvres to avoid collisionsed.

Key Enablers:

I Improved propulsion options for spacecraft, especially collision avoidance solutions for Small Spacecraft

II Development of non-propulsive collision risk reduction solutions (e.g. differential drag, attitude control to reduce cross section area)

C. Development of reliable autonomous systems for Conjunction detection and collision avoidance to significantly improve response times and reduce reliance on manual interventions.

Key Enablers:

I Development of reliable systems for integrated autonomous Conjunction detection and collision avoidance operations with coordination systems

II Reduction of the decision time to react to Conjunctions (e.g. late command paths)

III Reduced response time for ephemerides screening

3.4. MINIMISE RISKS LINKED TO UNTRACKABLE OBJECTS BY DESIGN

All space stakeholders need to minimise the risk that Untrackable Debris pose to space objects to ensure a low probability of generating more debris. Solutions to address this issue include:

A. Development of improved statistical models for the evolution and behaviour of Untrackable Debris and the long-term evolution of the space environment [see section 4.2]

Key Enablers:

I Development of space-based detection sensors and usage of processed data

II Regular measurements of debris density and update of reference debris population models

C. Design mitigation solutions, including by improving spacecraft design and protection, against Small Particles that cannot be detected or avoided in time

Key Enablers:

I Development and cataloguing of technologies for shielding and protecting critical equipment (e.g. batteries, pressurised tanks)

II Architectures that are resilient to Small Particle impacts (e.g. smart accommodation, separation of critical redundancies)

III Health monitoring systems to assess post-impact damage and predict remaining operating life (e.g. development of strain-based spacecraft health monitoring systems using fibre optic sensors) [see section 2.1b)]

IV *Use of additive manufacturing in the context of optimised topology to reduce mass of shielding solutions*

3.5. MINIMISE RISKS OF INTERNAL BREAK-UPS

To keep the probability of debris generation through collisions and break-ups below 1 in 1000 per object, it is essential to minimise the risk of internal break-ups during both the operational lifetime and post mission. Reliable passivation reduces the risk of in-orbit break-ups by depleting on-board sources of energy. While autonomous systems improve the likelihood of successful passivation, they also introduce new risks, such as premature activation, which must be managed. Solutions to address this issue include:

A. Improved and reliable modelling for internal break-ups, including those caused by unplanned events like passivation failures

Key Enablers:

I *Standardised methodologies and tools to assess failures in spacecraft elements and subsystems, that could lead to break-ups*

II *Development and benchmarking of tools to predict how hypervelocity impacts affect internal items* **[see section 3.1]**

III *Development/improvement of tests and databases to characterise the effects of hypervelocity impacts on spacecraft structures* **[see section 3.1]**

D. Adoption of technologies for reliable passivation

Key Enablers:

I *Systematic adoption of capabilities to permanently and irreversibly deplete and prevent future loading of on-board energy sources*

II *Robust passivation design architectures (e.g. health monitoring, watchdogs, autonomous passivation, etc.)*

III *Technologies for reliable passivation by external means/servicing mission to perform a fluidic passivation*

IV *Implementation of propellant offloading technologies*

C. Development of passive containment technologies for on-board sources of stored energy

Key Enablers:

I *Development of containment technologies for on-board energy sources (e.g. batteries, pressurised tanks)*

II *Guidelines to design pressurised vessels to prevent generation of debris*

III *Definition of testing methodologies and establishment of adequate testing facilities*

4. IMPROVE SPACE TRAFFIC SURVEILLANCE AND COORDINATION

With the increasing number of space objects being launched, space traffic coordination will play an essential role in ensuring sustainable operations. Routine and transparent information sharing, along with active participation of spacecraft operators, is a fundamental requirement for efficient and timely collision avoidance operations.

The following needs and solutions were identified:

4.1. IMPROVE SPACE TRAFFIC COORDINATION AND INFORMATION SHARING

Improved STC[9] will help prevent collisions and reduce the occurrence of unnecessary collision avoidance manoeuvres.
Solutions to meet this need include:

A. Closer international collaboration for transparency in data and intent despite geo-political/linguistic uncertainties

Key Enablers:

I *Adoption of standardised guidelines (e.g. CCSDS) with defined standards on manoeuvring rules, data exchange (ephemeris, manoeuvre plans, Spacecraft attitude States), uncertainty assessment (e.g. uncertainty realism), methodologies, and catalogue information*

II *Establishment of an international coordination system which can support data sharing, ensure interoperability, and facilitate multi-language coordination*

C. Improved communication, both between space surveillance segments and ground segments, as well as between parties involved in Conjunctions

Key Enablers:

I *Standardised infrastructure for the sharing of data which is safe, secure, and with both centralised and distributed infrastructures to enable automation, low latency and high service availability*

II *Standardised data infrastructure for the sharing of operational information, particularly operators' contact detail, operational information (mission phase, spacecraft status, manoeuvre notification, manoeuvre/operator capability) and validated spacecraft characteristics and operators' capabilities*

III *Machine-to-machine exchanges for close approach management and efficient, standardised operator-to-operator interaction*

IV *Established information-sharing about anomalies and failures*

C. A process to evaluate the accuracy and reliability of collision risk analysis providers to ensure that only providers who meet defined accuracy standards - based on standardised datasets and validated models - are used for operational decision-making.

Key Enablers:

[9] Space Traffic Coordination

I Methods and metrics to quantify collision risk analysis accuracy

II Collaborative platforms where providers can share insights, methodologies, and datasets

III. Access to information about any other objects involved in the Conjunction

IV Collection of data on manoeuvrability, ephemeris, collision-relevant surface area (accounting for collision geometry and spacecraft attitude)

V Availability of Covariance Realism data for different objects and operators (acting as a trustworthiness indicator)

F. Definition of Guidelines for safe collision avoidance operations addressing collision risk methods and the timeliness and quality of collision avoidance operations

Key Enablers:

I Automated close approach risk reduction scheme enabled by trusted, timely, screened and validated uncertainty of data. This will require compatibility of different automated systems

II Standard benchmark test for CAM services providers addressing availability, reaction time, and screening; validated data products; the ability to predict and handle accuracy; and level of automation.

III Open-source screening solutions to enable operators to perform internal optimisation of CAMs

4.2. IMPROVE SPACE SURVEILLANCE PERFORMANCE

Collision risk assessment is based on knowing the position and velocities of the objects involved. A reduction in uncertainty on these parameters will reduce the amount of false perceived risky close encounters, and hence reduce the burden on the operator. The capability to track smaller objects down to 5 cm in LEO and 20 cm in GEO will reduce the risk for catastrophic collisions in these orbital regions.
Current space surveillance systems face significant challenges in detecting and tracking smaller objects and monitoring currently Untrackable Debris. The limitations in sensitivity, throughput, and resolution of existing tracking systems hinder accurate and timely measurements of these objects.

Solutions to address this issue include:

A. Improved Characterisation of Space Object Risk

Key Enablers:

I Increased sensitivity and accuracy of space debris tracking systems (e.g. telescopes for on-demand measurements, radar campaigns for monitoring and cataloguing, laser ranging, non-traditional sensors, and other methods)

II Improved methods for tracking of smaller objects between 1 and 10 cm (e.g. optical, radio and laser ranging)

III Monitoring and cataloguing of currently Untrackable objects large enough to destroy or disable a spacecraft in a collision **[see section 3.4.a)]**

IV *More frequent observations of objects within space surveillance networks*

V *Removal of gaps in tracking of objects and enhance observation processing*

VI *Promotion of an increase in the number of terrestrial and on-orbit tracking systems*

VII *Tracking the change/trend of small size debris in different layers in LEO* **[see section 3.4]**

VIII *Establishment of tracking priorities based on a target orbit accuracy for objects (that do not have accurate state estimation capabilities)*

I. Technologies for improved trackability of objects, including the uptake of tracking aids could improve errors on Conjunctions and reduce false-positive rate

Key Enablers:

I *Optical, radio or other means for identification and tracking of small platforms and Mission-Related Objects across orbital regimes while preserving dark and quiet skies (e.g. retroreflectors, radio beacons)* **[see sections 3.1 and 6]**

II *Commercially available space situational awareness support*

III *Improved space surveillance performance for rideshare launches*

IV *Ground-based solutions to improve trackability*

V *Feasibility studies on materials that are more easily trackable post-fragmentation while preserving dark and quiet skies* **[see section 6]**

VI *Increased tracking capacity to track large quantities of retroreflectors*

4.3. ENHANCE CORRELATION AND UNCERTAINTY QUANTIFICATION METHODOLOGIES

At the heart of space surveillance segments, after creating observations, is the capability to identify when an object is re-observed and to derive a high accuracy orbit. Improvements in respectively correlation and uncertainty quantification lead to higher quality space surveillance products such as catalogues and close approach forecasts.

Solutions to meet this need include:

A. Accurate, Reliable, and Timely information on space debris population - addressing operational needs and modelling the environment

Key Enablers:

I *Using contextual information, e.g. photometry, to increase correlation accuracy over larger timespans*

II *Quantifying and reducing the uncertainty on measurements from all data sources (e.g. uncertainty realism)*

III *Reporting capabilities on data quality*

IV *Improved object propagation models using machine learning techniques* **[see section 3.1a)]**

V *Automation of data collection for efficiency, scalability, and timeliness of data distribution*

4.4. ROBUST TASKING OF TRACKING FOR LARGER CATALOGUES

With increasing amounts of debris and active spacecraft alike, current sensor networks can become overloaded leading to larger times between tracks and hence larger uncertainties on derived space surveillance products.

Making space debris catalogues and services available to other space actors or the public is a simple route to share knowledge of the space debris population and cross-validate models and measurements of space debris.
Solutions to address this issue include:

A. Informative hub about space debris tracking and collision risks.

Key Enablers:

I *Consolidated and open space debris catalogues and datasets with space debris detection across damage-causing size regimes*

II *Operator-usable mechanisms for on-demand space surveillance*

III *Availability of data sharing between SSA*[10] *providers (ideally raw measurements)*

D. Fusion of heterogenous space surveillance data sources

Key Enablers:

I *Test data for calibration and open access sensor products*

II *Improved data processing pipelines incorporating fusion methodologies that take into account uncertainty when mixing data products and in the provision of derived uncertainty*

III *Promoting the combination of non-traditional SSA sensors such as ground station (amateur or professional), in-orbit sensors, and other existing sensors, to provide additional data types for SSA*

[10] Space Situational Awareness

5. PREVENT CASUALTIES ON GROUND

The casualty risk for human populations and infrastructures is increasing as a result of the growing number of objects re-entering the Earth's atmosphere. Current simulation capabilities have known limitations and lack standardisation. Striving towards zero casualty from re-entering objects requires coordinated and collaborative efforts in:

- Re-entry risk evaluation methods and models
- Design solutions to reduce uncontrolled re-entry risks
- Improving controlled re-entry solutions for better system impact, reliability and cost-efficiency

The following needs and solutions were identified:

5.1. REDUCE RISKS LINKED TO UNCONTROLLED RE-ENTRY

All space stakeholders need to ensure that spacecraft is equipped with increased Demisability to reduce the risks linked to uncontrolled re-entry by burning up the object more completely in the atmosphere and thus reducing the number of fragments reaching ground.

Solutions to meet this need include:

A. Development of Technologies for Design for Demise, including fully demisable platforms and improvement of Demisability at the system and subsystem level (e.g. material, structure, equipment and payload levels); demisable technologies for launchers, considering environmental impacts as a constraint [see section 6]

Key Enablers:

I Development of fully demisable LEO spacecraft platform (e.g. accommodation strategies)

II Development of fully demisable spacecraft and launcher elements (e.g. tanks, COPVs, reaction wheels, magnetorquers, solar array drive mechanism, optical payload elements, payload interfaces, star trackers, structural joints, etc.)

III Research materials with enhanced Demisability

D. Development of techniques and processes for Design for Demise, enabling Demise at a system and subsystem level

Key Enablers:

I Research into benefits of additive manufacturing on Demisability of elements

II Research into use of exothermic reactions (e.g. thermite) for enhanced Demise

III Development of elements with heat flux-enhancing features (e.g. holes, lattice structures, etc.)

IV Techniques and process to enable pre-determined fragmentation sequences during re-entry

C. Improved and standardised tools, models and databases to assess Demise and casualty risk from re-entering objects

Key Enablers:

- I *Conducting in-flight re-entry experiments to validate models and verify on ground tests* **[see section 6]**
- II *Improved object physical characterisation through re-entry process (e.g. oxide formation, ablation) and reduce these uncertainties through testing*
- III *Comprehensive databases on material Demise properties (e.g. glasses, composites, etc.)*
- IV *Improved on-ground risk models and databases for human populations, including air and maritime traffic*
- V *Improved accuracy and precision models for re-entry trajectories and impact zones*
- VI *Standardised tools, models and databases*
- VII *Improved understanding of heating and ablation of objects with multiple length scales, holes, and lattices*
- VIII *Comparable and standardised setups and conditions for Demise testing*
- IX *Accurate models for determining spacecraft fragmentation sequences during re-entry*

J. Evaluate alternative re-entry and Disposal methods *focusing on safety, operational and technical feasibility*

Key Enablers:

- I *Development of a standardised risk evaluation method for alternative re-entry methods*
- II *Development of assisted re-entry as an alternative re-entry solution*
- III *Development of tools and modelling approaches to address assisted re-entry*

5.2. REDUCE TECHNICAL IMPACTS OF CONTROLLED RE-ENTRY

Implementing controlled re-entry minimises the casualty risk but faces challenges in widespread adoption due to substantial system impacts. Current spacecraft architectures often lack flexibility to handle various end-of-life scenarios, such as controlled re-entry.

Solutions to address this issue include:

A. Develop adaptable spacecraft architectures that can accommodate controlled re-entry and other end-of-life scenarios

Key Enablers:

- I *Adoption of flexible End-of-Mission propulsive modules (e.g. solid rocket motors, de-orbiting kits adapted to different missions)*
- II *Development of standard spacecraft platform designs that support controlled re-entry*
- III *Development of tracking methods to support validation of controlled re-entry trajec-*

tories **[see section 4]**

IV *Increased AOCS control capability at lower perigee (e.g. to reduce thrust needed for the last burn)*

V *Evaluation of propulsion trade-off in early design phases, enabling available propulsion solutions to be chosen according to mission constraints and needs*

VI *Increased propulsion subsystem efficiency to optimize Disposal phase*

G. Develop effective Technologies for Retention to reduce the risk of debris generation and on-ground casualties from non-demisable spacecraft structures.

Key Enablers:

I *Techniques for improved Retention of spacecraft elements or fragments to reduce casualty risk*

5.3. MINIMISING DEBRIS IMPACTS ON HUMAN POPULATION AND INFRASTRUCTURE

Re-entering debris pose a risk to human populations, particularly with growing populations of both humans and re-entering space objects.

Solutions to meet this need include:

A. Enhance coordination efforts for spacecraft and debris re-entry to reduce casualty risk and minimise the potential for damage to infrastructure.

Key Enablers:

I *Development of a standard alerting system for notification of objects that are projected to not fully Demise*

II *Assessment of re-entry impacts on air and maritime traffic management*

III *Increased frequency and accuracy of debris tracking to decrease risk to population and/or infrastructure* **[see section 4]**

IV *Improvement of re-entry corridors accuracy, to enable creation of additional re-entry corridors.*

6. UNDERSTAND AND MITIGATE ADVERSE CONSEQUENCES OF SPACE OBJECTS AND DEBRIS

6.1. UNDERSTAND ENVIRONMENTAL IMPACTS OF RE-ENTRY

Debris of all sizes re-entering the atmosphere and potentially reaching the ground or oceans could have various adverse effects on the environment, which are not yet fully understood or quantified.
Solutions to meet this need include:

A. Characterisation of materials used in spacecraft and their behaviour during re-entry for assessing their environmental impact

Key Enablers:

- I *Characterisation of ablation products formed when undergoing a destructive re-entry (e.g. understanding the particle-induced erosion and heat flux augmentation on ablators in re-entry)*
- II *Improved knowledge on size distribution and optical properties of emitted materials and their physical state*
- III *Understanding the composition of materials in rocket bodies, spacecraft and ancillary items used to deploy payloads*
- IV *Investigation of the proportion of surviving re-entering objects*
- V *Characterisation of unused propellant chemistry and particle size distribution*

B. Characterisation of impacts of re-entry on the atmosphere for grasping the long-term consequences of re-entry events

Key Enablers:

- I *Lab and in-situ measurements (e.g. sounding rockets-based flight experiments for atmospheric studies, dedicated sensing technologies) to characterise atmospheric impacts of Demise, leading to enhanced reentry models that include emissions.*
- II *Improvement in the modelling of physical and chemical processes in the upper atmosphere to assess the long-term impact of the injected material on the atmosphere*
- III *Studies on the Demise chemistry, focusing on ablation heights and altitude dependant emission profiles (e.g. chemistry of emitted materials and compounds in mesosphere and stratosphere)*
- IV *Characterisation of the impacts of re-entered propellant products*

E. Characterisation of impacts of re-entry on terrestrial and oceanic environments

Key Enablers:

- I *Lab and in-situ measurements to characterise material deposition in oceans and on land*
- II *Investigation into potential detrimental environmental impacts of surviving spacecraft elements*

6.2. PROTECT DARK AND QUIET SKIES

Emission of electromagnetic radiation from space objects and debris can adversely impact astronomical observations, both from ground and space, particularly wide-field optical and radio observations. These emissions, whether intentional (e.g. in-band radio transmission) or unintentional (e.g. reflected sunlight or radio noise from on-board electronics) can affect the scientific value of observatories.

Solutions to address these challenges include:

A. Prediction and mitigation of the unintended emission from space objects and debris to protect the integrity of astronomical observations

Key Enablers:

- I *Development of a set of technical guidelines for the design, manufacturing and operation of spacecraft based on the recommendations of the IAU*[11]
- II *Standardised, open-source models for unintentional emissions such as brightness and spectroscopic footprint*
- III *Sharing of Operational data (such as brightness data, antenna diagrams, orbital profiles, and predicted, real-time, and historical orbital elements)* **[see section 4]**
- IV *Assessment and modelling of unintended electromagnetic emissions during all project phases before launch of spacecraft*
- V *Measurement of unintended emissions during operations and during deorbiting, including from de-orbiting devices like drag sails and electromagnetic tethers* **[see sections 2.1 and 6.1]**
- VI *Database of space objects known to create significant astronomical interference correlated with orbital information and other databases* **[see section 4]**
- VII *Development and choice of materials, technologies and operational concepts minimising unintended emissions of spacecraft (e.g. Bi-directional Reflectance Distribution Function (BRDF) measurement and modelling, paintings, coatings, thermal management systems with well-defined output spectra, darkened multi-layer insulation, directional lighting systems, dielectric mirrors, electrochromic material, open-source modelling tools, radio shielding)* **[see sections 3 and 4]**
- VIII *Solutions to maintain trackability while reducing unwanted spacecraft emission (e.g. retroflectors with well-defined response functions limited to specific wavelengths, beacons for bright/large disposables such as launcher adapters especially if they complete more than one Earth-orbit before re-entry)* **[see sections 1 and 4]**
- IX *Characterisation of interference caused by scattering from artificial space objects with significant (radio) cross sections*
- X *Characterisation of brightness and spectral energy distribution of re-entering objects* **[see section 6.2]**

K. Prediction of interference caused by intended emissions

Key Enablers:

- I *Characterisation of potential radio interference into protected radio astronomy bands from adjacent transmissions*
- II *Coordination between radio quiet zones, professional astronomical observatories, and spacecraft concepts of operations*
- III *Characterization of intended emissions from space systems before and after launch*

[11] International Astronomical Union

IV *Passivation concepts for radio-emitting equipment after End of Mission*

V *Operational data sharing and capable hardware to allow for advanced observation planning and mitigation (e.g. frequency hopping, beam steering, active avoidance observation strategies)* **[see section 4]**

VI *Database of space objects with significant radio cross-sections capable of reflecting or scattering radio signals correlated with orbital information* **[see section 4]**

FROM ZERO DEBRIS TO A CIRCULAR ECONOMY IN SPACE

The current use of space operations follows a model where spacecraft are designed for single use, launched, operated, and then either disposed of in the atmosphere or placed in a graveyard orbit. Most spacecraft and launch vehicles either re-enter or become debris. Moving towards a more sustainable future, the next step is to implement a circular economy in space, which aims to reduce resource use and increase the value derived from space assets.

A circular economy, as defined by ISO 59004 involves maintaining a circular flow of resources, by recovering, retaining or enhancing their value, contributing to sustainable development. While initial progress has been made with in-orbit servicing missions, such as the life extension missions and the use of reusable launchers, achieving a true space circular economy presents several technical and technological challenges.

A circular economy in space will include an ecosystem of in-orbit servicing, offering several services such as in-orbit assembly, in-orbit manufacturing, in-obit refurbishment and reuse, and in-orbit recycling. The design of spacecraft themselves will have to change, with platforms designed to be disassembled, reassembled and upgraded to maximise the usage of existing space hardware, enable novel new mission architectures, and limit the depletion of raw materials on ground. This will require platforms which are designed to adapt to modular, interoperable elements, exchangeable payloads, and reconfiguration in orbit.

Building on the enablers discussed in Chapter 2, in-orbit servicing missions that demonstrate circular economy services need to be defined and implemented, and the necessary concepts of operations for Close Proximity Operations need to be defined while remaining committed to a Zero Debris approach. The robotic tools and technologies required for these services also need to be developed, as do new verification and validation techniques.

The first steps in addressing these challenges have already been taken, with key enablers discussed in this booklet contributing to the goal of a space circular economy. Furthermore, the advent of a circular economy in space will not supersede the Zero Debris approach or the technical enablers defined in this booklet. The impacts and risks of assembly, manufacturing, and recycling in space -- such as the generation of small debris or the unknown Demisability of structures manufactured in space-- will need to be understood and mitigated, and the mitigation of space debris, as addressed in this booklet, will be if anything more important than ever.