ZERO DEBRIS TECHNICAL BOOKLET

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1. INTRODUCTION

1.1. BACKGROUND

The orbital space environment is a finite resource under increasing strain. There is an urgent need for more ambitious actions on space debris prevention, mitigation, and remediation from all space stakeholders if we are to protect future missions, existing space assets, and the human population. The Zero Debris Approach initiated by ESA, strongly supported by its Director General, as a solution to the catastrophic degradation of Earth orbital environment, is one example of the ambitious actions required, and aims to totally stop the generation of debris in Earth and lunar orbits by 2030.

Building on the Zero Debris Approach, a collection of space stakeholders co-developed the Zero Debris Charter: a statement for space sustainability with a set of guiding principles and jointly agreed targets for 2030.

The Zero Debris Technical Booklet initiative aims to answer to the call to define collaboratively how to reach Zero Debris by 2030. This booklet builds upon the principles and targets set out in the Charter and other similar initiatives. To reach each principle and target, a list of new and capability improvement needs has been derived, that in turn flow-down to technical solutions and key enablers for these solutions.

1.2. SCOPE OF DOCUMENT

The Zero Debris Technical Booklet intends to define how to reach Zero Debris by 2030, listing the technical needs and potential solutions to achieve the principles and targets for 2030 set by the Zero Debris Charter[1] and other similar initiatives.

This booklet focuses on technical developments, and other incentives involving regulatory, political, and financial solutions are out of the scope of this document.

The development of this document involved all volunteer stakeholders of the Zero Debris community in an open and collaborative process.

1.3. TERMS OF USE

The participation to the co-development of the Zero Debris Booklet is voluntary and the outcome is for information.

This booklet is for the benefit of everyone involved in the Zero Debris effort and could be the support for different stakeholder contributions in the future.

ESA acts as a facilitator for the booklet, is one of the contributors and will be one of the beneficiaries.

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

2. NEEDS AND SOLUTIONS TOWARDS 2030

1. PREVENT RELEASE OF SPACE DEBRIS

The following needs and solutions were identified for this principle:

1.1. AVOID SMALL PARTICLE RELEASE

Need to avoid small particles release from pyrotechnics, solid or hybrid propellants, environment-induced degradation, and impacts with debris and micro-meteoroids.

Solutions to meet this need include:

a) Propulsive technologies avoiding release of small particles

For space qualified pyrotechnics, this issue has been broadly addressed. However solid rocket motor solutions may still release particles in orbit.

Key enablers:

- *Qualified particle-free solid and hybrid propellants*
- *Utilisation of adapted electric and/or water propulsion*
- *Development of slag-free ignition systems*

b) Characterisation of materials degradation for prolonged exposure to the space environment

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

Key enablers:

- *Qualification procedure to avoid flaking after prolonged time in orbit*
- *Development of multi-layer insulation and coating technologies preventing long term degradation*
- *Characterisation of materials degradation during launch phases (e.g. foam to dump loads)*

c) Technologies minimizing the release of small particles from impacts

Development of solutions minimizing the release of small particles when impacted by untrackable debris and micrometeoroids and improve understanding of generation of space debris through (hypervelocity) impacts.

Key enablers:

- *Development of specific shatterproof materials (e.g. solar array cover glass) and technologies to absorb impact (e.g. layered shielding and deflectors)*
- *For spacecrafts performing rendezvous operations, protection of contact zones using materials not subjected to long-term degradation*
- *Developing ejecta cloud models through experimental and numerical testing*
- *Define a standard test plan to verify the minimisation of small particles and to qualify systems*

1.2. NO RELEASE OF MISSION RELATED OBJECTS (MROs)

Need to restrict release of mission-related objects, from launchers and spacecraft: adapters, dual launch structures, dispensers, caps, etc.

Solutions to meet this need include:

a) Containment of launcher upper stage structural elements

Key enablers:

- *Launcher designs avoiding the release of dual launch structures, dummy masses, adapters, or dispensers in orbit*
- *Systems to retrieve or deorbit dead on arrival payloads*

b) Deorbiting systems for mission-related objects

Key enablers:

- *Demonstration and qualification of deorbiting kits for intentionally released elements*

2. GUARANTEE TIMELY AND SUCCESSFUL CLEARANCE

Achieving a timely and successful orbital clearance from Earth orbits after the end of mission is fundamental to avoid the accumulation of space debris in used orbits. Reaching a probability of successful orbital clearance of at least 99% entails need for improvement at different levels:

- Increasing the probability for an object to deorbit itself after end of mission, through improvement of platform
- designs and architectures
- Complementing these capabilities by external means such as Removal Services when necessary.
- Ensuring future launched objects are prepared to be removed

The following needs and solutions were identified for this target:

2.1. IMPROVE ORBITAL CLEARANCE WITH HIGH PROBABILITY OF SUCCESSFUL DEORBITING

Reducing the orbital clearance time or ensuring the disposal of space objects in low collision probability orbits will mitigate the risk of debris generation and disturbance to operational missions after end of life. Further efforts to develop technical and operational solutions are needed to improve the probability of successfully de-orbiting of spacecraft and launch vehicles at the end of their operational lives.

Solutions to meet this need include:

a) Reliable deorbiting systems for different orbital regions and object characteristics
Development of systems increasing the probability of an object to deorbit itself at the end of mission. Deorbiting systems and architectures currently exist for some use cases (e.g. deorbit systems for spacecraft in LEO) but need to be made affordable and more reliable in order to reach high clearance success rates. Other solutions could be explored for different orbital regions and use cases (e.g. disposal from MEO, mission extension, etc).

Key enablers:

- *Affordable, reliable disposal solutions for small spacecraft (e.g. electric propulsion systems, dragsails, aerobrakes, tethers)*
- *CubeSat designs compliant with high reliable and timely orbital clearance (e.g. plug and play 1 or 2U disposal subsystem)*
- *Evaluation of possible orbital clearance strategies for objects in Earth orbit (e.g. technical implications of re-entry for MEO, GEO, GTO, HEO, etc)*
- *Design architectures increasing probability of successful disposal (e.g. functional redundant architectures for the disposal capabilities, margins philosophy accounting for possible mission extensions)*
- *Autonomous deorbiting systems to be integrated before launch or in-orbit (e.g. propulsive deorbiting modules, drag augmentation devices, etc)*
- *Back up of resources for both active and passive de-orbiting*

b) Improved health monitoring
Development of robust failure detection and prediction methods and algorithms, clear decision-making criteria. Improving health monitoring will require coordination between developers and operators, and integration of lessons learned through experience.

Key enablers:

- *Systematic monitoring of probability of successful disposal using in-flight data*
- *Anomaly detection and prognostic methods for failure prediction taking advantage of return of experience (e.g. AI for failure prediction, improved feedback loops between operators and developers)*
- *Standardised, anonymised, anomaly and cross-platform lessons learned database*
- *Standardised, anonymised, cross-operator telemetry database*
- *In-situ spacecraft health monitoring with fibre sensors (e.g. embedded in CFRPs)*
- *Improved methods for accurate propellant determination*

c) Verification methods for timely and successful clearance

Key enablers:

- *Standard methodology for residual orbit lifetime calculation*
- *Standard methodology for probability of successful disposal calculation, including impacts with space debris or meteoroids*

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2.2. PREPARE SPACE OBJECTS FOR REMOVAL

For space objects which fail to remove themselves from orbit, external services can be implemented. To this end, removal interfaces and aids are required to facilitate close proximity operations, capture and removal.

Solutions to meet this need include:

a) Removal interfaces adapted to different orbital regions and object characteristics
Development of interfaces for objects of different nature (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).

Key enablers:

- *Standardisation & interoperability of removal interfaces*
- *Aids for precise attitude reconstruction of uncontrolled objects from ground/in space (e.g. laser retroreflectors)*
- *Navigation aids for close proximity and capture operations compatible with different rendezvous sensor suits*
- *Mechanical interfaces adapted to different user needs*
- *Detumbling solutions adapted to different user needs*
- *Minimize form factor, weight, and cost of removal interfaces to facilitate adoption*
- *Support expandable and ready to assemble architecture in space for satellite repair (at module level)*
- *Develop electromagnetic compatibility between target object and servicer during CPO*

2.3. DEMONSTRATE REMOVAL SERVICES

Even with highly reliable disposal systems, spacecraft are still subject to fail to deorbit at the end of their operational life. To guarantee a success rate of orbital clearance exceeding 99%, particularly in congested orbits, the introduction of external removal services can complement self-deorbiting capabilities. Although there are ongoing developments in such services, solutions generally lack the required technical maturity, in-orbit demonstration, and financial viability.

Solutions to meet this need include:

a) Improved characterisation of object to be removed
Improved knowledge of the attitude, states, and structural integrity of debris to assess risks and feasibility of removal services.

Key enablers:
- *Technologies or systems to characterize state and structural integrity of object (e.g. in-situ inspections, dedicated observation campaigns)*
- *Capability to observe and characterize attitude states from ground, and/or from space assets (e.g. ISS)*

b) Technologies for rendezvous and capture
Development of building blocks required to enable approach, capture and removal by an external servicer, in particular taking advantage of removal interfaces.

Key enablers:
- *Qualified low-cost sensors and cameras for close proximity operations.*
- *Qualified low-cost robotics, capture mechanisms, etc.*
- *Capability to control non-cooperative tumbling target (e.g. adapted AOCS of the servicer)*
- *Demonstration of robotic subsystems for active debris removal and in-orbit servicing*

c) Mature removal services ecosystem
An interoperable ecosystem of removal services and servicers following in-orbit demonstration of removal services will help meet demand for removal services in the 2030 horizon.

Key enablers:
- *Removal Services demonstration missions*
- *Insurance, liability, and a licensing pathway for Removal Services.*
- *Standardise and improve Close Proximity Operations safety (e.g. Standards and guidelines for safe CPO, improved models for characterisation of risks during capture phase)*
- *Platforms for gathering lessons learned on removal missions and close proximity operations*

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- *Platform for operators and developers to share information for facilitation of future removal operations (e.g. inertia tensor, surface material properties, uncontrolled attitude motions, possible interface or capture points)*
- *Development of in-orbit recycling technology*
- *Adapt upper stages to remove debris after placing payloads into orbit*
- *Systems to retrieve or deorbit dead on arrival payloads*
- *Establishment of multi-vendor service for removal*

2.4. ENABLE CIRCULAR ECONOMY IN SPACE

Solutions to meet this need include:

a) Technologies for In-Orbit Servicing

Key enablers:

- *Technologies for reusing/recycling in orbit so not to have to throw away some components / materials*

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3. PREVENT DEBRIS GENERATION THROUGH BREAK-UPS OR COLLISIONS

To guarantee a correlation between the orbital environment evolution and risks in orbit, this target defines a threshold for the probability of space debris generation of 1 in 1000 per object. This metric combines the debris generation resulting from internal break-ups and resulting from collisions with other space objects, throughout the entire orbital lifetime (during operations and after end of life). Keeping the probability of debris generation through collisions and break-ups below 1 in 1000 per object therefore requires a combined action on:

- Minimizing the risk of internal break-ups
- Minimizing the probability of debris generation through collisions both with trackable and untrackable objects.

The following needs and solutions were identified for this target:

3.1. IMPROVE COLLISION RISK ASSESSMENT

The risk posed by collisions drives collision avoidance manoeuvres and requires improvements and harmonisation. During the design phase, the quantification of cumulative collision probability over the total orbital lifetime can also be used to select less risky orbits for operational lifetime and for disposal of space objects.

Solutions to meet this need include:

a) Standardised methodology for collision probability assessment ~~during design~~
Formalisation of input conditions for the analysis for what concerns space debris population models, spacecraft properties, and treatment of uncertainties.

Key enablers:

- *Accurate debris hard body radius estimation (e.g. measured by laser ranging)*
- *Open reference and improved space debris population models, to predict the future position of space objects and their interactions with one another*
- *Improved, more frequent, and more accessible predictions of the future debris environment*
- *Accurate estimation of impact area for the asset*
- *Comparison of accuracy in space surveillance and the onward impact to risk error*
- *Improvement of collision risk assessment for dragsails*
- *Guidelines and methodology for cumulative collision probability assessment (depending on the mission phase, debris population to be considered)*
- *Establish a standardized formula for calculating collision probability, incorporating diverse inputs like object trajectories, sizes, and operational statuses, to ensure consistent and accurate risk assessments across providers*
- *Standardized methodology for collision probability re-assessment during operations*
- *For rideshare launches, methods to assess the collision risk after orbit injection*
- *Better atmospheric density, space weather and propagation models*
- *Standardised set of guidelines and technical approach advances for launch COLA assessment, both before and after launch*
- *Research (development of tools) on multiple providers collision risk assessment aggregation and effective decision-making*
- *Data analysis to predict future collisions based on the history collision break-ups*
- *Machine learning algorithms to predict collision probabilities with greater accuracy by incorporating historical collision data, satellite behaviour models and predictive maintenance indicators*
- *Define/standardise the probability thresholds and associated methodologies for the decision to perform COLA manoeuvre and the residual risk after manoeuvre execution*

b) ~~Benchmark~~ Quality assessment of collision risk analysis providers
Assuring that collision risk analysis providers meet a certain accuracy threshold, for example on standardised datasets, before provided collision risks are used operationally.

Key enablers:

- *Methods and metrics for quantifying collision risk analysis accuracy*
- *Collaborative platform where different providers can share insights, methodologies, and data sets*
- *Certification system for collision risk analysis providers*
- *Access to information regarding secondary object during conjunctions*
- *Collection of manoeuvrability, ephemeris, collision-relevant surface area data (which can be collision geometry and satellite attitude dependant)*
- *Covariance realism information available for different objects and operators (i.e. trustworthiness indicator)*

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c) Methodology for assessing consequences of collisions and break-up modelling

Key enablers:

- ~~*Collision risk assessment integrating consequences of collisions*~~
- *Fragmentation models*
- ~~*Hypervelocity impacts tests*~~
- *Improved understanding of collision consequences for dragsails (e.g. modelling and tests)*
- *Increase confidence on Ballistic Limit Equations*

3.2. STANDARDIZED EVALUATION OF IMPLIED AND ENCOUNTERED RISKS

Current debris mitigation guidelines are formulated using different approximations (e.g. lifetime limitations) instead of the risk of debris generation, which is the phenomenon that space debris mitigation really must address. As a result, different designs and operational concepts can be compliant with guidelines whilst still having a significant different effect on the environment. As an alternative approach, metrics and methodologies can be developed to directly quantify the risk of debris generation.

Solutions to meet this need include:

a) Space debris consequences analysis and international standardisation of risk methodologies

Development and adoption of risk-based approaches able to quantify the likelihood and the severity of debris generation events, considering different design and operational aspects of single missions. These can in turn aid in the formalisation of risk assessments by maturing the required inputs, supporting database, and applied methodologies.

Key enablers:

- *Space debris indexes to measure the consequence of space debris generation*
- *Standardised risk methodologies, focused on risk detection in support of licencing*
- *Agreed metric to evaluate debris impact of missions*
- *Different methods depending on orbital regimes (e.g. Acceptable collision risk in increasingly congested orbits)*
- *Orbit capacity scheduling and maintenance action plan*
- *Risk assessment including aspects beyond space debris issues (e.g. spectrum, LCA, etc)*

b) Space environment capacity

The current debris mitigation guidelines are formulated by considering single objects, so they cannot dynamically account for variations in the space traffic, or for the actual current level of implementation and success of post-mission disposal manoeuvres. To address this limitation, the concept of space traffic management based on the environment capacity was proposed.

Key enablers:

- *Dynamic models of the future space traffic (technical, economical, and societal) and resulting interactions*
- *Methods to measure capacity consumption related to space debris risks*
- *Safe and reliable access to different orbital regions (extend capacity concept beyond LEO)*

3.3. IMPROVE COLLISION AVOIDANCE

Collision avoidance is increasingly burdensome on operators as orbits become more congested and frequency of conjunctions increases. The collision avoidance process and coordination between operators needs to be improved, and a greater number of space objects need to be capable of avoiding collision using on-board propulsion.

Solutions to meet this need include:

a) ~~Large adoption of manoeuvrability for spacecraft~~ Increase manoeuvre capabilities availability

Key enablers:

- *Collision avoidance solutions for small spacecraft (e.g. propulsion system with limited system/mission impact, ideally usable also for disposal, simple propulsion technologies for CubeSats)*

b) Increased autonomy for collision avoidance operations

Key enablers:

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- *Systems for autonomous conjunction detection and collision avoidance operations*
- *Improved conjunction prediction algorithms (e.g. machine learning based solutions)*
- *Explore open-source screening solutions to enable operators to perform internal optimization of CAMs*
- *Reduction of the lead-time to react to conjunctions (e.g. late command paths)*
- *Ability to make fast special ephemeris screening- needs to be fast to automatize the CAMs*
- *Mandatory registration to an SSA service provider (e.g. 18th SPCs, EU SST, Space-Track, etc)*

3.4. MINIMIZE RISKS LINKED TO UNTRACKABLE OBJECTS

Small untrackable space debris objects pose a risk to spacecraft. Minimising the risk that these small debris objects pose to spacecraft helps to ensure a low probability of debris generation.

Solutions to meet this need include:

a) Improved statistical models for untrackable objects propagation, and long-term environment evolution
Long-term modelling techniques able to handle or represent significantly larger populations than what considered in current studies. These improved models will ultimately facilitate the selection of orbits minimizing the risks of collision with untrackable objects.

Key enablers:

- *In-situ detection sensors and processed data*
- *Regular measurements of debris density and update of reference debris population models*
- *Develop and benchmark tools to predict propagation of hypervelocity impacts to internal items*
- *Develop/improve tests and database to characterise hypervelocity impacts and effects on structures and items*

b) Design mitigation solutions against untrackable objects

Key enablers:

- *Shielding technologies, containment of break-ups caused by impacts and protection of critical equipment (e.g. batteries, pressurized tanks*
- *Common catalogue of shielding solution*
- *Design architectures resilient to untrackable debris impacts (e.g. smart accommodation, separation of critical redundancies)*
- *Shielding technologies, containment of break-ups caused by impacts and protection of critical equipment (e.g. batteries, pressurized tanks)*
- *Health monitoring system enabling assessment of post-impacts damage and prediction of the remaining operating life (e.g. development of strain based SHM systems using fibre optic sensors)*

3.5. MINIMIZE RISKS OF INTERNAL BREAK-UPS

Keeping the probability of debris generation through collisions and break-ups below 1 in 1000 per object requires minimising the risk of internal break-ups which generate debris, during operational lifetime and after end of life. After end of life, reliable passivation allows to significantly reduce the risk of break-ups in orbit. Concepts such as autonomous passivation are explored, however implying other risks such as early termination of the mission (e.g. premature triggering of autonomous passivation systems) that need to be mitigated.

Solutions to meet this need include:

a) Improved internal break-up modelling

Key enablers:

- *Standardize methodologies and tools to assess failures on spacecraft units and subsystems, which may lead to break-up and/or prevent successful disposal*
- *Develop and benchmark tools to predict propagation of hypervelocity impacts to internal items*
- *Develop/improve tests and database to characterize hypervelocity impacts and effect on structures and items*

b) Technologies for reliable passivation
Technologies for passivation exist but are not systematically adopted in spacecraft design.

Key enablers:

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- *Systematic adoption of capabilities to permanently and irreversibly deplete and prevent future loading of on-board energy sources*
- *Robust passivation design architectures (e.g. health monitoring, watchdogs, autonomous passivation, etc)*
- *Technologies for reliable passivation by external means/servicing mission to perform a fluidic passivation*
- *Definition of a new attitude mode specific for passivation with the objective of reducing the storage of energy*
- *Propellant offloading technologies*

c) Passive energy containment solutions

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

Key enablers:

- *Containment technologies for energy sources in small spacecraft (e.g. batteries)*
- *Design guidelines to protect pressurized vessels from generating debris*

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4. IMPROVE SPACE TRAFFIC SURVEILLANCE AND COORDINATION

With the increasing number of space objects being launched, space traffic coordination will play an essential role to ensuring sustainable operations. This target encourages routine and transparent information sharing, and active participation of spacecraft operators to guarantee efficient and timely collision avoidance operations.

The following needs and solutions were identified for this target:

4.1. IMPROVE SPACE TRAFFIC COORDINATION AND INFORMATION SHARING

Improved Space Traffic Coordination (STC) will help to prevent collisions and reduce unnecessary collision avoidance manoeuvres.

Solutions to meet this need include:

a) Closer international ~~coordination~~ collaboration

Transparency in data and intent despite geopolitical uncertainties.

Key enablers:

- *Adoption of CCSDS standards for all spacecraft operators when exchanging close approach information*
- ~~*Standardized collision risk methods*~~
- *Automated close approach risk reduction schemes*
- *Standardised guidelines at international level in case a coordination is not possible*
- *Establishment of an international coordination body (which will help to avoid duplicate and parallel coordination efforts by national/regional entities)*

b) Improved communication

Between space surveillance segments and ground segments as well as communication intentions between parties involved in conjunctions.

Key enablers:

- *Improved, standardised infrastructures enabling sharing of data (e.g. easy identification and defined contact procedures for all objects, alerting services)*
- ~~*Objects and conjunction data database*~~ *International, politics-agnostic, and privacy-preserving data repository for all space systems (e.g. operational orbits, manoeuvre plans)*
- *Operators point of contact database*
- *Automation of data exchange and decision processes*
- *Provide manoeuvre status after TCA to the other party involved*
- *Standardised data format/contents*
- *Automated and standardised platform to communicate intent to manoeuvre (i.e. change in nominal trajectory incoming) and to communicate that an operator has taken responsibility for manoeuvring on a given conjunction*

c) Guidelines for safe collision avoidance operations

Definition of standards concerning the collision risk methods, the timeliness and quality of collision avoidance operations.

Key enablers:

- *Standardized collision risk methods during operations*
- *Guidelines for intra and inter constellation coordination*
- *Establishment of minimum set of capabilities for collision avoidance operation services*
- *Collision avoidance communication to aircraft and ships, when re-entering (through NOTMAR - for ships and NOTAM - for aircraft)*
- *Standardised guidelines for decision making on collision avoidance procedures for two operative missions*
- *Classification guideline to group spacecraft and ground systems in different categories depending on their reaction capability to conjunctions (e.g. level of autonomy, ground/space based, timeline to reaction, reaction capability, etc)*
- *Standardized risk thresholds to consider a collision risk among operated satellites as unacceptable*
- *Certification or licensing process for collision avoidance operators*

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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 while increasing the available orbital capacity. The capability to track smaller objects down to 5cm in LEO and 20cm in GEO will reduce the risk for catastrophic collisions in these orbital regions.

Solutions to meet this need include:

a) Improved sensors for space surveillance

Key enablers:

- *Increased sensitivity and resolution of space debris tracking systems (e.g. telescopes for on-demand accurate measurements, radars campaigns for monitoring and cataloguing, etc)*
- *Improved optical and laser ranging methods for tracking of smaller objects*
- *In-situ monitoring and cataloguing of lethal nontrackable objects (LNT) for sub-catalogue*
- *Increased revisiting time on objects within space surveillance networks and observation processing*
- *Promote the increase of tracking systems (facilities around the world and in-orbit)*
- *Track the change/trend of small size debris in different layers in LEO*
- *Establish tracking priorities based on a target orbit accuracy for objects (that do not have accurate state estimation capabilities)*
- *Improved space surveillance performance for rideshare launches*

b) Technologies for improved trackability of ~~small~~ objects

The uptake of tracking aids could improve errors on conjunctions and reduce false-positive rate

Key enablers:

- *~~Cost-effective~~ tracking ~~aids~~ devices for identification and tracking of small platforms and mission related objects (e.g. retroreflectors)*
- *Commercially available space situational awareness support hardware*

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

Better data is becoming available on the highest risk space debris objects. Improved space surveillance data could reduce the false-positive rate.

Key enablers:

- *Using contextual information, e.g. photometry, to increased correlation accuracy over larger timespans*
- *Improved data processing timelines mixing heterogeneous sensor networks when deriving uncertainties*
- *Quantifying and reducing the uncertainty on measurements from all data sources (e.g. covariance realism)*
- *Use of reinforcement learning, or other policy based statistical method to handle uncertainty*
- *Improved object propagation models using machine learning techniques*
- *Automation of data collection for efficiency and scalability*
- *Improved surveillance data to reduce the false-positive rate*

4.4. ROBUST TASKING OF TRACKING FOR LARGER CATALOGUES

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

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Solutions to meet this need include:

a) Informative hub about space debris tracking and collision risks

Making space debris catalogues available to other space actors or the general public is a simple route to share knowledge of the space debris population and cross-validate models and measurements of space debris.

Key enablers:

- *Consolidated and open space debris catalogues and datasets with space debris detection across damage causing size-regimes*
- *Standardized space surveillance catalogue information, including tracking revisit information and data quality metrics*
- *Operator solution to target object tracking in a space surveillance segment in an agnostic way*
- *Means for direct exchange of raw data measurements between SST providers*
- *Adjust the tracking tasking dynamically to the need of the operators, to ensure optimised tracking for the most dangerous events*

b) Fusion of heterogenous space surveillance data sources

Leading models current differ by an order of magnitude for the 10 cm debris population.

Key enablers:

- *Calibrate test data and open access surveillance sensor products*
- *Data fusion methods for heterogenous sensor networks*
- *Use the support of ground station (Amateur Radio or professionals) to track satellite signals*
- *Satellites already used for Earth or atmosphere observation subcontracted for the observation of space debris as secondary mission*
- *Co-ordinating existing sensors relevant to SST such that in their "downtime" they can be utilised as part of a central tracking network*

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5. PREVENT CASUALTIES ON GROUND

The casualty risk on-ground for human populations and infrastructures is increasing together with the growing number of objects re-entering the Earth atmosphere. Current simulation capabilities have known limitations and are not harmonised. Striving towards zero casualty for re-entering objects will require coordinated and collaborative efforts in the fields of:

- Re-entry risk evaluation methods and models
- Design solutions reducing uncontrolled re-entry risks
- Controlled re-entry solutions improvement in terms of system impacts, reliability and cost efficiency

The following needs and solutions were identified for this target:

5.1. REDUCE RISKS LINKED TO UNCONTROLLED RE-ENTRY

Increased demisability reduces the risks linked to uncontrolled re-entry by burning up more completely the object in the atmosphere thus reducing the number of fragments reaching ground.

Solutions to meet this need include:

a) Technologies for Design for Demise

Development of fully demisable platforms and improvement of demisability at material, equipment and payload levels; development of demisable technologies for launchers.

Key enablers:

- *Fully demisable LEO spacecraft platforms (e.g. standard large/medium fully demisable platforms product lines)*
- *Demisable spacecraft and launcher equipment (e.g. demisable tanks, demisable reaction wheels, demisable magnetorquers, demisable SADM, demisable optical payload elements, demisable star trackers, etc)*
- *Pre-determined fragmentation sequence during re-entry (e.g. equipment release sequence, early break-up technologies, containment techniques)*
- *New materials with better demisability*
- *New demisable technology development considering the environmental impact of the demise/burn-up in the atmosphere (e.g. replace harmful substances)*
- *Demisable COPVs for spacecraft considering EP subsystem onboard spacecraft constellations*
- *Use of exothermic reaction (e.g. thermites)*
- *Increased demisability by additive manufacturing (e.g. for optical payloads)*
- *Development of components with holes or lattice structures for increased heat flux*

b) Improved tools and models for re-entry risk assessment

Improve and standardize models and methods to assess demise using in-orbit demonstrations, and casualty risk on ground assessment.

Key enablers:

- *Re-entry experiments to demonstrate lab-testing in flight*
- *Reduced uncertainties on the characteristics of objects reaching ground (e.g. by Ground testing and derived improved modelling)*
- *Characterization and compilation of database on materials demise (e.g. glasses, composites, etc)*
- *Improved on-ground risk estimates for human populations*
- *Predict with higher accuracy the re-entry trajectory and impact zone on Earth by developing new models*
- *Standard or commonly shared tools and database of population distribution on Earth*
- *Improve understanding of heating of objects with multiple length scales, holes, and lattices*
- *Comparable test setup and conditions for demise tests*

c) Evaluate alternative re-entry methods

Alternative ways of targeting disposal at end of life, can form an alternative to the classical uncontrolled or controlled re-entry strategies. To enable alternative disposal methods for future missions, further evaluation of safety, operational and technical feasibility are required.

Key enablers:

- *Development of a standardized risk evaluation method for alternative re-entry methods*
- *Assisted re-entry as an alternative to uncontrolled re-entry*
- *Ability of Drama to address assisted re-entry or re-entry from HEO/GTO (link with SDMP for exotic orbits*

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5.2. REDUCE TECHNICAL IMPACTS OF CONTROLLED RE-ENTRY

Implementing controlled re-entry minimizes the risks to the ground, but it also entails substantial system impacts. Mitigating these technical challenges is crucial to facilitating the widespread adoption of controlled re-entry.

Solutions to meet this need include:

a) Adaptable spacecraft architectures

Key enablers:

- *Flexible end of life propulsive modules (e.g. solid rocket motors, deorbiting kits adapted to different missions)*
- *Spacecraft standard platform designs adaptable to controlled ~~or uncontrolled~~ re-entry*
- *Tracking aids to ensure external, precise validation of trajectory on controlled re-entry*
- *Increase AOCS control capability at lower perigee (e.g. to reduce thrust needed for the last burn)*
- *Propulsion trade off addressed early in the design phase, available propulsion solutions chosen according to mission constraints and needs*

5.3. MINIMIZING SPACE DEBRIS IMPACTS ON HUMAN POPULATION AND INFRASTRUCTURE

Re-entering space debris poses a risk to human populations on ground and in the airspace, particularly with growing populations of both humans and space objects due to re-enter the atmosphere.

Solutions to meet this need include:

a) Improved re-entry coordination

Key enablers:

- *Alerting system for notification of objects that are projected to not burn up fully*
- *Assessment of re-entry impacts on air traffic management*
- *Communication between aviation agencies specific to re-entry of satellites and space debris*
- *More frequent tracking of larger debris objects to decrease risk to population and/or infrastructure (e.g. worldwide data sharing between all space actors)*
- *Creation of more re-entry corridors and support the improvement of re-entry accuracy*

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6. UNDERSTAND AND MITIGATE ADVERSE CONSEQUENCES OF SPACE DEBRIS

The following needs and solutions were identified for this principle:

6.1. UNDERSTAND ENVIRONMENTAL IMPACTS OF RE-ENTRY

Spacecraft and launcher upper stages re-entering and demising in the atmosphere, as well as reaching the ground or oceans could have a variety of adverse effects on the Earth environment, but these are not yet fully understood or quantified.

Solutions to meet this need include:

a) Characterization of impacts of re-entry on Earth's environment; atmospheric, oceanic, and terrestrial
The environmental impacts of space debris re-entry are relatively unknown. Space debris re-entry could open a range of possible new impacts to be assessed which are usually not currently considered for life cycle assessment of space missions, such as upper atmospheric effects on climate, human toxicity of re-entering objects, or water/ocean and land toxicity.

Key enablers:

- *Characterization of ablation products formed when undergoing a destructive re-entry (Understanding the particle-induced erosion and heat flux augmentation on ablators in re-entry)*
- *Lab and in-situ measurements to characterize atmospheric impacts of demise, leading to design models (e.g. sounding rockets-based flight experiments for atmospheric studies, dedicated sensing technologies)*
- *Lab and in-situ measurements to characterize material deposition in oceans and on land (depending on toxic batteries or nuclear propulsion / thermal sources for lunar missions)*
- *Improvement in the modelling of physical and chemical processes in the upper atmosphere to understand the long-term impact of the injected material on atmosphere*
- *Improved knowledge on size distribution and optical properties of injected materials and their injection form*
- *Atmospheric studies of the evolution of materials due to re-entries (research on ablation heights and altitude dependant injection profiles; chemistry of injected materials and compounds in mesosphere and stratosphere)*
- *Material composition of individual rocket bodies, satellites and ancillary items used to deploy payloads*
- *Investigate proportion of surviving re-entering objects*
- *Characterize impact of unused propellant dispersion*
- *Development of bio based materials*

6.2. PROTECT DARK AND QUIET SKIES

Space debris and active spacecraft can adversely affect astronomical observations from ground and space, particularly wide-field optical and radio observations. This can limit the scientific return of observatories and impacts our societies in various ways.

Solutions to meet this need include:

a) Prediction and limitation of the visual brightness of spacecraft and space debris according to requirements specified by IAU

Key enablers:

- *Standardized models for visual brightness assessment*
- *Database of space objects creating visual disturbance correlated with orbital information*
- *Development of materials, technologies and operational concepts mitigating brightness of spacecraft (e.g. paintings, MLI, coatings, directional lighting systems, dielectric mirror, black paint, electrochromic material)*
- *Solutions to maintain the trackability while reducing the brightness (e.g. retroflectors)*

b) Prediction and limitation the radio interference from spacecraft on radio astronomy

Key enablers:

- *Characterization of potential radio interference into protected radio astronomy bands from adjacent transmissions and unintentional radiation*
- *Corelation between radio quiet zones and mission concepts of operations*
- *Passivation concepts for radio-emitting equipment after end of life*

c) Facilitate communication between operators and astronomers

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