ESA's Space Debris Mitigation Requirements

Space Debris Mitigation Team

07/10/2024
ESA-TECQI-HO-2024-002968

Disclaimer

The content of this presentation is intended for personal and non-commercial use of their users. Permission is granted to users to reprint or copy information for personal non-commercial use when providing appropriate credit by citing the source plus date of issue.

For commercial use, authorisation need to be sought.

Users may not modify, publish, transmit, participate in the transfer or sale of, reproduce, translate into other languages, create derivative works from, distribute, perform, display or in any way exploit any of the content, material or images, in whole or in part, without obtaining prior written authorisation.

What to expect from today

A general lecture on space debris

A detailed engineering session

What to expect from today

A general lecture on space

iled engineering session

A (hopefully useful) overview of ESA’s Space Debris Mitigation Requirements and related verification methodologies

What to expect from today

Francesca Letizia

Emma Stevenson

Marco Papa

Daniele Bella

Calum Turner

Ines De Chiclana

Sergio Ventura

Stijn Lemmens

Housekeeping rules

This session
is recorded

The slides will
be distributed

On-site

Please keep questions for
the end of the presentation

OR

Online

Put your questions in the
Q&A section of WebEx

The chat section is
not monitored

Zero Debris Approach development

> *In ESA we are implementing a policy that, by 2030, we have a '**net zero pollution**' strategy for objects in space, by consistently and reliably removing them from valuable orbits around Earth immediately after they cease operations.*
> *We need to **lead** by example here.*

Josef Aschbacher, ESA Director General

Policy update recommendations considering environmental needs and impact on future missions, informed by an extensive **simulation campaign**

Roadmap for technical developments & standards, providing an estimation of the **resources** needed and a **phase-in schedule**

EOP | TIA | SCI | STS | NAV | TEC

Zero Debris CDF and Standard development

Zero Debris Scope

Developing ESA Zero Debris approach | **Engaging partners, building a community**

ESA SDM Policy & Standard

Technical requirements for ESA missions and contributions

ESA Technical Developments

ESA support to industry's transition and compliance to SDM standards

Zero Debris Technology Booklet

Crowd-sourced technical solutions to reach Zero Debris targets by 2030

Zero Debris Charter

Jointly defined principles and targets for long term space sustainability

Zero Debris Scope

Developing ESA Zero Debris approach

Engaging partners, building a community

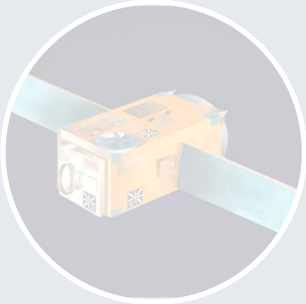
ESA SDM Policy & Standard

Technical requirements for ESA missions and contributions

ESA Technical Developments

ESA support to industry's transition and compliance to SDM standards

Zero Debris Technology Booklet



Crowd-sourced technical solutions to reach Zero Debris targets by 2030

Zero Debris Charter

Jointly defined principles and targets for long term space sustainability

ESA Space Debris Mitigation Regulation status

esa

- Policy
- Standard
- Handbook

Updated in 2023

ESA/ADMIN/IPOL(2023)1
ESA Space Debris Mitigation Policy

Born in 2023

ESSB-ST-U-007
ESA Space Debris Mitigation Requirements

Updated in 2024

ECSS-U-AS-10C
Space sustainability - Adoption Notice of ISO 24113

Since 2017

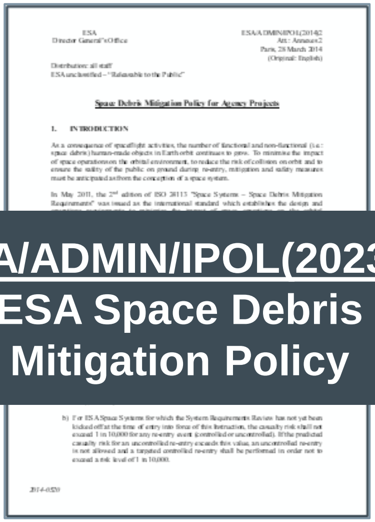
ESSB-ST-U-004
ESA Re-entry Safety Requirements

Update in 2024

ESSB-HB-U-002
ESA Space Debris Mitigation Compliance Verification Guidelines

ESA's Space Debris Mitigation Policy

Who?



ESA/ADMIN/IPOL(2023)1
ESA Space Debris Mitigation Policy

- Definition of the perimeter of applicability — ESA space systems, operations under ESA's responsibility, contribution to international activities, procurement of launch services
- Applicable to all missions regardless of their phase
- Introduction of the Space Debris Mitigation Assessment Board — It provides recommendations in case of Mission Extension Reviews, anomalies affecting space debris mitigation measures, and requests for deviations/waivers

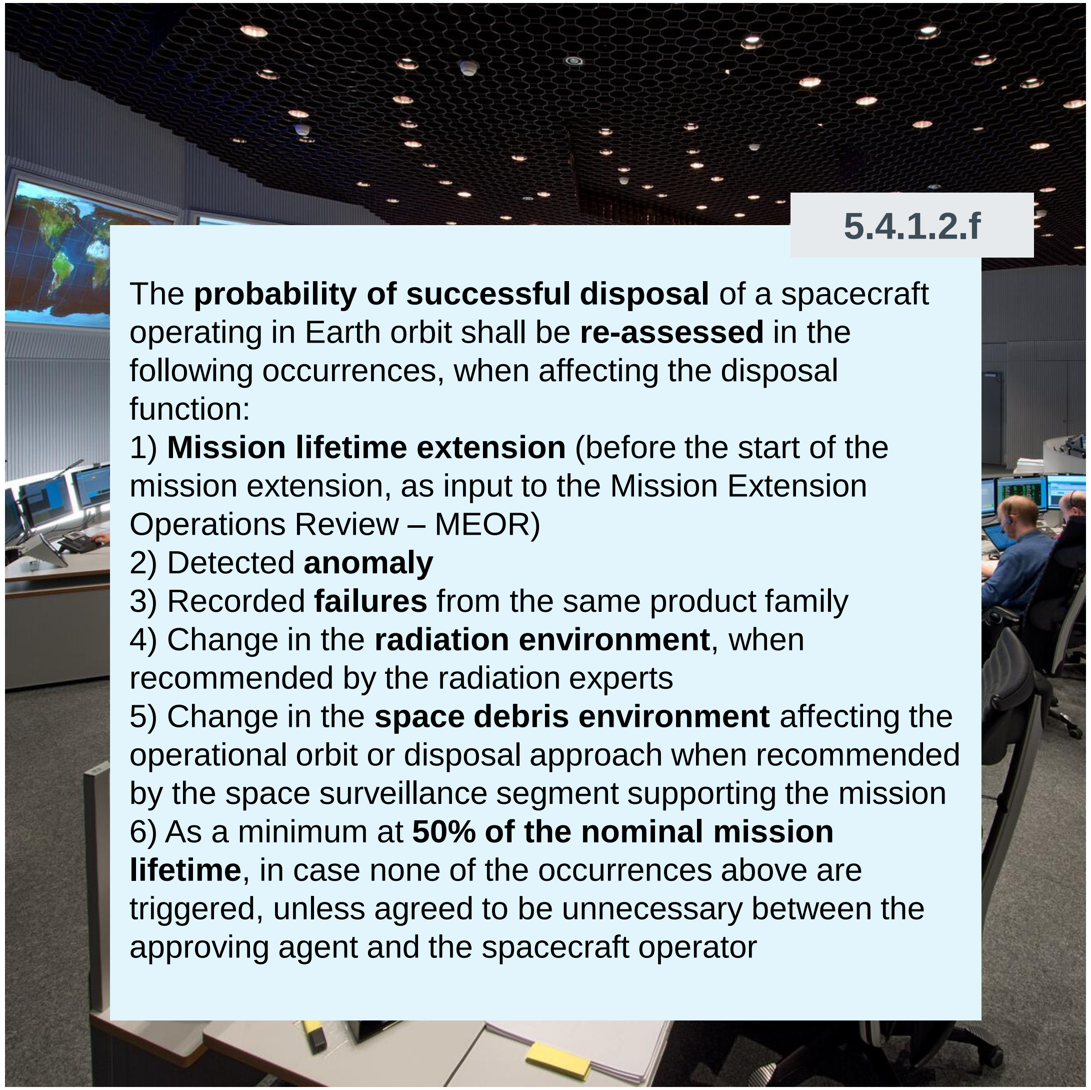
https://technology.esa.int/upload/media/ESA-ADMIN-IPOL-2023-1-Space-Debris-Mitigation-Policy-Final.pdf

FREQUENTLY ASKED QUESTION

Responsibility for the operational requirements

If ESA's role is expected to end with the support to the mission development, then it is not our responsibility/role to monitor the implementation of operational requirements, and they are to be interpreted as

- **constraints** for the space/ground segment **development** i.e. the space segment has to have all the features/capabilities required to implement the operational requirements
- guidelines/**recommendations** for the **operators** on how to conduct operations in line with ESA's space debris mitigation principles.



5.4.1.2.f

The **probability of successful disposal** of a spacecraft operating in Earth orbit shall be **re-assessed** in the following occurrences, when affecting the disposal function:
1) **Mission lifetime extension** (before the start of the mission extension, as input to the Mission Extension Operations Review – MEOR)
2) Detected **anomaly**
3) Recorded **failures** from the same product family
4) Change in the **radiation environment**, when recommended by the radiation experts
5) Change in the **space debris environment** affecting the operational orbit or disposal approach when recommended by the space surveillance segment supporting the mission
6) As a minimum at **50% of the nominal mission lifetime**, in case none of the occurrences above are triggered, unless agreed to be unnecessary between the approving agent and the spacecraft operator

ESA's Space Debris Mitigation Requirements

What's new

What?


DOCUMENT

ESA Space Debris Mitigation Requirements

ESSB-ST-U-007
ESA Space Debris Mitigation Requirements

Clearance criteria

+ **5 years in LEO**
+ Collision probability threshold
+ Apogee below 375 km for constellations
+ If graveyard, no crossing with known constellations

Probability of successful disposal

+ ≥ 90% considering both **internal** (reliability) and **external** (impacts) factors
+ ≥ 95% for large constellations
+ Monitoring and reassessment

COLA & STM

+ Encoding of current best practices (e.g. data sharing)
+ Recurrent manoeuvre capability in GEO, in LEO for high and very high-risk objects, and for constellations
+ Collision probability threshold for action ≤ 1:10000

Design for removal

+ Preparation for removal for high-risk objects in the protected regions

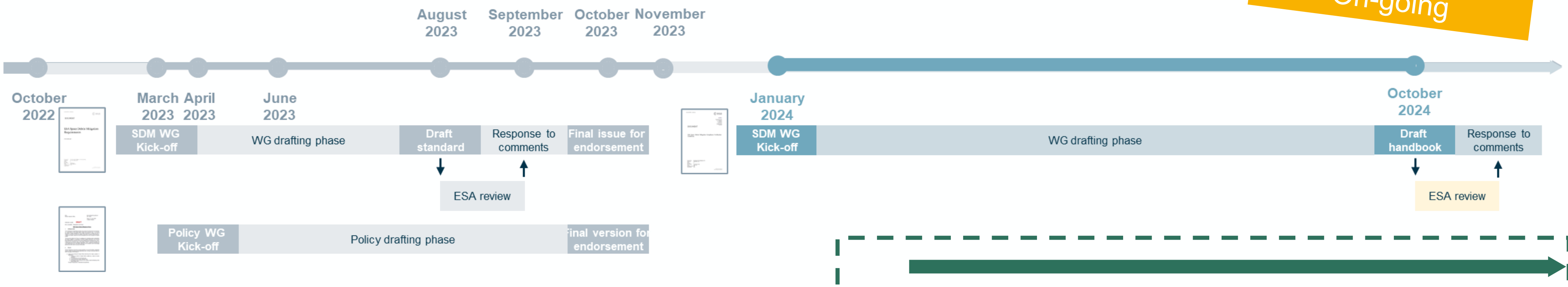
https://technology.esa.int/upload/media/ESA-Space-Debris-Mitigation-Requirements-ESSB-ST-U-007-Issue1.pdf

COLA: Collision Avoidance | STM: Space Traffic Management

ESA's Space Debris Mitigation Compliance Verification Guidelines

On-going

How?



ESSB-HB-U-002
ESA Space Debris Mitigation Compliance Verification Guidelines

- Guidelines on suitable methodologies for verification
- Indication of what's expected at the different mission phases
- Revision of ESA's available tool for compliance analysis
- Update/coordination of/with related documents

drama

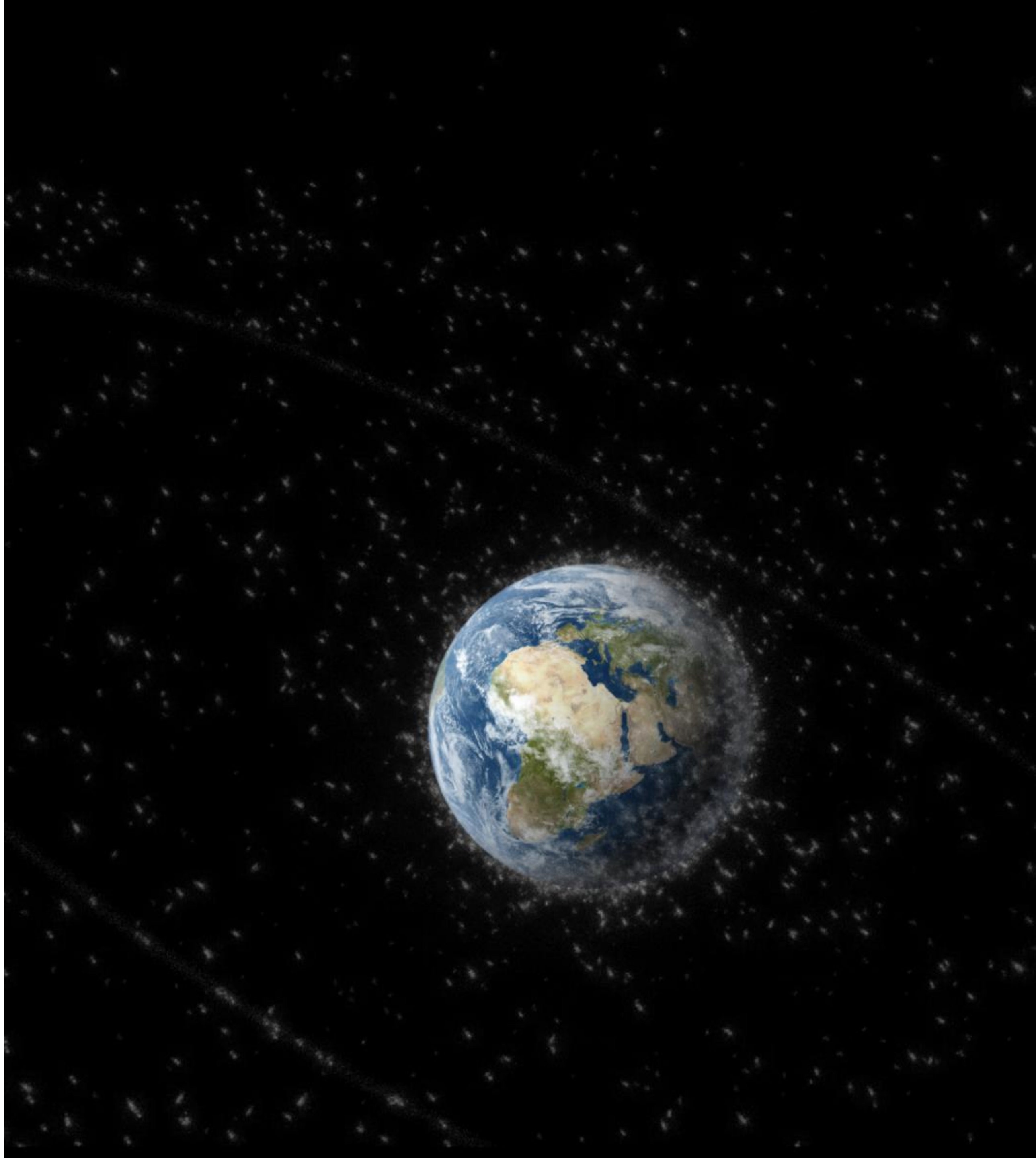
Update & planned releases to support analyses

ESA's Space Debris Mitigation Toolkit

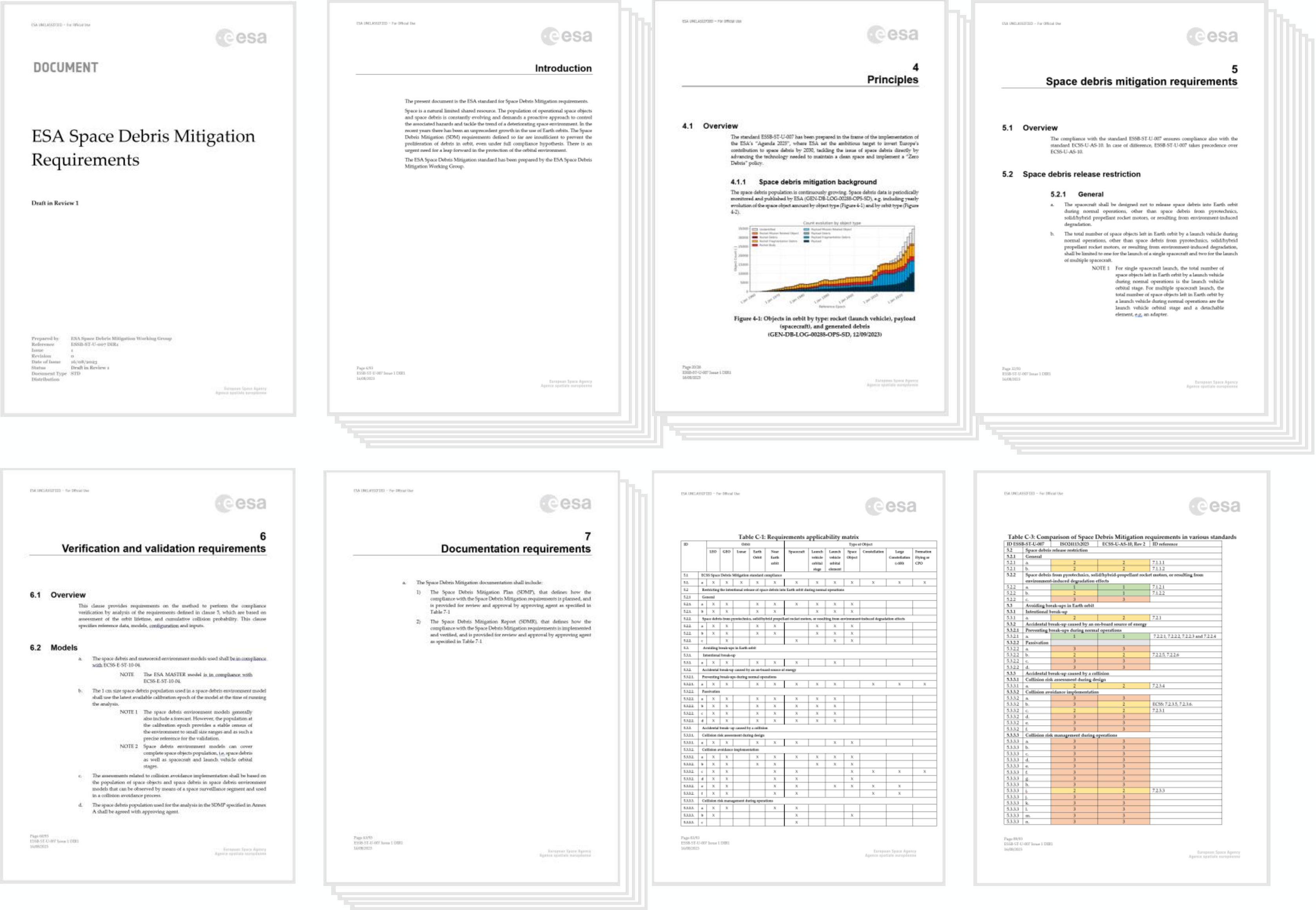
Design-for-Demise, Close Proximity Operations

SPACE DEBRIS MITIGATION REQUIREMENTS

a bit more in detail



The Document

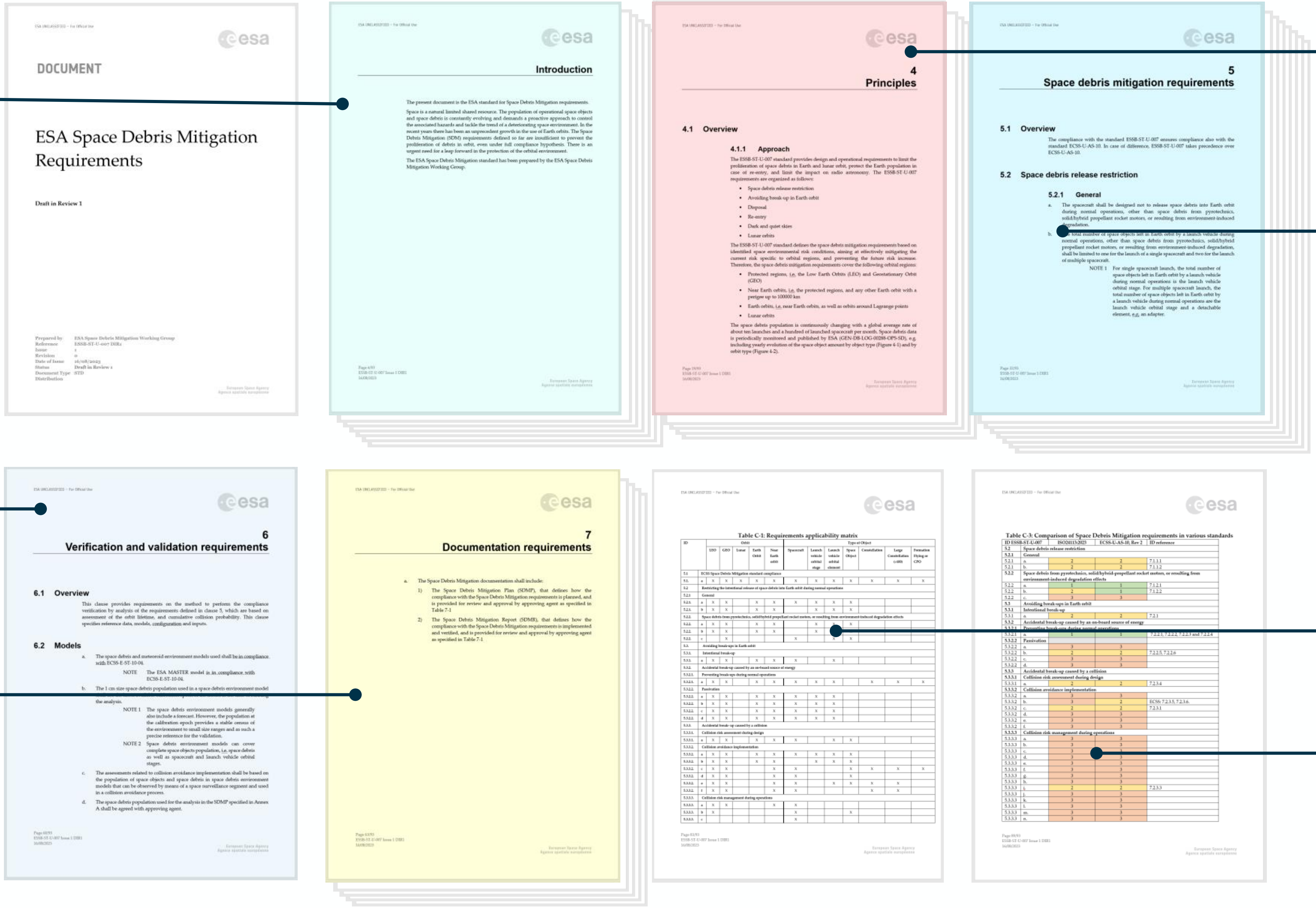


The Document

Frontmatter
Introduction, scope, definitions

Verification & Validation requirements
Indications on key models and data inputs for the required analyses
(complementing ESSB-HB-U-002 ESA Space Debris Mitigation Compliance Verification Guidelines)

Documentation requirements
Including expected content for reporting



Principles
Rationale for each requirement

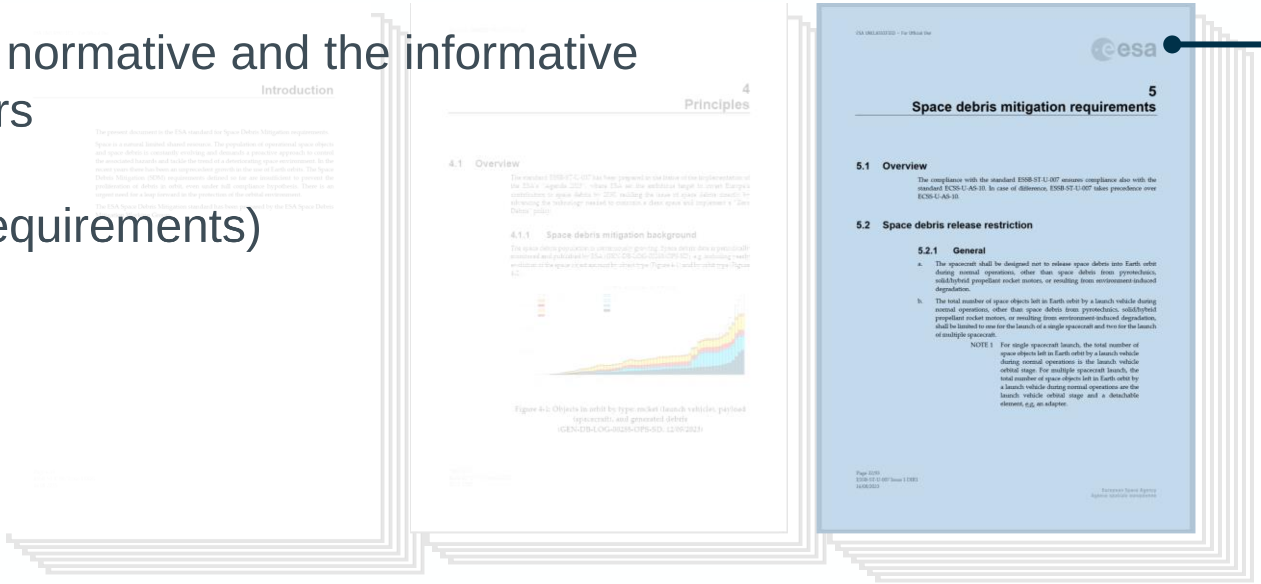
Space Debris Mitigation Requirements
Space debris release, Avoid breakups in Earth orbit, Disposal, Re-entry, Dark and quiet skies, Lunar orbits

Requirement Applicability Matrix
Requirement mapping based on orbital region and object type
Comparison wrt ISO24113:2023 and ECSS-U-AS-10

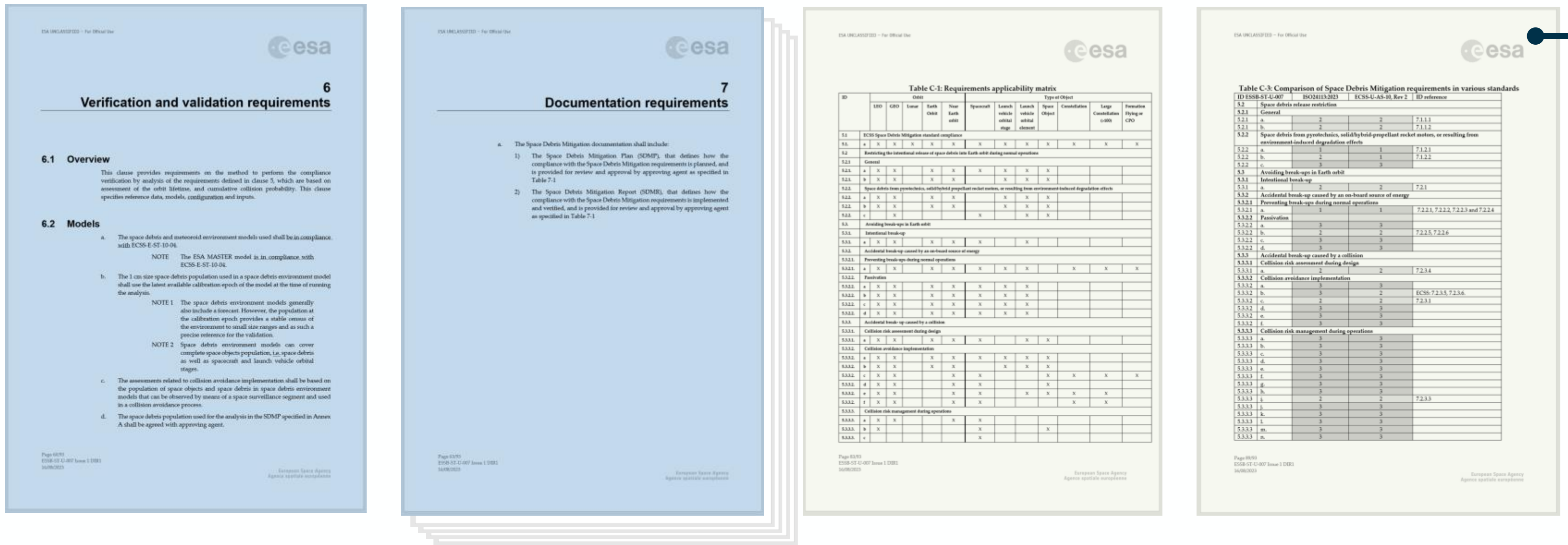
A clarification on the Document

In case of discrepancies between the normative and the informative sections, the normative is what matters

(e.g. with respect to the mapping of requirements)



Normative



Informative

Do you have the requirements in excel/DOORS format?

FREQUENTLY ASKED QUESTION

Yes, both a DOORS version (ESA internal link only) and Excel version are available for download.

The Excel version is a compliance matrix template with already indicated of the apportionment of requirements between space and ground segment/operations.

ESSB Req. Identifier	Requirement	Text of Note of Requirement	Category	Note to category	Owner	Compliance status (C/PC/NC/NA)	Verification method(s)	Justification	Close-out Reference	Close-out Status	Additional Remarks
5.2.1a	The spacecraft shall be designed not to release space debris into Earth orbit during normal operations, other than space debris from pyrotechnics, solid or hybrid propellant rocket motors, or resulting from environment-induced degradation.		Design								
5.2.1b	The total number of space objects left in Earth orbit by a launch vehicle during normal operations, other than space debris from pyrotechnics, solid or hybrid propellant rocket motors, or resulting from environment-induced degradation, shall be limited to one for the launch of a single spacecraft and two for the launch of multiple spacecraft.	NOTEFor single spacecraft launch, the total number of space objects left in Earth orbit by a launch vehicle during normal operations is the launch vehicle orbital stage. For multiple spacecraft launch, the total number of space objects left in Earth orbit by a launch vehicle during normal operations are the launch vehicle orbital stage and a detachable element, e.g. an adapter.	Design								
5.2.2a	Pyrotechnics shall be designed not to release space debris larger than 1 mm in their largest dimension into Earth orbit.		Design								
5.2.2b	Solid or hybrid propellant rocket motors shall be designed and operated not to release space debris larger than 1 mm in their largest dimension into Earth orbit.	NOTEThe main aim of this requirement is to limit the generation of slag debris ejected into Earth orbit during the final phase of combustion.	Design								
5.2.2c	A spacecraft or launch vehicle orbital element operating in the GEO protected region with a continuous or periodic presence shall be designed not to release space debris larger than 1 mm in their largest dimension resulting from the environment-induced degradation of adhesives and hook and loop fasteners for an orbit lifetime of 50 years including normal operations and after the disposal.	NOTEEnvironment-induced degradation mechanisms are based on electromagnetic radiation and the energetic particle environment, excluding impacting space debris and meteoroids. The objective is to minimise debris from multi-layer insulation, which is a known space debris source.	Design								
5.3.1a	In Earth orbit, intentional break-up of a spacecraft or launch vehicle orbital element shall not be performed.	NOTEDesign for demise measures leading to a fragmentation during atmospheric re-entry are not considered intentional break-ups, provided it is demonstrated that they result in a reduced re-entry casualty risk, and they do not generate additional on-orbit collision risk.	Design								

https://technology.esa.int/page/space-debris-mitigation

ESA internal link

Requirements

Classical requirements with specified thresholds/**targets**

Pyrotechnics shall be designed not to release space debris larger than 1 mm in their largest dimension into Earth orbit.

Intentional break-up of a spacecraft or launch vehicle orbital element shall not be performed.

A spacecraft or launch vehicle orbital stage operating in Earth orbit shall be designed to guarantee a probability of successful passivation through to the end of life of:
1) At least 0,90
2) At least 0,95, when operating in the LEO protected region in an orbit with a natural orbital decay duration longer than 25 years
3) At least 0,95, when operating in the GEO protected region

Seed requirements i.e. request of quantification/assessment

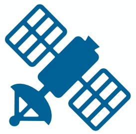
During the design, the developer of a spacecraft operating in near Earth orbit with a recurrent manoeuvre capability shall quantify the operational impact during normal operations due to conjunctions.

The developer of a spacecraft or launch vehicle orbital element injected in near Earth orbit shall quantify:

- the expected number of conjunctions at 10^{-4} and 10^{-6} collision probability threshold,
- the estimated number of collision avoidance manoeuvres triggered thereby on other spacecraft

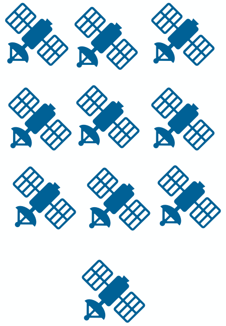
during normal operations and after end of life until re-entry or up to 100 years.

ESSB-ST-U-007 scope: space system type



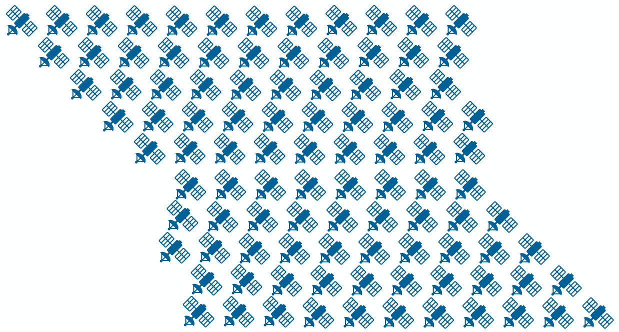
Single spacecraft

Request for collision avoidance capability in GEO and LEO if high or very high risk



Constellation
(≥ 10 spacecraft)

Request for collision avoidance capability in near-Earth orbit



Large constellation
(≥ 100 spacecraft)

System reliability > 0.95

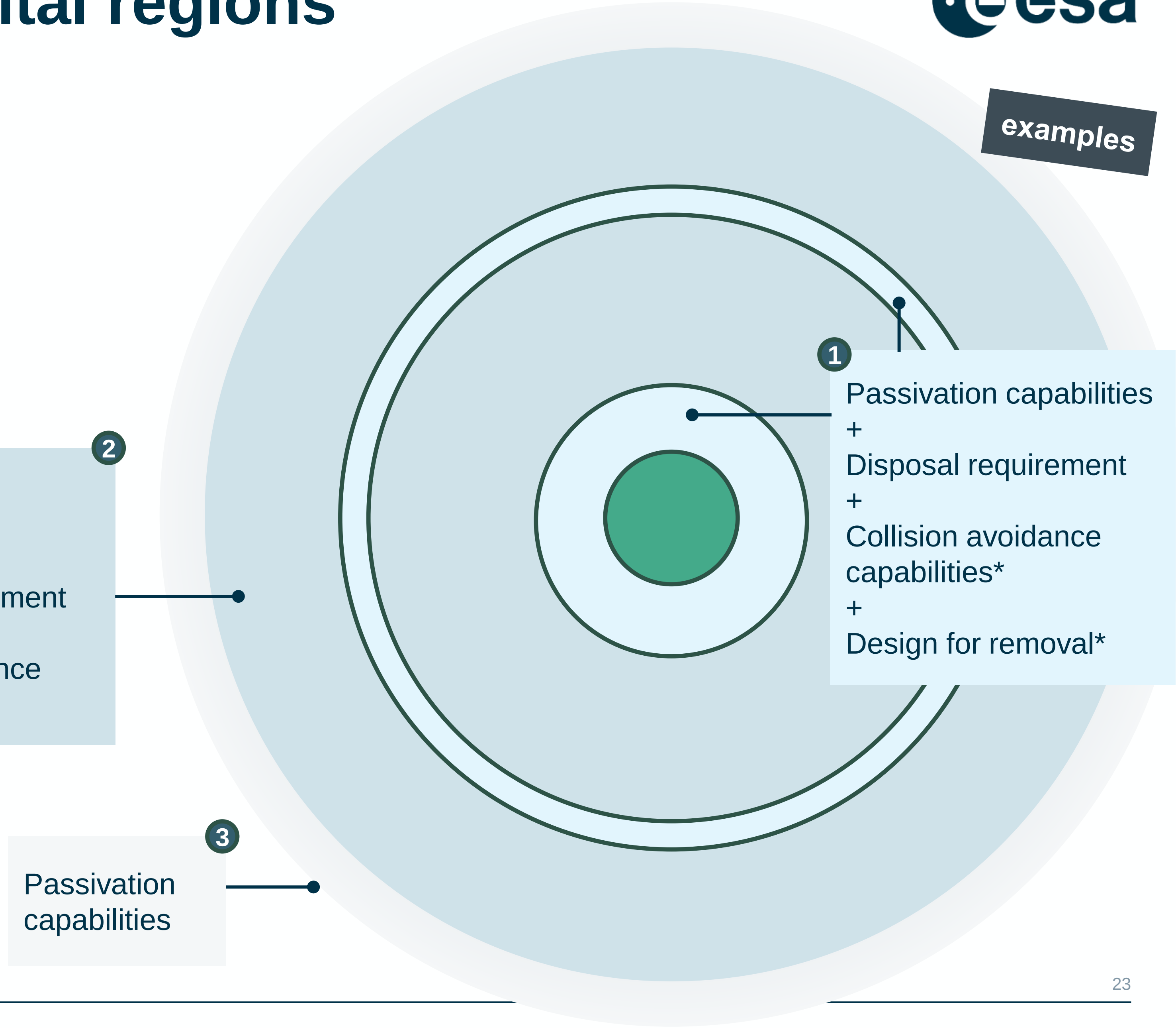
In LEO, disposal below 375 km and injection orbit with natural decay time < 5 years

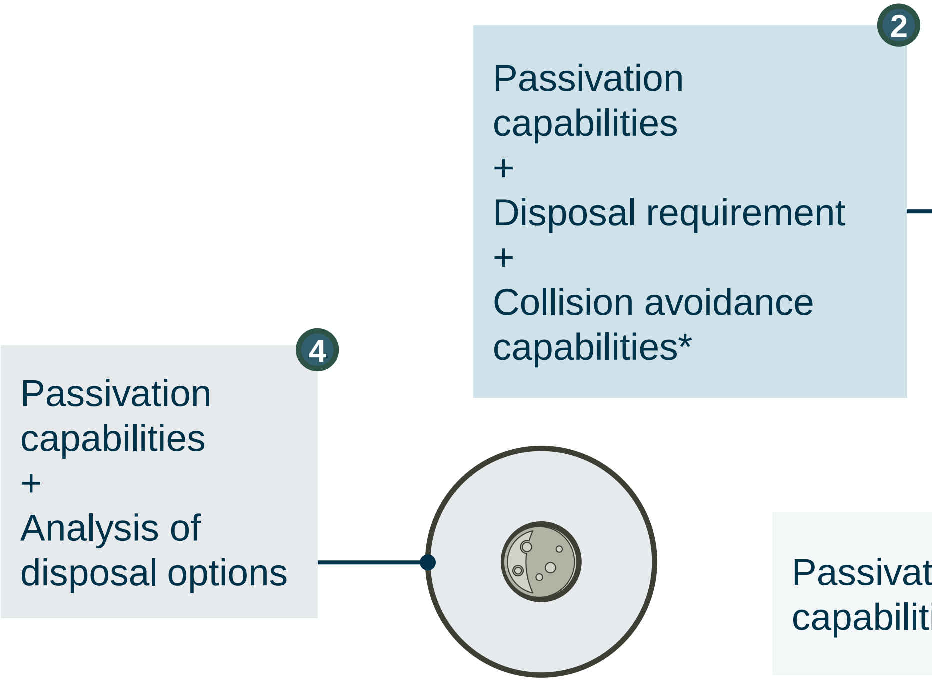
Re-entry casualty risk per spacecraft < $1:10^6$

Launch vehicle
(including elements, and orbital stages)

ESSB-ST-U-007 scope: orbital regions

1. Protected regions (i.e. LEO and GEO)
2. Near-Earth orbits (perigee < 100000 km)
3. Earth orbits (including **Libration Point Orbits**)
4. Lunar orbits (including Libration Point Orbits)





*for objects not at low risk

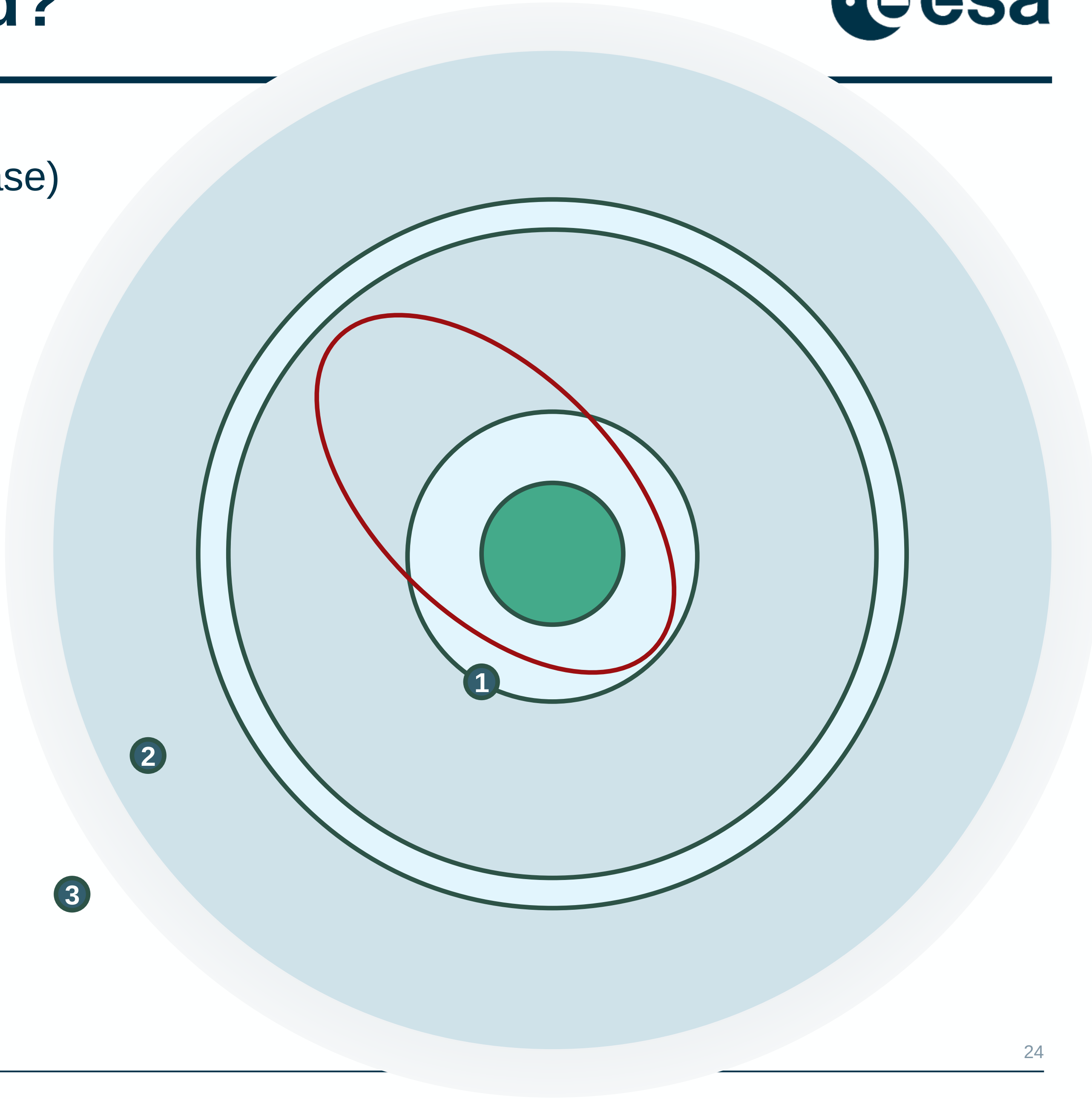
FREQUENTLY ASKED QUESTION

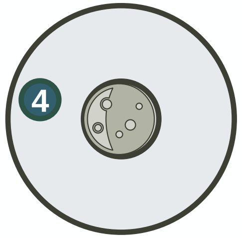
How are GTOs and HEOs treated?

Distinction between **operating** (active and in the region)**,** **crossing** (inactive and in the region), **injected into** (release)

Example

A spacecraft injected into a GTOs and performing a (low-thrust) orbit raising up to its operational slot in GEO is **operating in LEO** for the initial phase of its mission and the corresponding requirements shall be verified





GTO: Geostationary Transfer Orbit | HEO: High Eccentric Orbits

ESSB-ST-U-007 rationale

LIFETIME

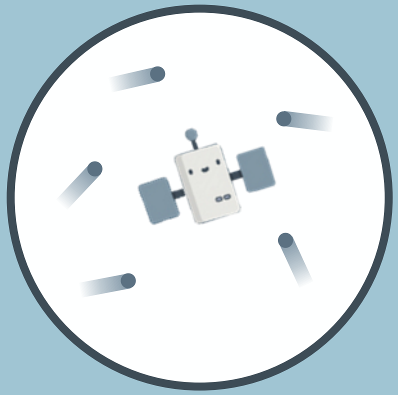
High risk
natural orbital decay duration between 5 and 25 years

Medium risk
natural orbital decay up to 5 years and crossing altitudes above 375 km

Very high risk
natural orbital decay duration longer than 25 years

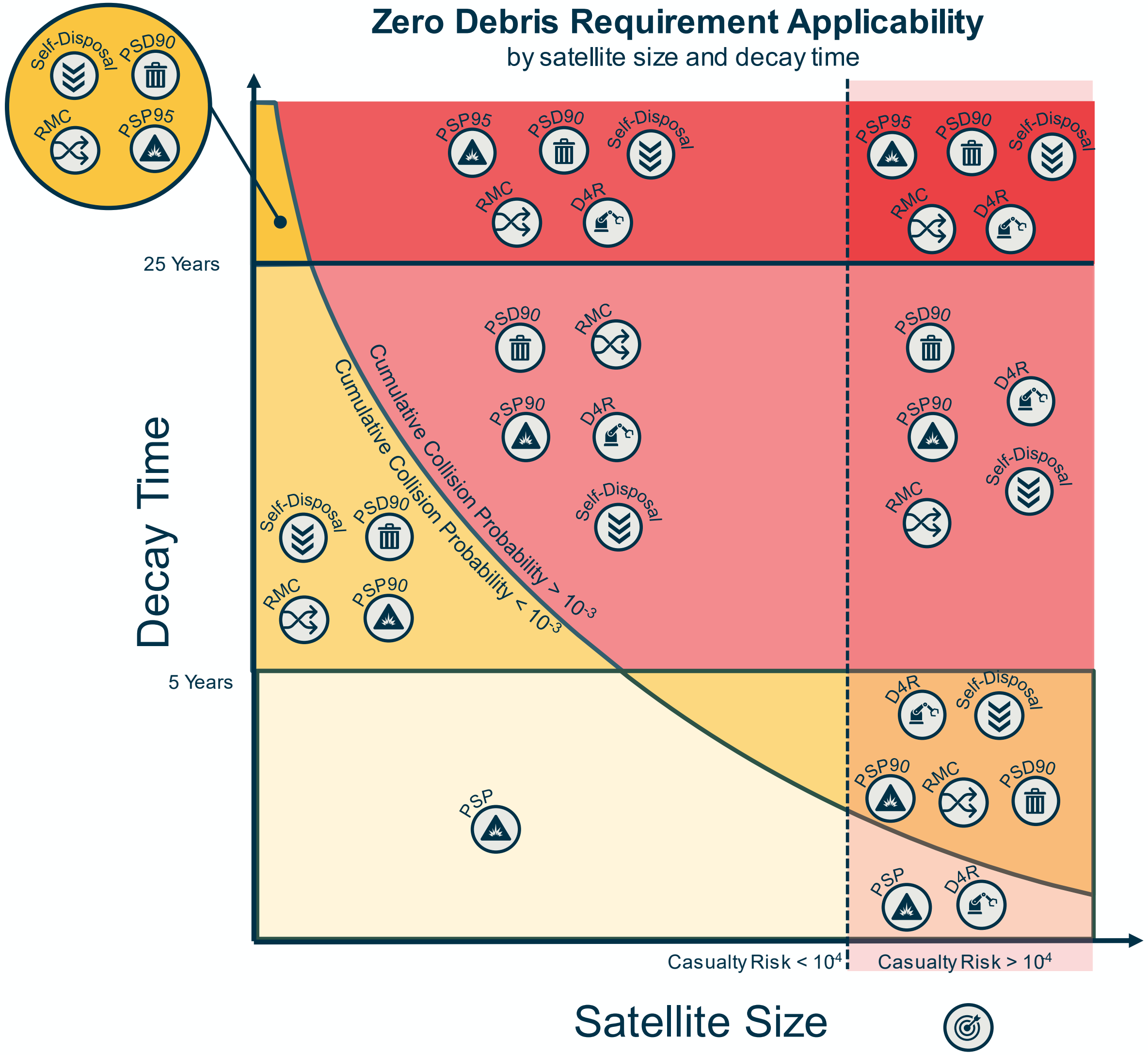
COLLISION PROBABILITY

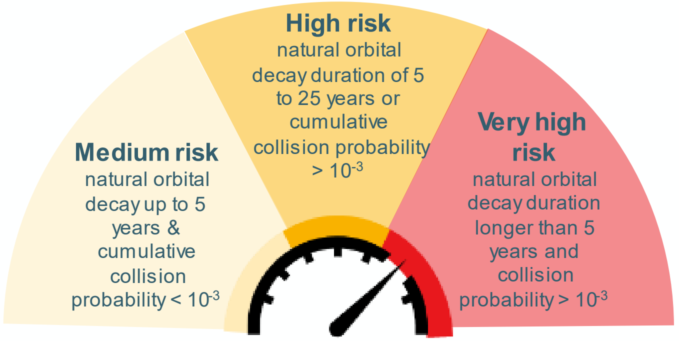
Collision probability with **space debris** objects larger than **1 cm**



A space object in Earth orbit without capability of performing collision avoidance manoeuvres and with a cumulative collision probability with space objects larger than 1 cm above **1 in 1000** is considered **environmentally hazardous**.

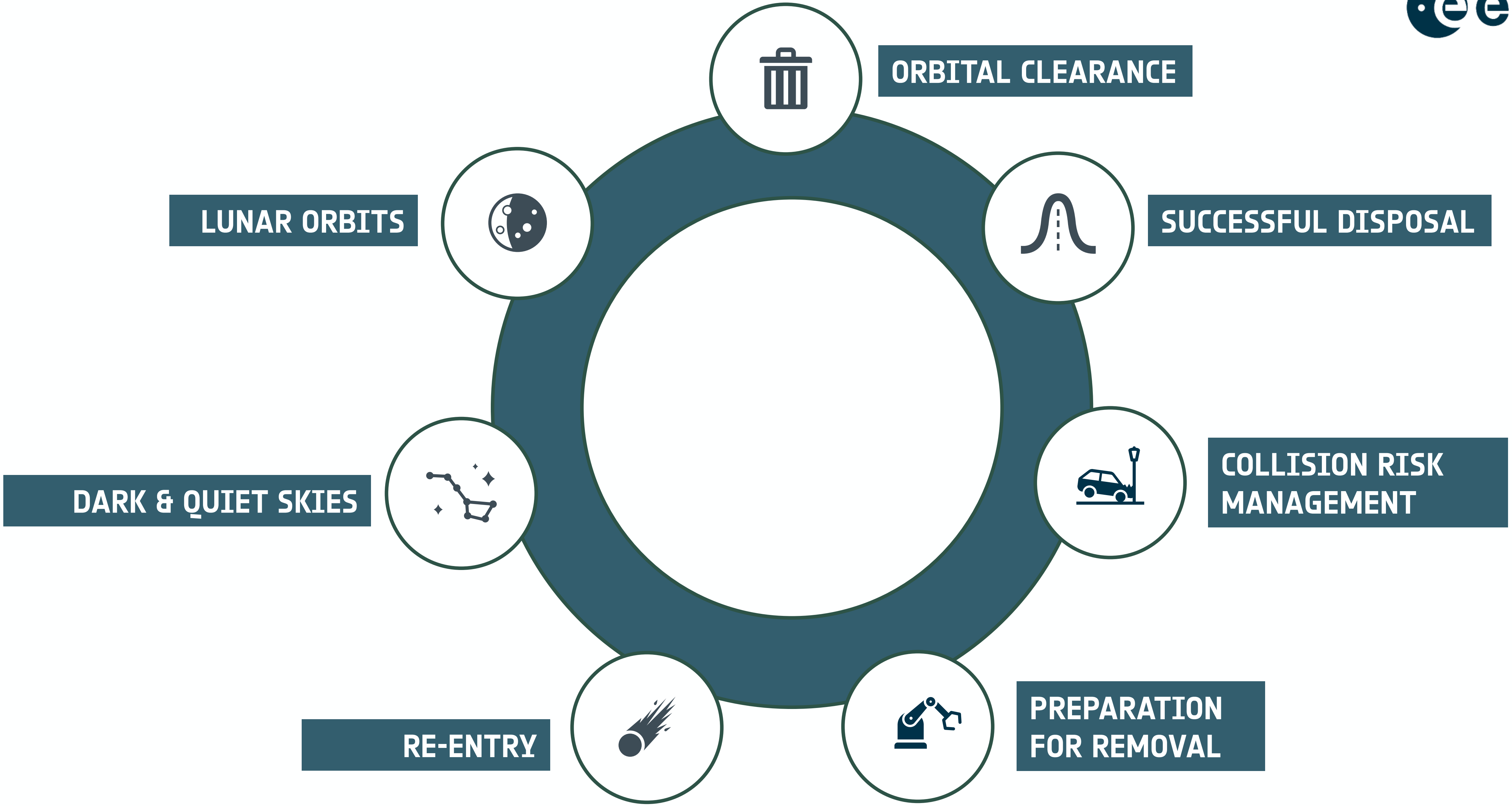
ESSB-ST-U-007 rationale – example for single satellite

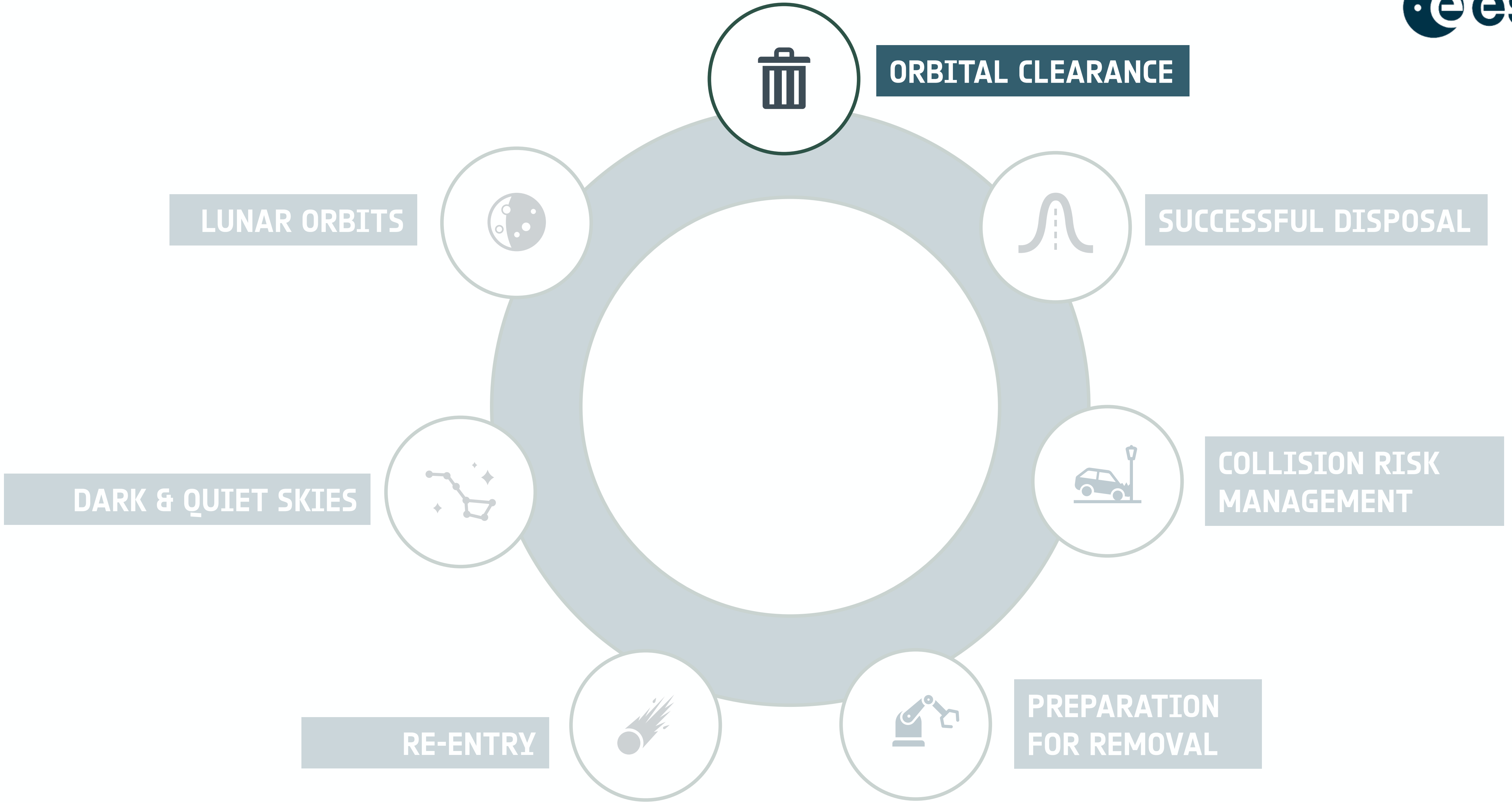




Key

- PSD90 — Probability of Successful Disposal > 90%
- D4D — Design for Demise
- D4R — Design for Removal
- RMC — Recurrent Manoeuvre Capability
- PSPX — Probability of Successful Passivation > X%
- Self-Disposal — Self-Disposal Capability
- Controlled re -entry


ORBITAL CLEARANCE
LUNAR ORBITS
SUCCESSFUL DISPOSAL
DARK & QUIET SKIES
COLLISION RISK MANAGEMENT
RE-ENTRY
PREPARATION FOR REMOVAL


ORBITAL CLEARANCE
SUCCESSFUL DISPOSAL
COLLISION RISK MANAGEMENT
PREPARATION FOR REMOVAL
RE-ENTRY
DARK & QUIET SKIES
LUNAR ORBITS

LEO clearance: lifetime limitation

novelty level

5.4.2.3.a

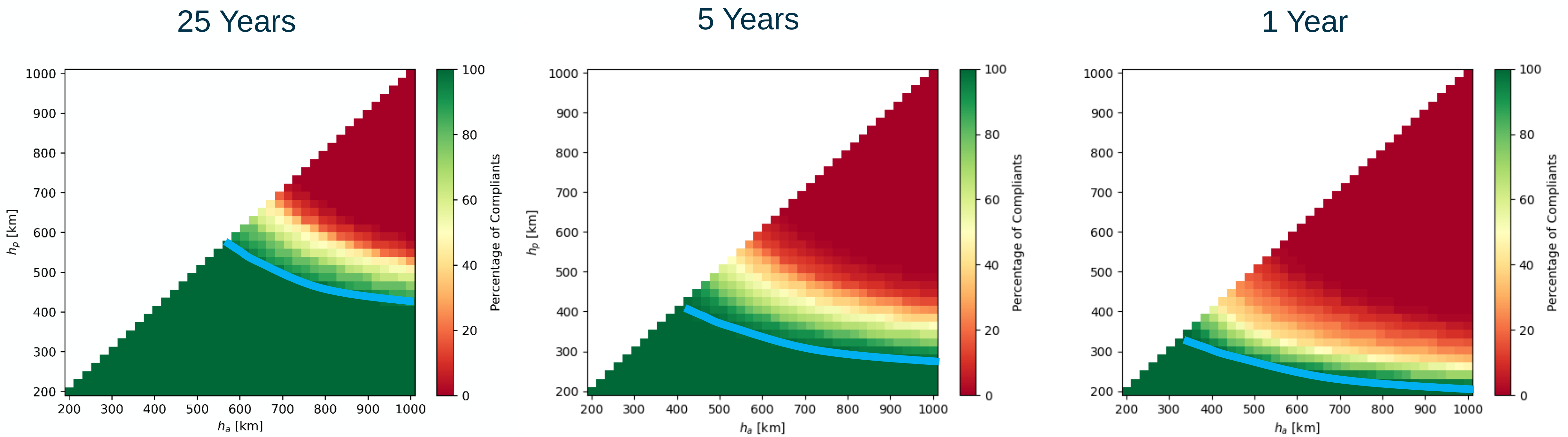
LEO protected region clearance

a. The orbit clearance of a spacecraft or launch vehicle orbital element from the LEO protected region shall satisfy both following conditions:

1) the orbit lifetime is less than 5 years […]

[…]

Requiring a faster passive reentry will **lower the orbital altitude needed for disposal**, which depends on the satellite characteristics



Ballistic coefficient linearly sampled between 10th and 90th percentile of the values seen in LEO | Disposal epoch sampled across solar cycle
Inclination sampled between 0 and 180 degrees, drag coefficient = 2.2, reflectivity coefficient = 1.3

LEO clearance: lifetime limitation

novelty level

5.4.2.3.a

LEO protected region clearance

a. The orbit clearance of a spacecraft or launch vehicle orbital element from the LEO protected region shall satisfy both following conditions:

   1) the orbit lifetime is less than 5 years […]

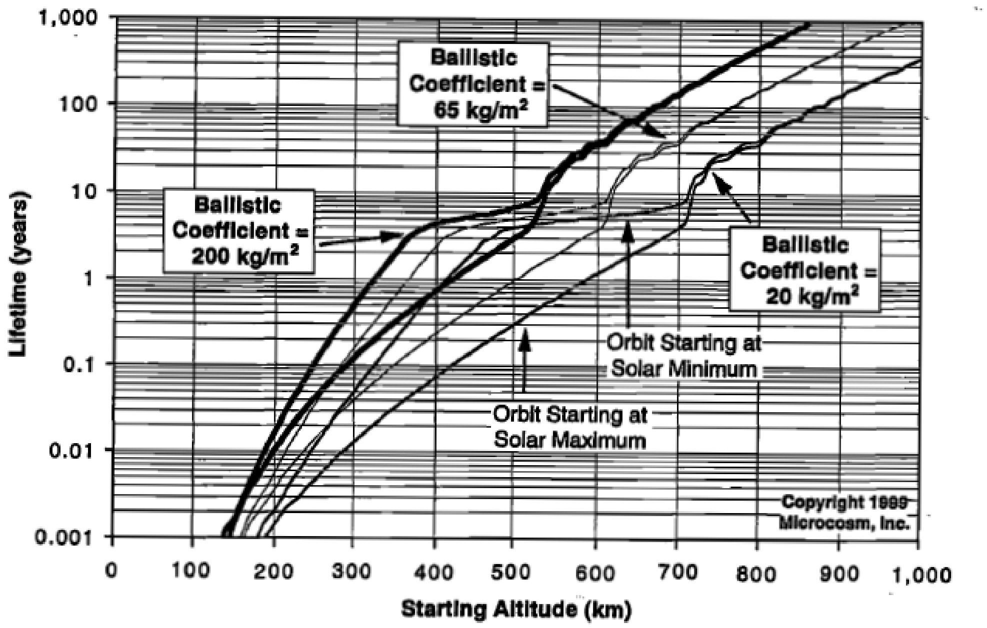
[…]

6.2

Verification and validation requirements

f) The orbit lifetime of a space object shall be assessed **probabilistically**, including at least the variability by moving the starting point through a **full solar cycle** […]

g) For the orbit lifetime assessment, […] the **50th percentile** for orbit with eccentricity below 0,3 at end of life […]



Larson & Wertz, SMAD, 2005

How to compute

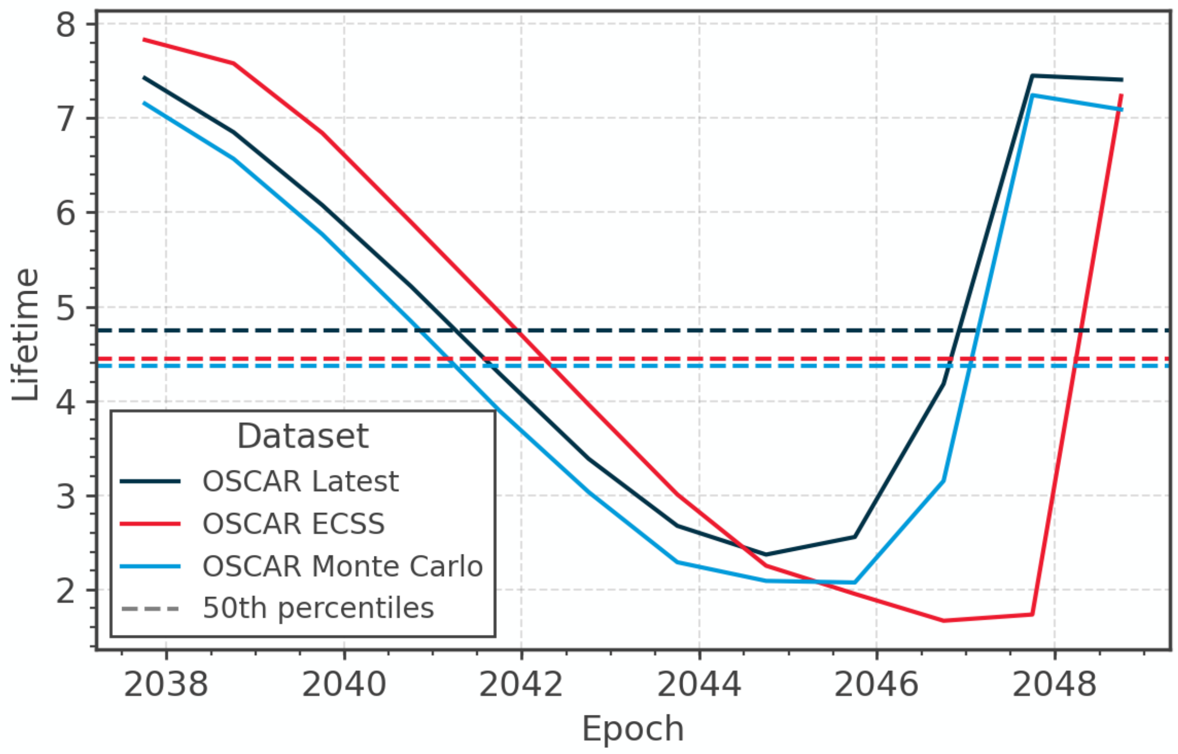
1. Select the end of operation epoch sampling from the solar cycle (yearly steps)
2. Consider additional uncertainties, if relevant (some guidelines in ESSB-HB-U-002)
3. Propagate the trajectory and obtain the distribution of orbital lifetimes
4. Compare the 50th-percentile to the 5-year limit
5. Use multiple solar activity models to increase confidence in the results

I am going to launch in YYYY and the lifetime is > 5 years

Example

Launch in 2039 for a mission without propulsion capabilities

What matters is the median of the distribution, so it is accepted that the predicted natural decay for the selected launch epoch is expected to be > 5 years



LEO clearance: collision probability criterion

novelty level

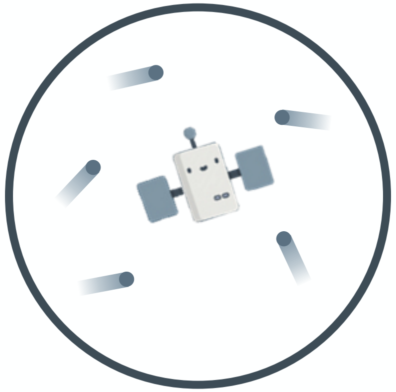
5.4.2.3.a

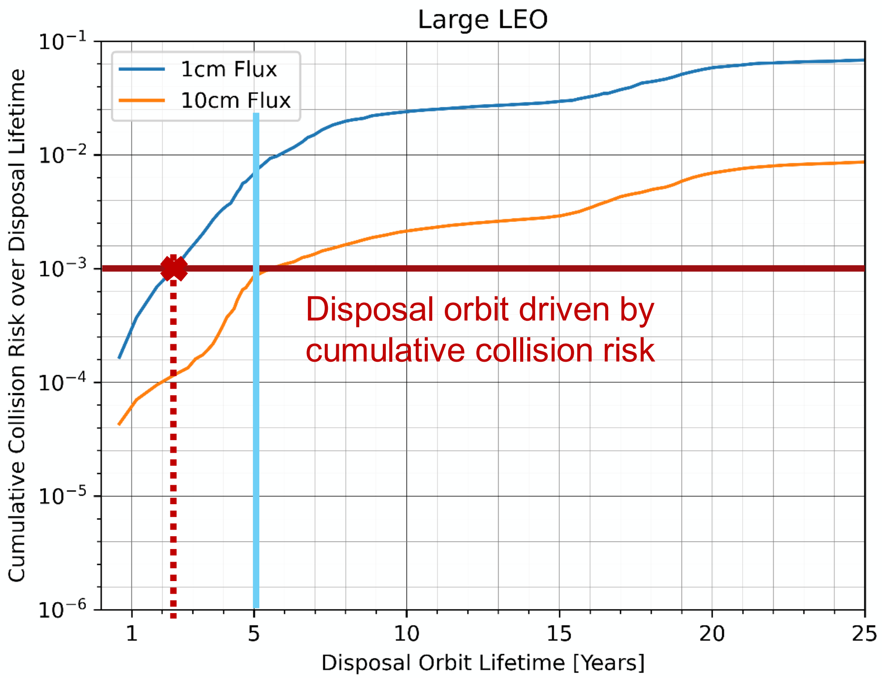
LEO protected region clearance

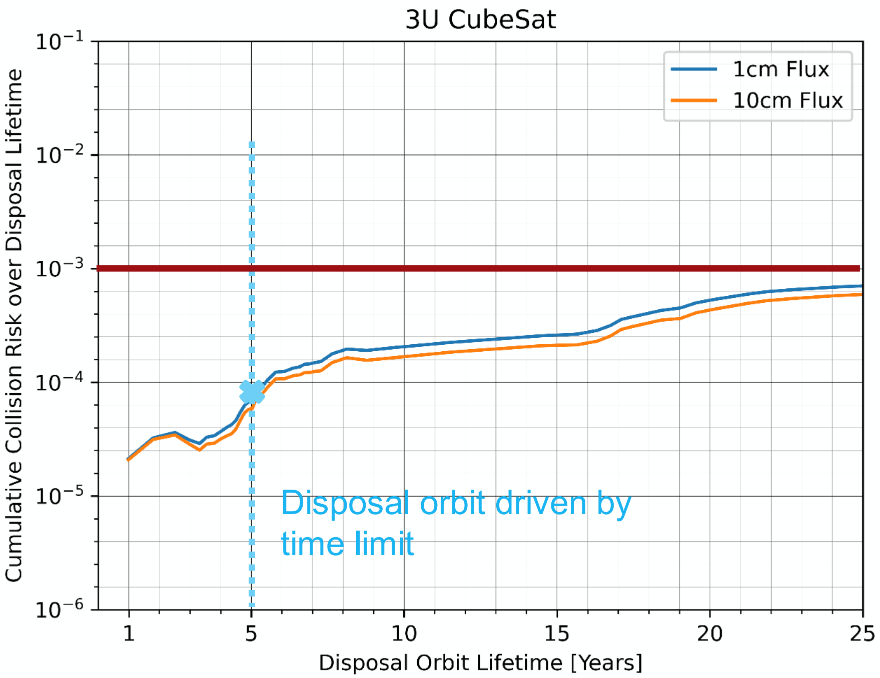
a. The orbit clearance of a spacecraft or launch vehicle orbital element from the LEO protected region shall satisfy both following conditions:

1) the orbit lifetime is less than 5 years […]
2) the cumulative collision probability from its end of life until re-entry with space objects larger than 1 cm is below 10^{-3}

[…]







LEO clearance: collision probability criterion

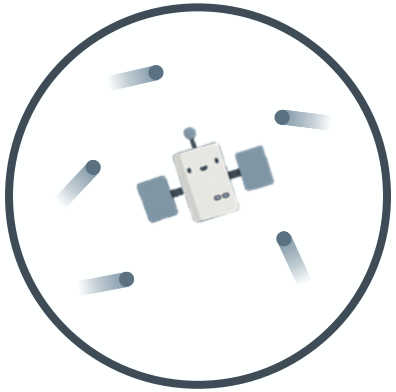
5.4.2.3.a

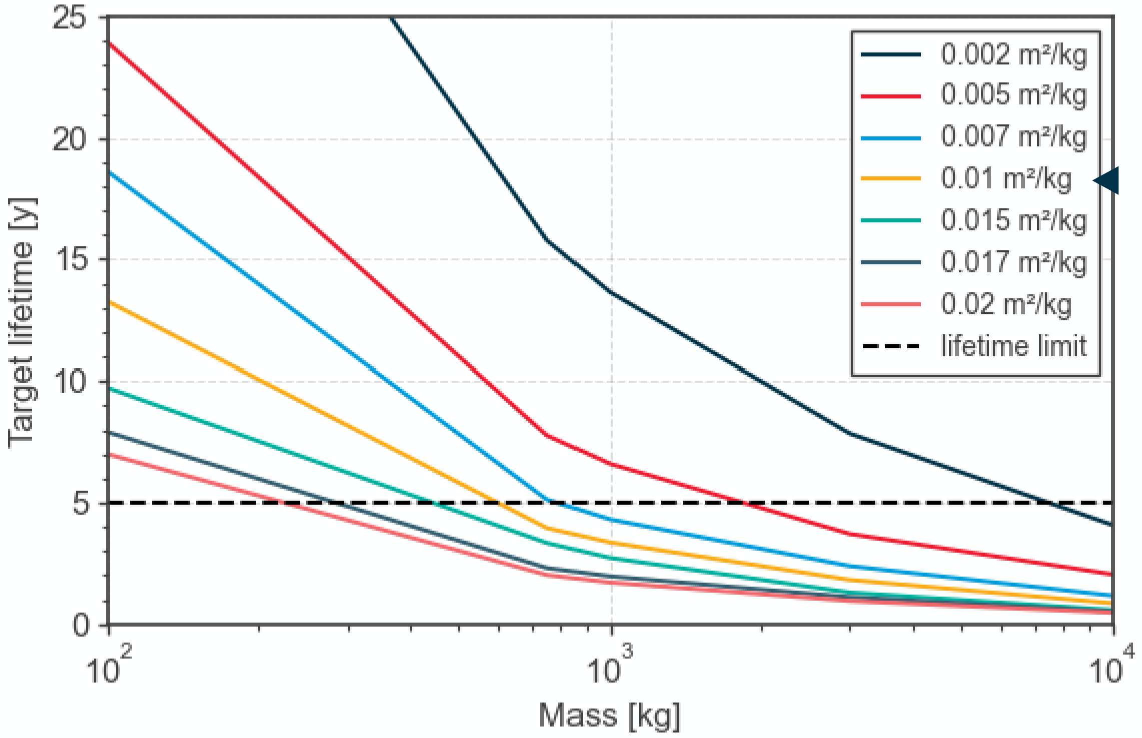
LEO protected region clearance

a. The orbit clearance of a spacecraft or launch vehicle orbital element from the LEO protected region shall satisfy both following conditions:

1) the orbit lifetime is less than 5 years […]
2) the cumulative collision probability from its end of life until re-entry with space objects larger than 1 cm is below 10^{-3}

[…]





Example

Mean value for active satellites (non-constellation)

Threshold reached at ~ 600 kg

Much smaller satellites (e.g. CubeSats) can refer to the handbook and do not need to perform a specific analysis

HANDBOOK

HANDBOOK

novelty level

LEO clearance: collision probability criterion

5.4.2.3.a

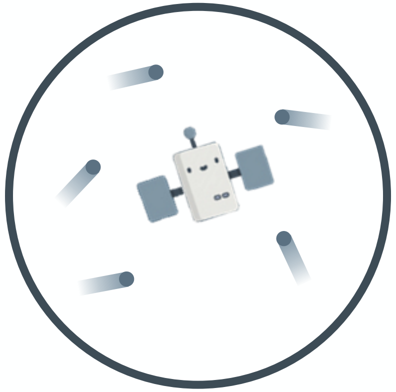
LEO protected region clearance

a. The orbit clearance of a spacecraft or launch vehicle orbital element from the LEO protected region shall satisfy both following conditions:

1) the orbit lifetime is less than 5 years […]

2) the cumulative collision probability from its end of life until re-entry with space objects larger than 1 cm is below 10^{-3}

[…]



Included also in ECSS-U-AS-10C Rev.2 (2024)

How to compute

1. Use **space debris population** only, with objects ≥ **1 cm**
2. Use **calibrated** population (no prediction) (e.g. from ESA's MASTER)
3. Include **solar panels** (i.e. everything for which it is not demonstrated that an impact with a 1 cm object does not result in debris generation) and exclude appendages for which debris generation is not expected (e.g. wire antenna, foils)
4. Compute on a range of epochs or select epoch such that the decay duration is the closest to the **median** computed in the lifetime assessment

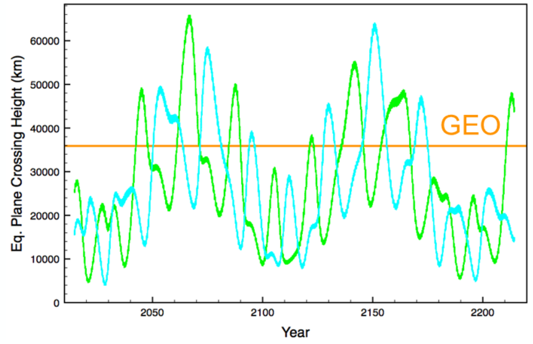
Environment conditions frozen at the **Space Debris Mitigation Plan Approval** (usually SRR)

General Earth orbit clearance

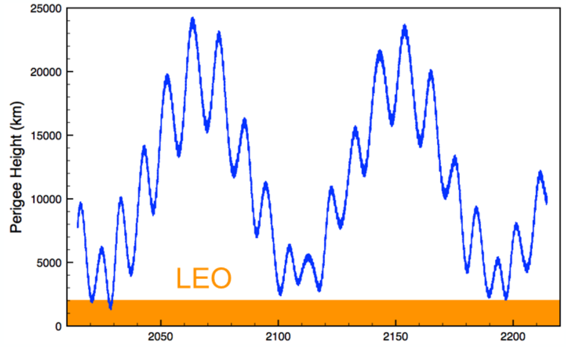
5.4.2.1.a

General Earth orbit clearance
The orbit clearance of a spacecraft or a launch vehicle orbital element in Earth orbit at its end of life shall be achieved by one of the following means, in order of preference:

1. Immediate Earth atmospheric re-entry after end of mission
2. Disposal in an orbit with a natural orbital decay that satisfies the orbit clearance requirements for the LEO protected region
3. If not operating in, nor crossing, the LEO protected region, disposal in a **graveyard orbit** that satisfies both following conditions:
   a. Long-term perturbation forces **do not** cause it to **cross** the **protected regions** nor the **operational orbits of known constellations** that operate at a fixed operational altitude, within 100 years after its end of life
   b. Its **cumulative collision probability** with space objects larger than 1 cm is below 10^{-3} for up to 100 years after the end of life



GEO and LEO crossings for the original INTEGRAL orbit (before manoeuvre in 2015)



5.4.2.3.b

LEO protected region clearance
[…]
The orbit clearance of a spacecraft or launch vehicle orbital element not operating in the LEO protected region, but **crossing the LEO protected region** after its end of life shall satisfy the following conditions:
1. the total orbit lifetime after end of life is less than 100 years
2. the cumulative collision probability from end of life until re-entry with space objects larger than 1 cm is below 10^{-3}
3. the orbit lifetime starting from the epoch of first intersection with the LEO protected region is less than 25 years
[…]

General Earth orbit clearance – example: MEO

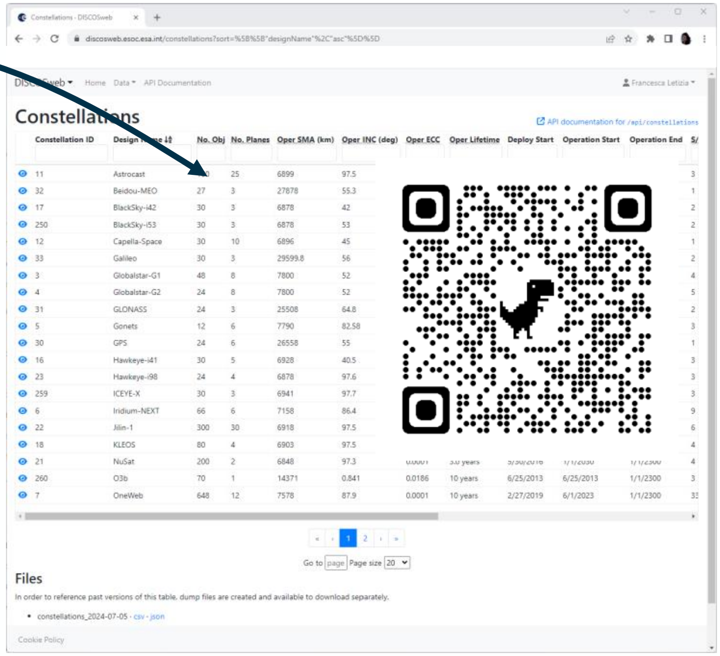
5.4.2.1.a

General Earth orbit clearance
The orbit clearance of a spacecraft or a launch vehicle orbital element in Earth orbit at its end of life shall be achieved by one of the following means, in order of preference:

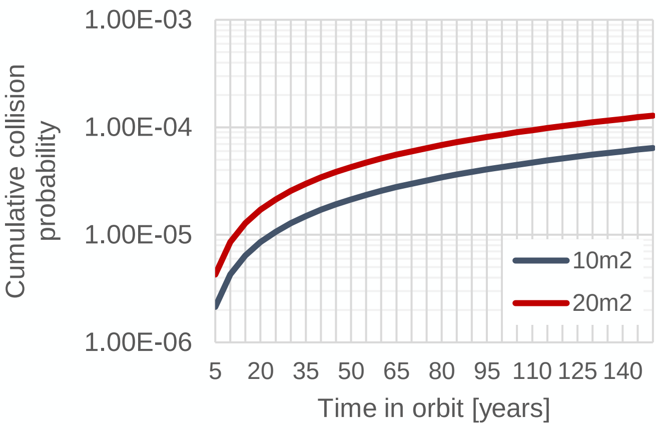
1. Immediate Earth atmospheric re-entry after end of mission
2. Disposal in an orbit with a natural orbital decay that satisfies the orbit clearance requirements for the LEO protected region
3. If not operating in, nor crossing, the LEO protected region, disposal in a **graveyard orbit** that satisfies both following conditions:
    a. Long-term perturbation forces **do not** cause it to **cross** the **protected regions** nor the **operational orbits of known constellations** that operate at a fixed operational altitude, within 100 years after its end of life
    b. Its **cumulative collision probability** with space objects larger than 1 cm is below 10^{-3} for up to 100 years after the end of life

Data for the analysis in (a) available through DISCOSweb

https://discosweb.esoc.esa.int/constellations



(b) condition not expected to be the driving one

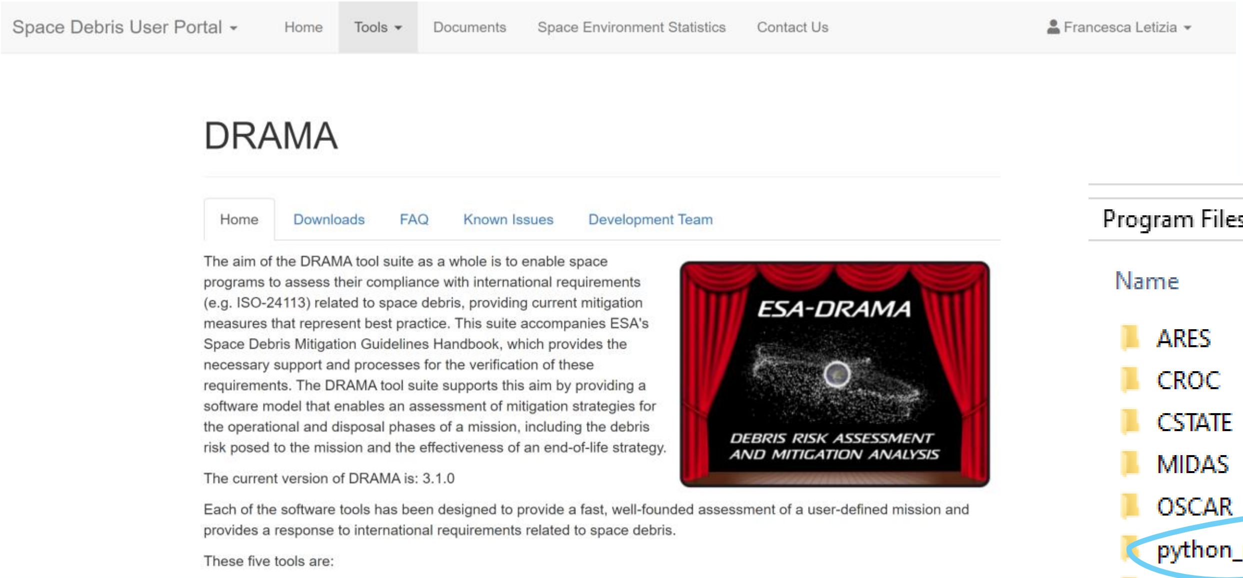


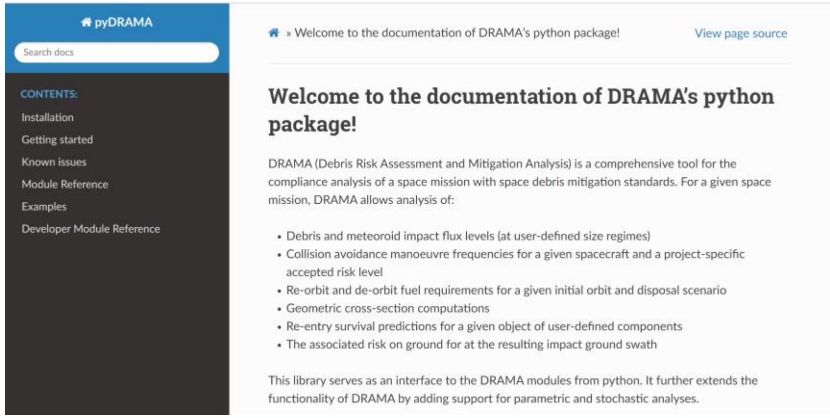
Example of cumulative collision probability assessment in a Galileo-like orbit for two values of cross-sectional area (MASTER reference population)

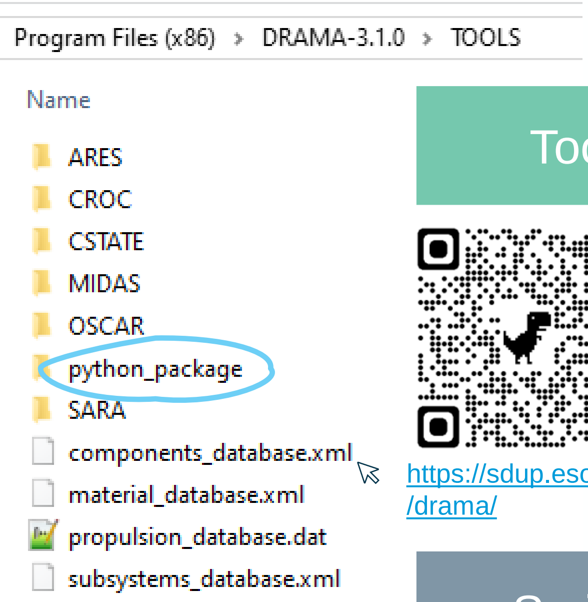
Orbital clearance: how to

Tools available:
e.g. ESA's DRAMA already distributed with a **python wrapper** to facilitate the execution of probabilistic assessments

Intention to make available some basic scripts while the analysis is not available in the DRAMA GUI





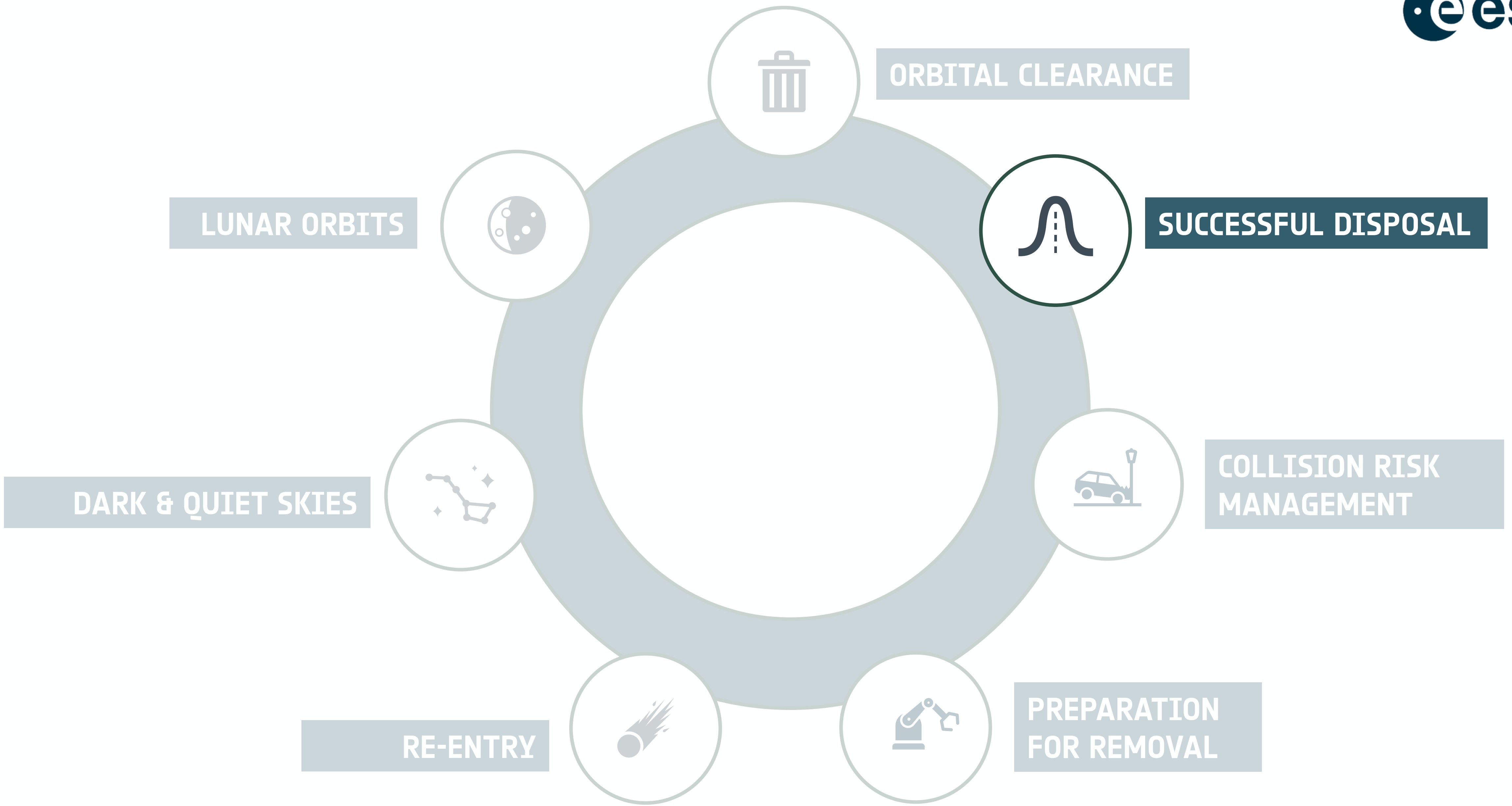


Tools

https://sdup.esoc.esa.int/drama/

Scripts

https://debris-forum.sdo.esoc.esa.int/


ORBITAL CLEARANCE
SUCCESSFUL DISPOSAL
COLLISION RISK MANAGEMENT
PREPARATION FOR REMOVAL
RE-ENTRY
DARK & QUIET SKIES
LUNAR ORBITS

novelty level

Probability of successful disposal

5.4.1.1.a

The overall probability of successful disposal of a spacecraft or launch vehicle orbital stage in Earth orbit shall be kept above **0,9** through to end of life, including the contributions from system reliability **and** from collisions with space debris or meteoroids preventing the successful disposal.

Probability of successful disposal

novelty level

De-orbit + Passivation = Disposal

5.4.1.1.a

The overall probability of successful disposal of a spacecraft or launch vehicle orbital stage in Earth orbit shall be kept above **0,9** through to end of life, including the contributions from system reliability **and** from collisions with space debris or meteoroids preventing the successful disposal.

5.3.2.2.a

A spacecraft or launch vehicle orbital stage operating in Earth orbit shall include **passivation capabilities**.

5.3.2.2.c

A spacecraft or launch vehicle orbital stage operating in Earth orbit shall be designed to guarantee a probability of **successful passivation** through to the end of life of:
1) At least 0,90
2) At least 0,95, when operating in the LEO protected region in an orbit with a natural orbital decay duration longer than 25 years

What's new

Passivation capabilities now required also for spacecraft performing controlled re-entry

Passivation success rate with an explicit figure

How to handle the case of controlled re-entry?

We are not asking to demonstrate 90% probability of successful passivation in the contingency case.

Demonstrate that the 90% is achievable in the nominal case e.g. if the spacecraft has a nominal lifetime of 10 years, it should be verified that the components that would be used for passivation have a reliability compatible with the 90% value after 10 years

5.3.2.2.a

A spacecraft or launch vehicle orbital stage operating in Earth orbit shall include **passivation capabilities**.

5.3.2.2.b

A spacecraft or launch vehicle orbital stage operating in Earth orbit shall be **passivated** before the end of life **unless a successful controlled re-entry** is performed.

5.3.2.2.c

A spacecraft or launch vehicle orbital stage operating in Earth orbit shall be designed to guarantee a probability of **successful passivation** through to the end of life of:
1) At least 0,90
2) At least 0,95, when operating in the LEO protected region in an orbit with a natural orbital decay duration longer than 25 years

Probability of successful disposal

novelty level

Calculation methodology (reliability contribution):

- Identify all the equipment in charge of the disposal functional chain
  → **list of components**
- Identify all the equipment whose failure could prevent the successful disposal (through failure propagation, for instance)
  → **list of components**
- Build the Reliability Block Diagram (RBD)
  → **functional logic** (series / parallel configuration)
- Define the applicable **timeline** for the disposal probability
- Use the failure rate data for the different equipment to compute the disposal probability.

How to obtain it? (in order of preference)

1. Manufacturers' data
2. Physics of failures (FIDES, etc.) — Training by ESA RAMS experts can be organised
3. Reliability data handbooks
4. In-flight data (only applicable if the number of data is sufficient) — Important for developers & operators to collect data on behaviour in orbit
5. Similarity (scaled-down to the mission)

Probability of successful disposal

novelty level

De-orbit + Passivation = Disposal

5.4.1.1.a

The overall probability of successful disposal of a spacecraft or launch vehicle orbital stage in Earth orbit shall be kept above **0,9** through to end of life, including the contributions from system reliability **and** from collisions with space debris or meteoroids preventing the successful disposal.

Included also in ECSS-U-AS-10C Rev.2 (2024)

Starting point for the analysis: **Guideline on Small Debris Risk Assessment** (MIDAS)

Probability of successful disposal

novelty level

5.4.1.1.a

De-orbit + Passivation = Disposal

The overall probability of successful disposal of a spacecraft or launch vehicle orbital stage in Earth orbit shall be kept above **0,9** through to end of life, including the contributions from system reliability **and** from collisions with space debris or meteoroids preventing the successful disposal.

Included also in ECSS-U-AS-10C Rev.2 (2024)

1. Identify relevant mission **phase**, **trajectory** conditions, and **pointing** scenario
2. Define the **space system design**
3. Identify **critical components** for the disposal implementation
4. Identify **ballistic limit equation** and **failure model** (e.g. perforation) for the critical components
5. Determine the **surface at risk** for each critical component
6. Determine the expected number of collisions causing failure per component
7. Determine the system level **Probability of No Failure**

Starting point for the analysis: **Guideline on Small Debris Risk Assessment** (MIDAS)

Probability of successful disposal

novelty level

De-orbit + Passivation = Disposal

5.4.1.1.a

The overall probability of successful disposal of a spacecraft or launch vehicle orbital stage in Earth orbit shall be kept above **0,9** through to end of life, including the contributions from system reliability **and** from collisions with space debris or meteoroids preventing the successful disposal.

Early phases (0-A)	**Definition phases** (B-C)	**Later phases** (C onwards)
Conservative assessment based on impact rate with 1 cm objects Indication of the allocation for reliability aspects	Assessment with simplified models (e.g. with DRAMA/MIDAS, but also other tools available) that consider the selected shielding and component placement	If needed, assessment with refined 3D models (e.g. ESABASE2) + updates when a re-estimation of the disposal probability is requested

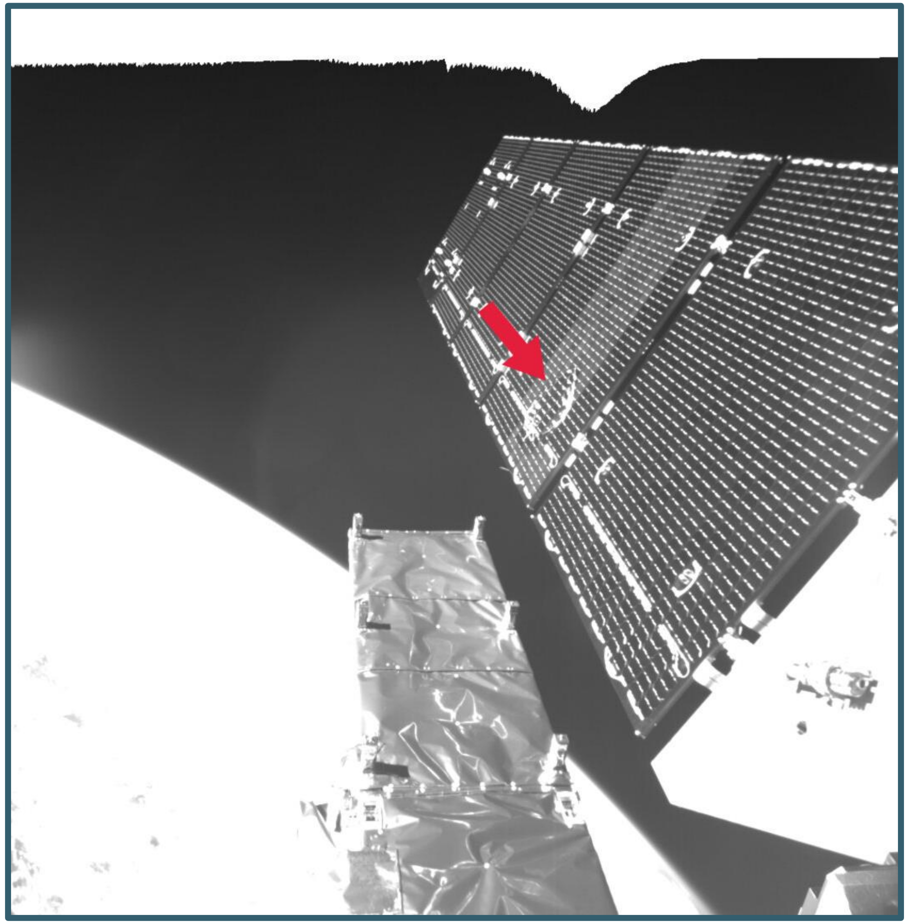
<u>Example</u>
if the probability of impacts with 1 cm objects over the operational lifetime is 2% (typical value for medium/large satellite in SSO) and the probability of successful disposal requirement is 90%, then the minimum reliability of the disposal items and functions needed for compliance is 91,84%

SSO: Sun Synchronous Orbits

Vulnerability assessment

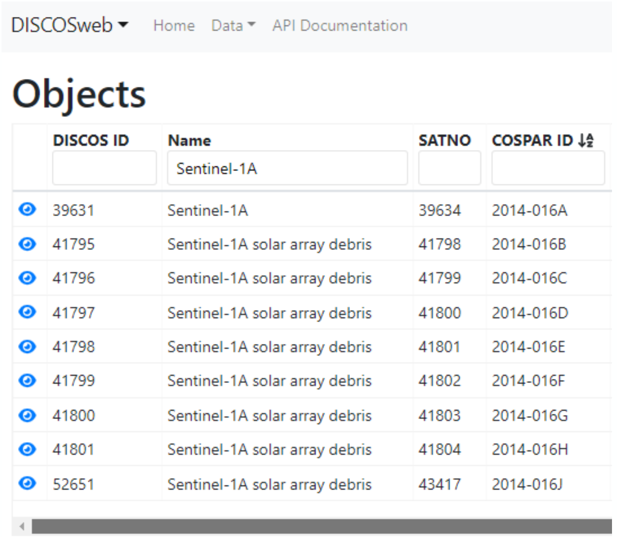
Damage assessment

H. Krag et al, Acta Astronautica, Vol. 137, 2017



Impact on Sentinel-1A's solar panel (2016)

Debris generation



DISCOSweb Home Data API Documentation

Objects

DISCOS ID	Name	SATNO	COSPAR ID
	Sentinel-1A		
39631	Sentinel-1A	39634	2014-016A
41795	Sentinel-1A solar array debris	41798	2014-016B
41796	Sentinel-1A solar array debris	41799	2014-016C
41797	Sentinel-1A solar array debris	41800	2014-016D
41798	Sentinel-1A solar array debris	41801	2014-016E
41799	Sentinel-1A solar array debris	41802	2014-016F
41800	Sentinel-1A solar array debris	41803	2014-016G
41801	Sentinel-1A solar array debris	41804	2014-016H
52651	Sentinel-1A solar array debris	43417	2014-016J

Vulnerability assessment

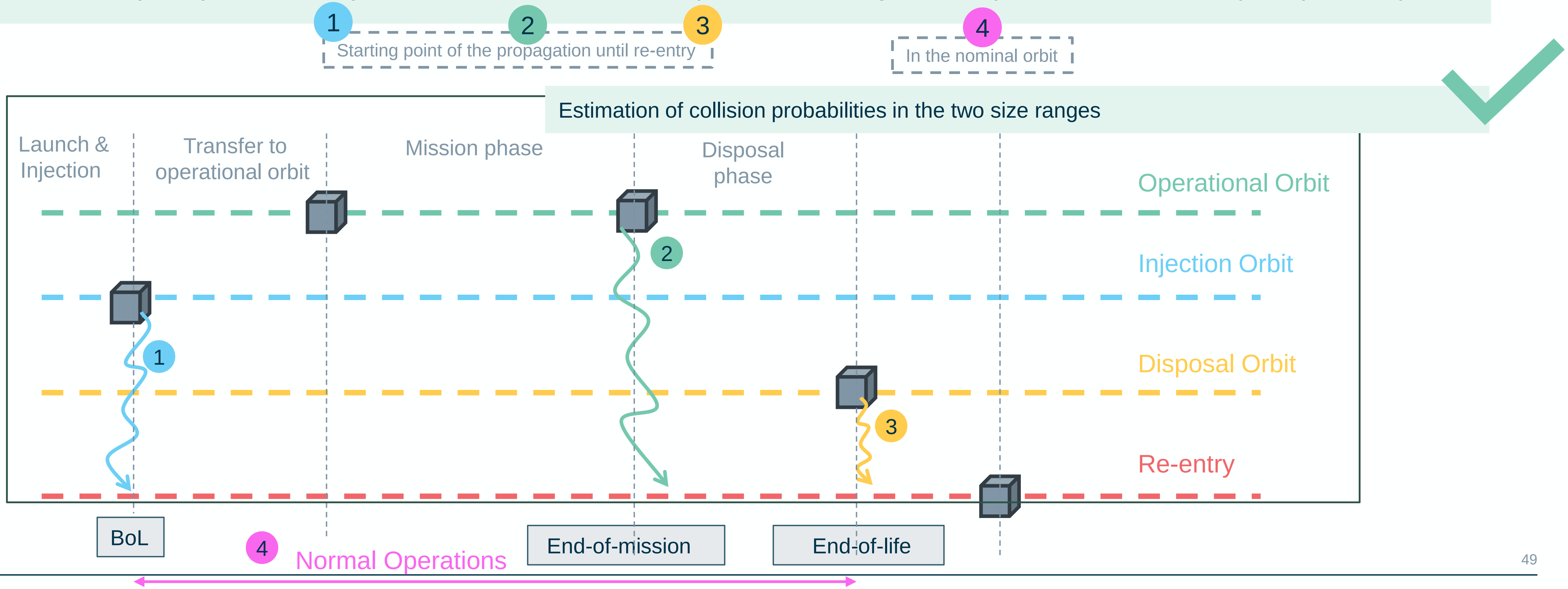
novelty level

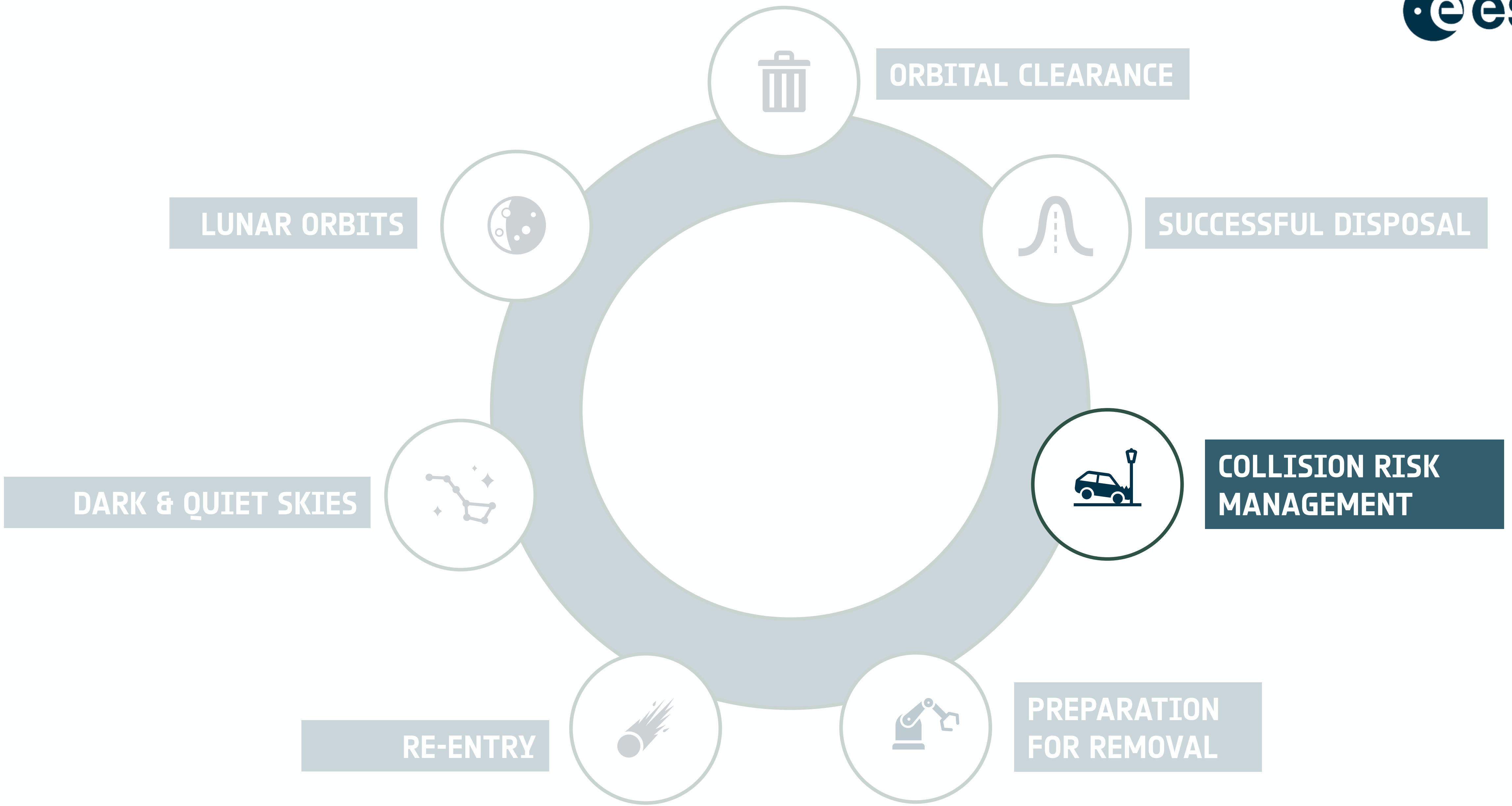
5.3.3.1

Collision risk assessment during design

The developer of a spacecraft or launch vehicle orbital element operating in Earth orbit shall quantify the probability that space debris or meteoroid impact causes the spacecraft or launch vehicle orbital element to break-up, including:

1. Impacts with space debris and meteoroids larger than 1 mm and smaller than 1 cm
2. Impacts with space debris and meteoroids larger than 1 cm
3. A free drift trajectory after orbit injection, end of mission, and disposal, and during normal operations, until re-entry or up to 100 years

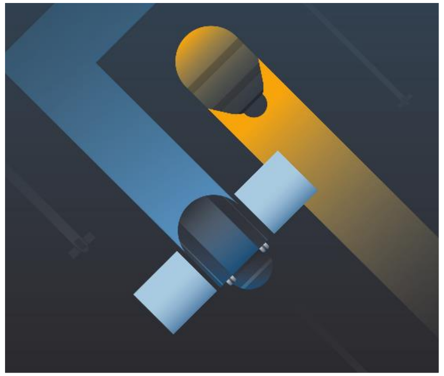



ORBITAL CLEARANCE
SUCCESSFUL DISPOSAL
COLLISION RISK MANAGEMENT
PREPARATION FOR REMOVAL
RE-ENTRY
DARK & QUIET SKIES
LUNAR ORBITS

Collision risk management

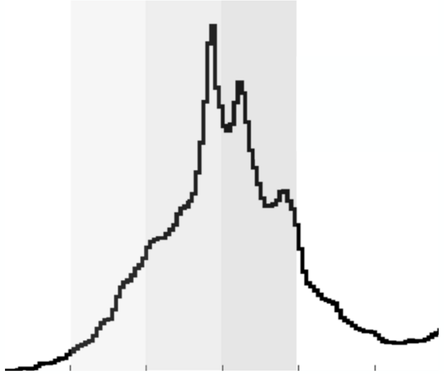
Not having manoeuvre capabilities does not mean that nothing can be done

Manoeuvre capabilities



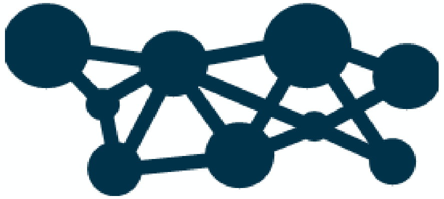
- Reaction threshold
- CAM size
- Timeliness of the reaction

Characterise risk



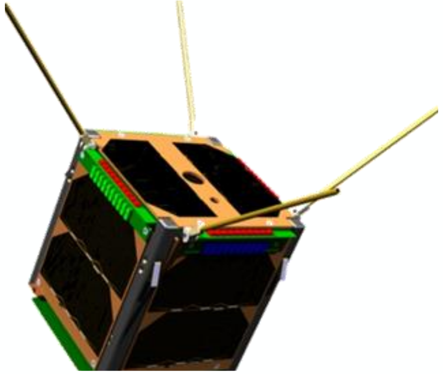
- Assess vulnerability to impacts
- Assess expected number of conjunctions

Ease interactions



- Procedure for contact
- Ephemerides available for distribution using standard formats

Ensure trackability



- Engage with SST data provider
- Facilitate identification

Image credits: © LEDSAT team

CAM: Collision Avoidance Manoeuvre | SST: Space Surveillance and Tracking

Collision risk management

novelty level

5.3.3.2.d

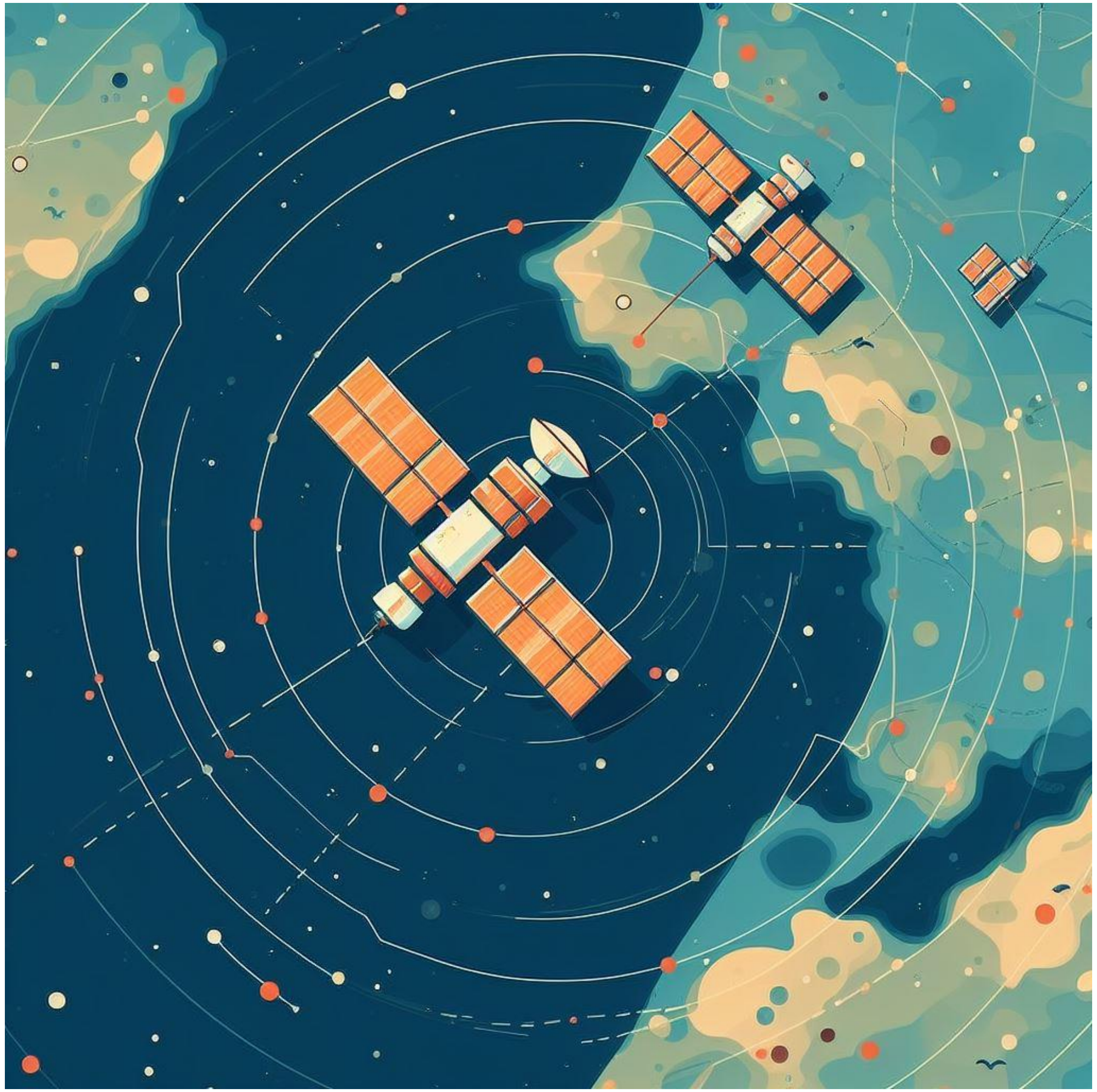
During the *design*, the developer of a spacecraft operating in near Earth orbit with a recurrent manoeuvre capability shall quantify the **operational impact** during normal operations due to conjunctions.

5.3.3.2.e

The developer of a spacecraft or launch vehicle orbital element injected into near Earth orbit shall quantify, during normal operations and after end of life until re-entry or up to 100 years:
1) The **expected number of conjunctions** at 10^{-4} and 10^{-6} collision probability threshold, and
2) The **estimated number of collision avoidance manoeuvres** triggered thereby on other spacecrafts

5.3.3.3.d

The operator of a spacecraft operating in near Earth orbit with a recurrent manoeuvre capability shall perform the assessment of:
1) The **resources allocation** for the acceptable collision probability for individual conjunctions and its impact on the mission *design* […]



How do we estimate the impact on other spacecrafts?

FREQUENTLY ASKED QUESTION

5.3.3.2.e

The developer of a spacecraft or launch vehicle orbital element injected into near Earth orbit shall quantify, during normal operations and after end of life until re-entry or up to 100 years:
1) The expected number of conjunctions at 10^{-4} and 10^{-6} collision probability threshold, and
2) **The estimated number of collision avoidance manoeuvres triggered thereby on other spacecrafts**

Options (not exclusive)
1: Use own data from **past operations**
2: Simulations

Minimal workflow:

1. Conjunction analysis — Perform classical analysis with DRAMA/ARES to extract the number of expected conjunctions above a certain threshold

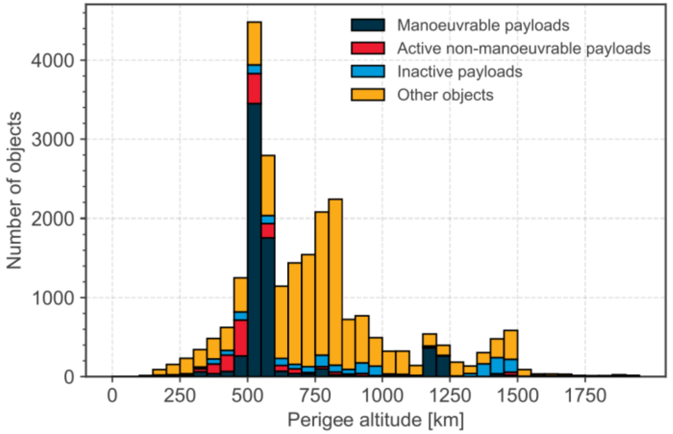
2. Info on other spacecrafts — Retrieve the number/share of spacecraft vs total catalogued population

3. Combine — Use the share from the point 2 to scale the results obtained in 1.

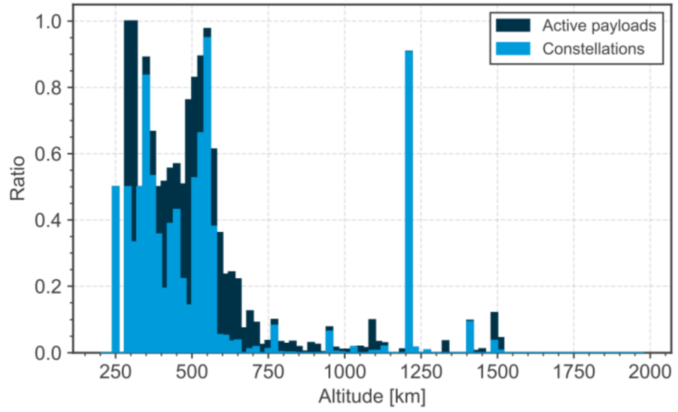
2

Information available from ESA's Space Environment Report

https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

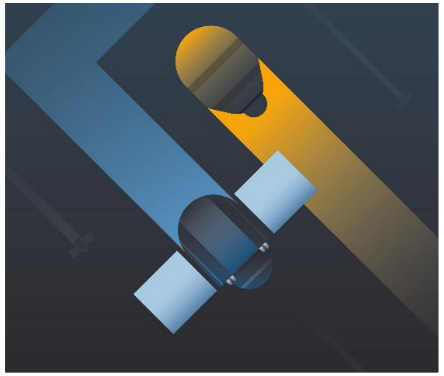


Active payloads to catalogued objects: destination orbits



Collision risk management

Manoeuvre capabilities



- Reaction threshold
- CAM size
- Timeliness of the reaction

5.3.3.2.c

A spacecraft operating in near Earth orbit shall have a **recurrent manoeuvre capability** if it satisfies at least one of the following conditions:
1) It is operating in the **GEO** protected region
2) It is injected into an orbit **crossing** the **LEO** protected region with a natural orbit decay duration longer than **5 years**
3) Its **cumulative collision probability** with space objects larger than 1 cm is above $\mathbf{10^{-3}}$ through to its end of life
4) It is part of a **constellation**
5) It is performing **close proximity operations**, or **formation flying**

recurrent manoeuvre capability
capability of a spacecraft to perform repeatable manoeuvres on-orbit that can cause a change to the orbit over a limited amount of time
NOTE The repeatability of the manoeuvres implies that multiple manoeuvres of a targeted accuracy can be implemented by a spacecraft.

CAM: Collision Avoidance Manoeuvre | SST: Space Surveillance and Tracking

What about differential drag?

FREQUENTLY ASKED QUESTION

5.3.3.2.c

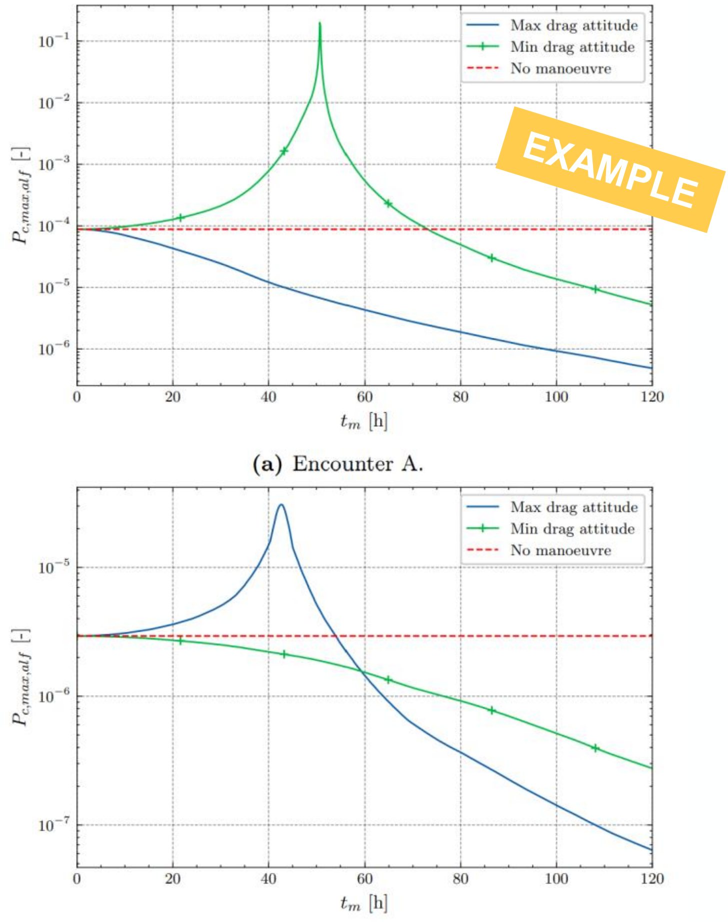
A spacecraft operating in near Earth orbit shall have a **recurrent manoeuvre capability** if it satisfies at least one of the following conditions:
1) It is operating in the **GEO** protected region
2) It is injected into an orbit **crossing** the **LEO** protected region with a natural orbit decay duration longer than **5 years**
3) Its **cumulative collision probability** with space objects larger than 1 cm is above $\mathbf{10^{-3}}$ through to its end of life
4) It is part of a **constellation**
5) It is performing **close proximity operations**, or **formation flying**

recurrent manoeuvre capability
capability of a spacecraft to perform repeatable manoeuvres on-orbit that can cause a change to the orbit over a limited amount of time
NOTE The repeatability of the manoeuvres implies that multiple manoeuvres of a targeted accuracy can be implemented by a spacecraft.

Differential drag is **not compatible** with the requirements.

Request to achieve a **specific risk reduction** in a **limited time**, which cannot be guaranteed in a **robust way** with differential drag

Examples from F. Turco et al, Acta Astronautica, 2023



(a) Encounter A.

(b) Encounter B.

CAM: Collision Avoidance Manoeuvre | SST: Space Surveillance and Tracking

novelty level

Collision risk management during operations

5.3.3.3.a

During normal operations of a spacecraft in near-Earth orbit with a recurrent manoeuvre capability, the acceptable collision probability threshold shall be below **10^{-4}** per conjunction.

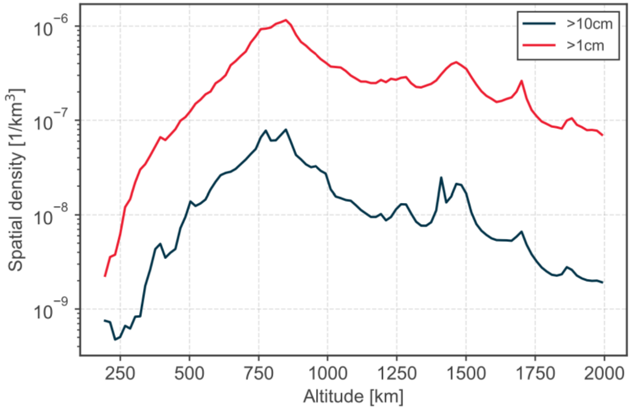
5.3.3.3.i

For a spacecraft operating in near Earth orbit with a recurrent manoeuvre capability, […] the operator of the spacecraft shall perform collision avoidance manoeuvres to reduce the collision probability by at least **two orders of magnitude** below the threshold.

5.3.3.3.b

During the normal operations of a spacecraft in the LEO protected region with a recurrent manoeuvre capability, on an orbit with an average density of space debris larger than 1 cm above 10^{-7} km^{-3}, the acceptable collision probability threshold shall be the lower of the following values: 1) 10^{-4}, and 2) The collision probability value such to **reduce the annual collision probability** by at least **90%** with respect to not performing collision avoidance manoeuvres

These requirements are operational in nature, but have an impact on the **design** (including the deltav budget), so they shall be addressed already in early mission design phases



ESA's Space Environment Report

Starting point for the analysis: **Guideline on Collision Avoidance** (ARES)

Why a CAM size in terms of risk reduction?

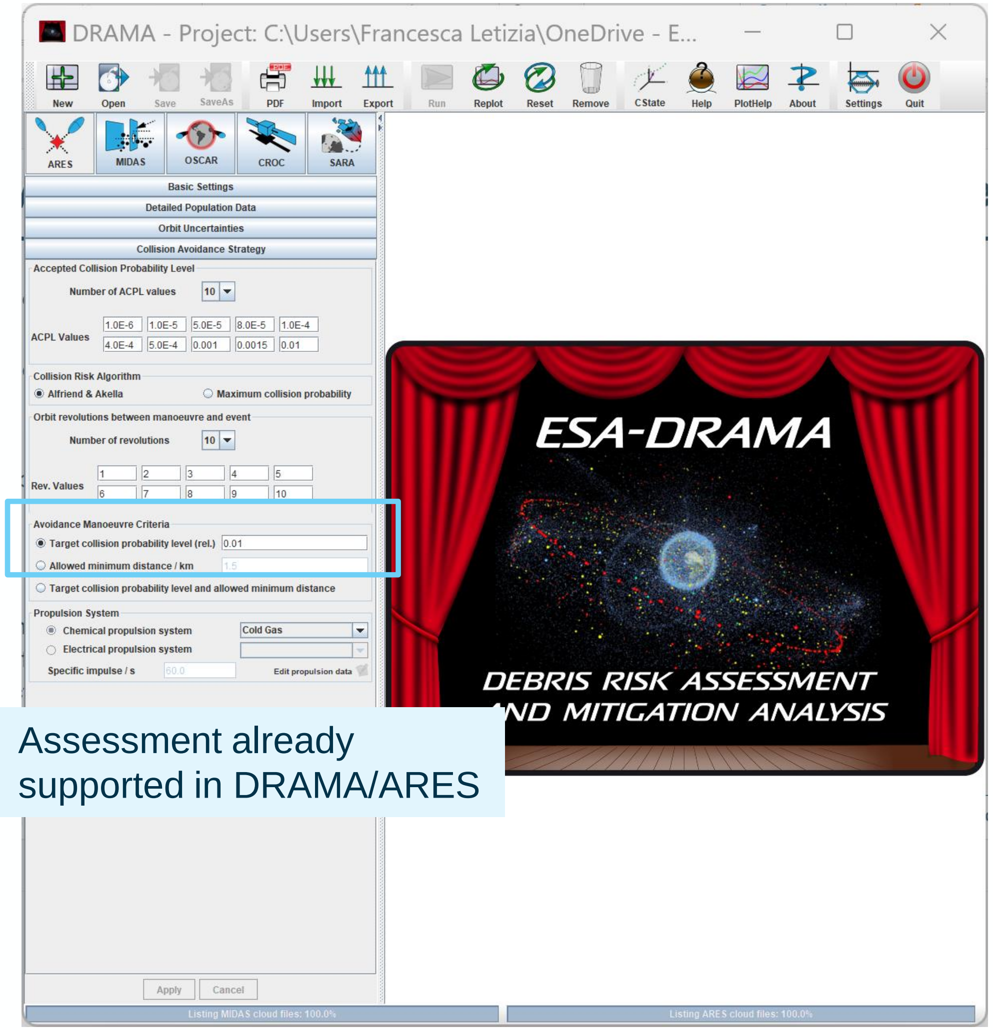
Objectives of a CAM:

- Reduce risk of the event to the background/accepted one
- Avoid that the event needs to be actioned again after the CAM

Collision probability targets better suited to achieve such objectives than separation distances

Example:

Past recommendation of 200m radial separation may not be suitable for low LEO missions (e.g. Aeolus) where the effect of drag is such that the position uncertainty on the chaser is larger



Assessment already supported in DRAMA/ARES

CAM: Collision Avoidance Manoeuvre

Collision risk management during operations

novelty level

5.3.3.3.g

The space and ground segments associated with spacecraft operating in near Earth orbits shall be designed to have **ephemerides** available for collision avoidance purposes in **less than 1 day** after orbital injection.

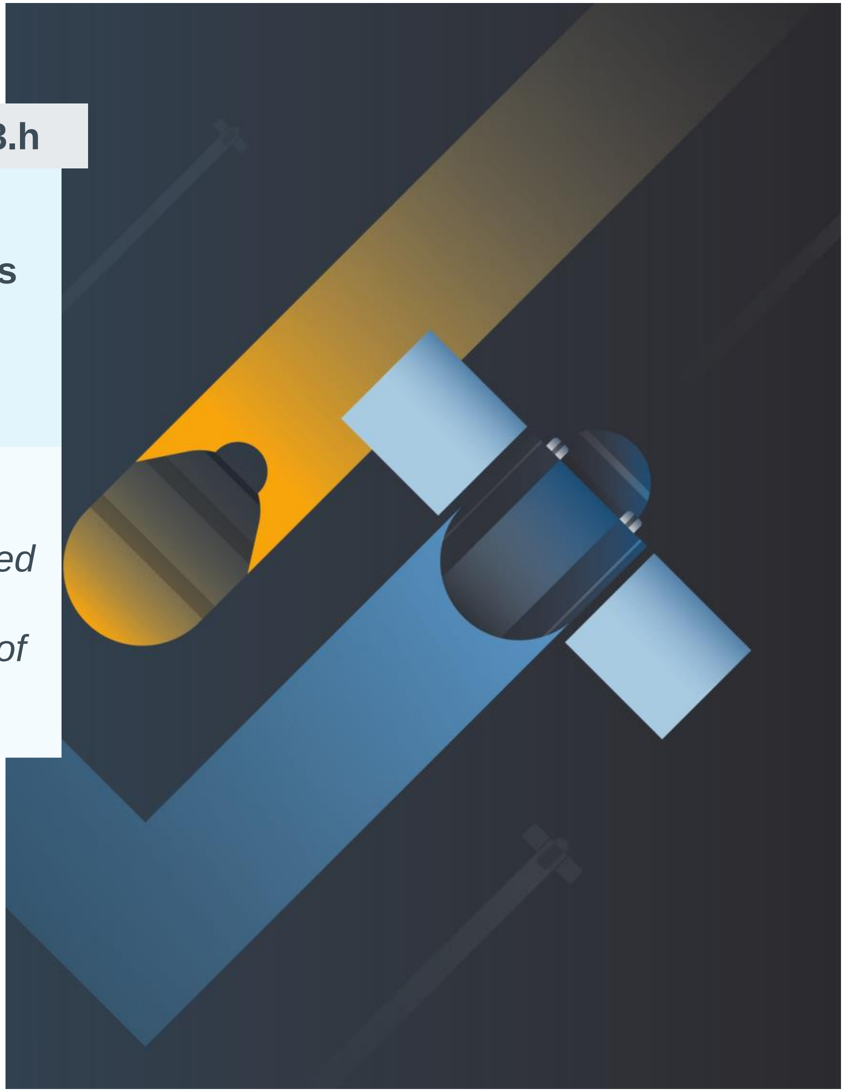
5.3.3.3.j

A spacecraft operating in near Earth orbit, after receiving a warning for a conjunction with a collision probability above the threshold during normal operations, shall perform a collision avoidance action, including:
1) **Manoeuvres**, if the warning is received up to **12 hours** before the conjunction and the spacecraft is operational
2) **Assessment** in less than **4 hours** after the warning
3) Actively communicating its status or ephemerides, if unable to perform manoeuvres

5.3.3.3.h

A spacecraft with a recurring manoeuvre capability shall be able to implement a collision avoidance manoeuvre within **2 days** when injected into a near Earth orbit with a natural orbital decay duration longer than 5 years.

It is understood that in case of rideshare launches with no manoeuvre periods imposed by the launcher this cannot happen. In that case, the time will be counted from the end of the no manoeuvre period



Are 24/7 operations required for compliance?

5.3.3.3.j

A spacecraft operating in near Earth orbit, after receiving a warning for a conjunction with a collision probability above the threshold during normal operations, shall perform a collision avoidance action, including:
1) **Manoeuvres**, if the warning is received up to **12 hours** before the conjunction and the spacecraft is operational
2) **Assessment** in less than **4 hours** after the warning
3) Actively communicating its status or ephemerides, if unable to perform manoeuvres

Ephemerides exchange described in 5.3.3.3.m

No, they are not required

- **Assessment** can be performed through the (automatic) processing of a CDM
- In case of **manoeuvres**,
  - The **space segment** shall be able to implement the required separation (to achieve the 2 orders of magnitude reduction of the collision probability) in less than 12 hours (relevant for very low thrust missions)
  - The **ground segment** should target operations with 12 hours coverage/day (this defines the time when warning can be acted on) – aspects such as platform limitations, passes availability, etc. can be discounted for the assessment

CDM: Conjunction Data Message

Space surveillance and tracking

novelty level

5.3.3.5.a

The developer of a spacecraft or launch vehicle orbital element injected into Earth orbit shall guarantee that it can be **tracked** by a space surveillance segment supporting collision avoidance processes.

5.3.3.5.b

The ground segment of a spacecraft or launch vehicle orbital stage injected into a near Earth orbit shall include a **space surveillance segment**.

5.3.3.5.c

During normal operations, the operator of a spacecraft in Earth orbit shall **quantify the position and velocity accuracy of the combined ground, space, and space surveillance segment** […]

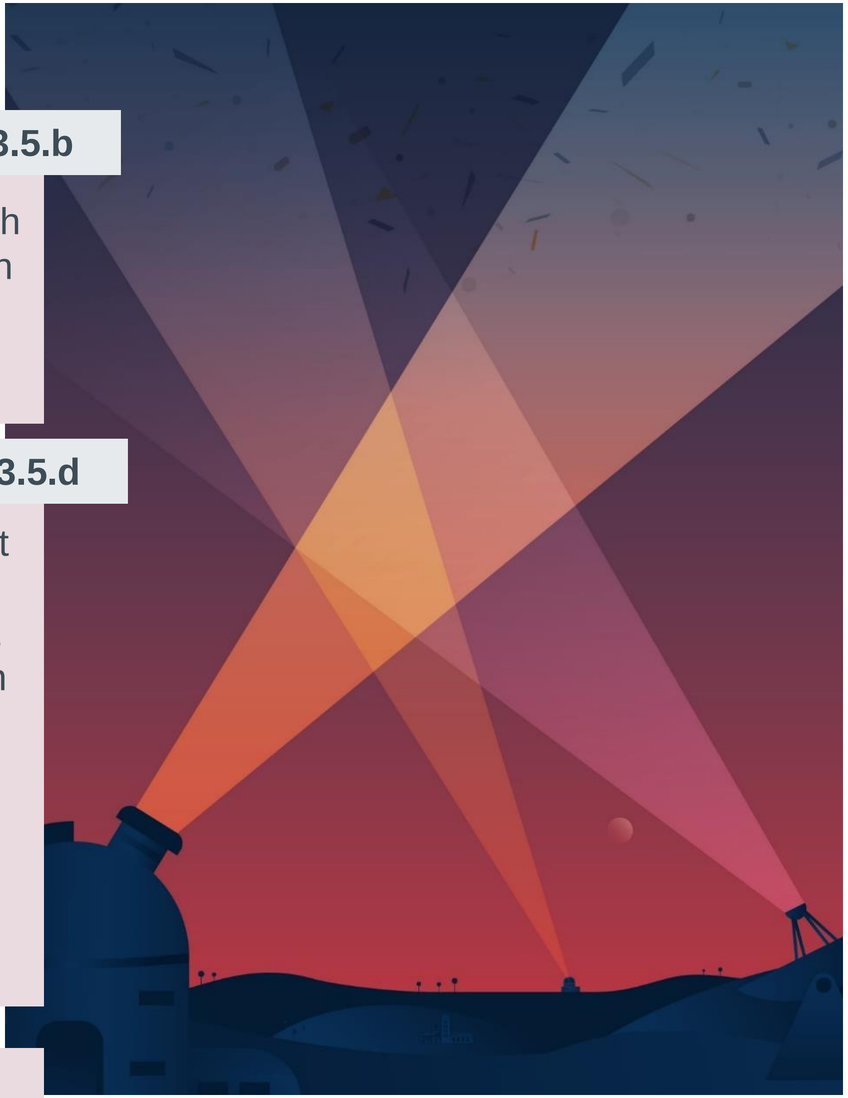
5.3.3.5.d

A spacecraft or launch vehicle orbital element injected into the protected regions shall guarantee that a space surveillance segment supporting collision avoidance processes can achieve a **position accuracy** during normal operations as well as after end of life higher than **100 m** in the **LEO** protected region and higher than **1000 m** in the **GEO** protected region along the orbit determination interval outside of manoeuvre periods.

5.3.3.5.e

The developer and operator of a spacecraft or launch vehicle orbital element injected into Earth orbit shall guarantee that it can be **unambiguously identified** by a space surveillance segment within **1 day after on-orbit injection**.

…



Need to demonstrate that we are identified in 1 day?

FREQUENTLY ASKED QUESTION

5.3.3.5.e

The developer and operator of a spacecraft or launch vehicle orbital element injected into Earth orbit shall guarantee that it can be **unambiguously identified** by a space surveillance segment within **1 day after on-orbit injection**.

Example: cubesat on a rideshare launch

No, as the actual identification will depend also on the Space Surveillance Segment's processes. Here we are asking about the **capability** i.e. enable a fast identification

- **Collaborate** with the space surveillance segment and share **predicted** launch **trajectory** and early operations and manoeuvring **plans**.
- **Inform** surveillance segment early about possible **mislabelling** in the catalogue (e.g. using the TLE).
- Review **launch sequence**, in case of rideshare, to avoid uncoordinated release of spacecraft and cause mislabelling in the catalogue.
- Identify **ground segment capabilities** to share early orbital information derived from telemetry and on-board GNSS data.

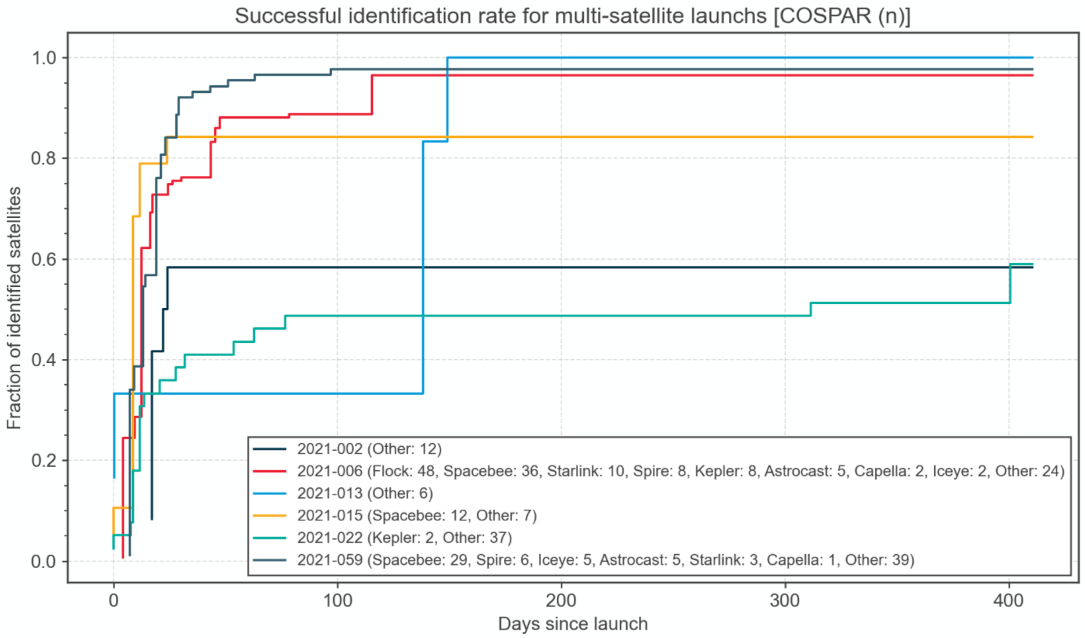
TLE: Two-Line elements

Ensure trackability

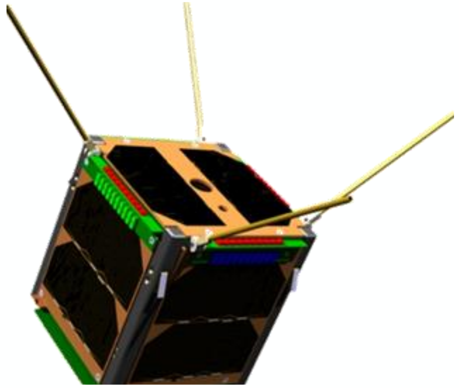
CubeSat Confusion: small satellites, with similar shape, released simultaneously and with lower reliability rates than traditional missions

M. Skinner, CubeSat Confusion: Technical and Regulatory Considerations, 2021 (Available online)

Delay in identification can result in mission failure and interference with other operators



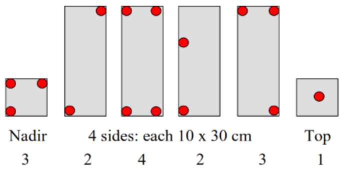
Available technologies



LED

https://www.s5lab.space/index.php/ledsat-home/

Passive laser retro-reflector

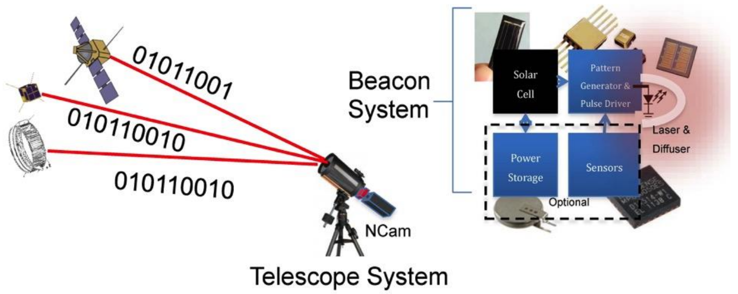


https://www.thorlabs.com/navigation.cfm?guide_id=2539

More information available from NASA, State-of-the-Art of Small Spacecraft Technology

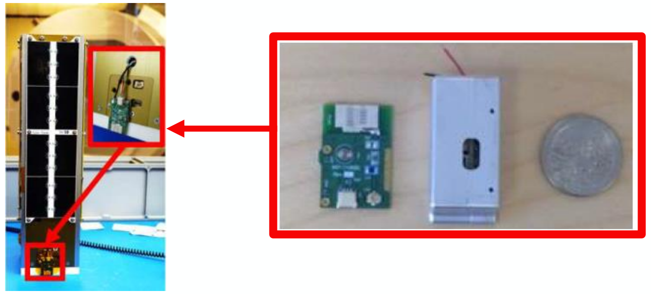
https://www.nasa.gov/smallsat-institute/sst-soa/identification-and-tracking-systems/

Modulated laser

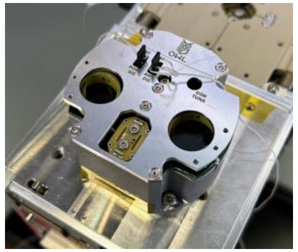


ELROI: A License Plate for Your Satellite
https://amostech.com/TechnicalPapers/2018/Poster/Holmes_Rebecca.pdf

Space transponder



SRI International's CubeSat Identification Tag (CUBIT): System Architecture and Test Results from Two On-Orbit Demonstrations
https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=4451&context=smallsat



Plug and play device equipped with a battery, GNSS tracker, omnidirectional antenna
https://owl.c3s.space/

Space surveillance and tracking

novelty level

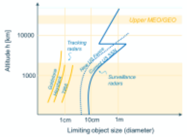
Providers of SST data for free exist

Valuable to register even w/o manoeuvre capabilities

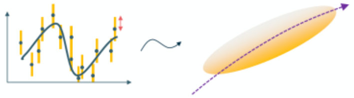
Immediately compliant with many requirements
(e.g. probabilistic assessment, daily screening, …)

Trackability performance can be assessed with different levels of detail

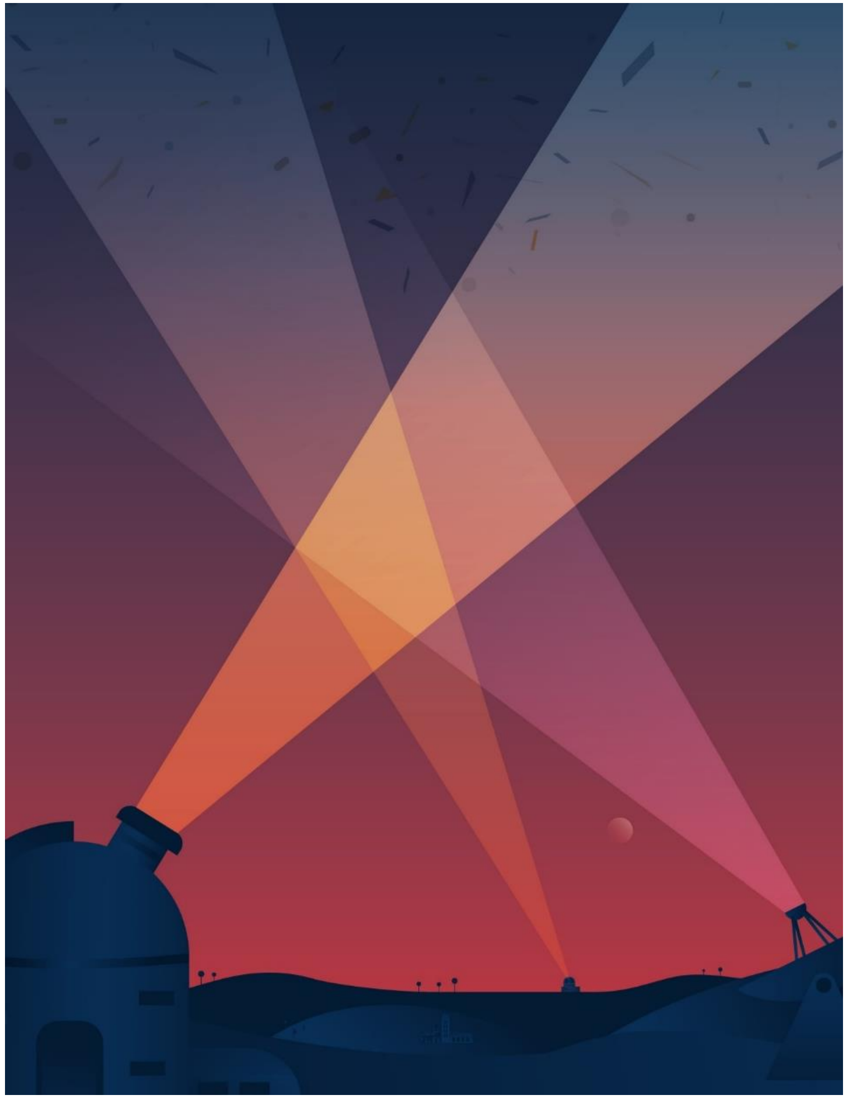
Declared performance, analysis in public literature, past operational experience
e.g. single values, look-up tables



Trackability curve
included in the updated Handbook



Own simulations
upcoming DRAMA functionality in January 2025



novelty level

Space surveillance and tracking

Providers of SST data for free exist

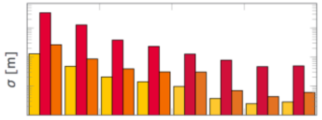
Valuable to register even w/o manoeuvre capabilities

Immediately compliant with many requirements
(e.g. probabilistic assessment, daily screening, …)

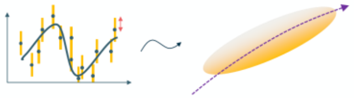
Trackability performance can be assessed with different levels of detail

Accuracy performance can be assessed with different levels of detail

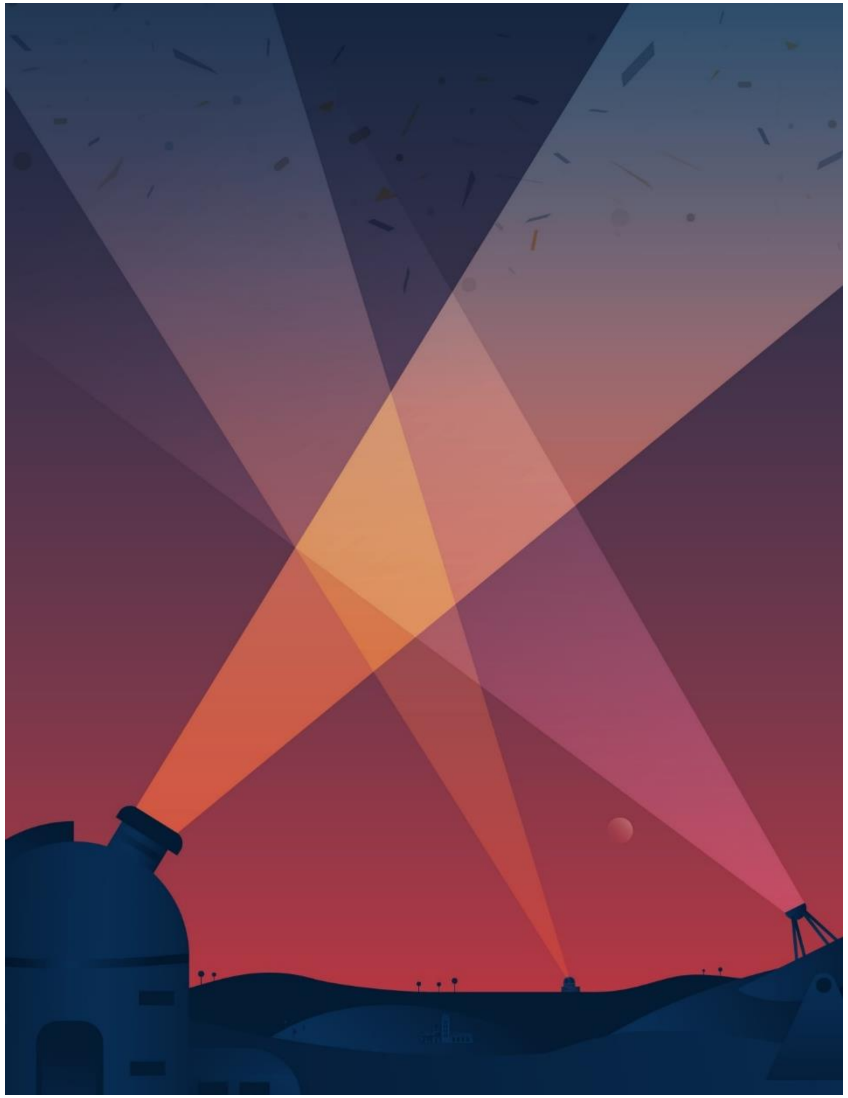
Declared performance, analysis in public literature, past operational experience
e.g. single values, look-up tables



ESA's assessment
e.g. based on historical CDMs



Own simulations
upcoming DRAMA functionality in January 2025



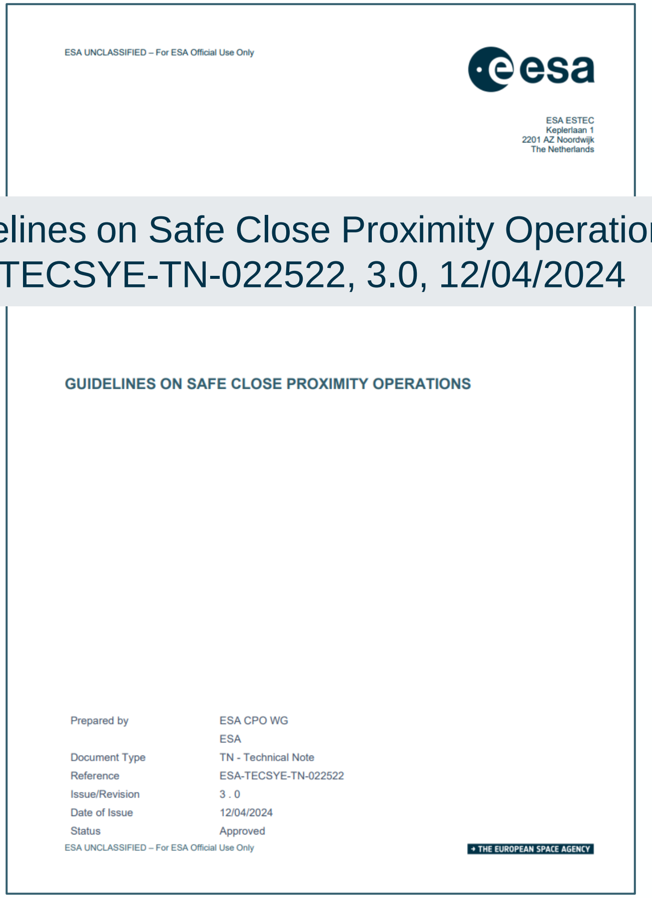
Close-proximity operations

novelty level

5.3.3.4.a

The probability of **unintentional contact** during CPO or formation flying in Earth orbit must remain below **10^{-4}**

This is the core requirement, serving as the **foundation** for all subsequent requirements, which explains the conditions for its verification


ESA UNCLASSIFIED – For ESA Official Use Only

ESA ESTEC
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands

GUIDELINES ON SAFE CLOSE PROXIMITY OPERATIONS

Prepared by	ESA CPO WG ESA
Document Type	TN - Technical Note
Reference	ESA-TECSYE-TN-022522
Issue/Revision	3 . 0
Date of Issue	12/04/2024
Status	Approved

ESA UNCLASSIFIED – For ESA Official Use Only

→ THE EUROPEAN SPACE AGENCY

Guidelines on Safe Close Proximity Operations, ESA-TECSYE-TN-022522, 3.0, 12/04/2024

5.3.3.4.b: Quantification of the probability

Verification methodology to assess the probability:

- **CONOPS** detailing decision gates & phase definition
- **RAMS** analysis of all functional chains and units involved accounting for performance uncertainties and environmental perturbations
- Simulation of the nominal/reference **trajectories**

5.3.3.4.c - 5.3.3.4.f: Additional requirements on health monitoring, redundancy, contingency operations, safe trajectories and collision avoidance measures.

CONOPS: CONcept of OPerationS | RAMS: Reliability, Availability, Maintainability, Safety

Close-proximity operations

Early phases (0-A)	**Later phases** (B-C)	**After production** (D onwards)
Initial collision risk assessment. Safe trajectory design.	Detailed design and verification of on-board systems for health monitoring and autonomous collision avoidance Analysis of RAMS data, integration of redundant systems, and review of failure scenarios.	Real-time collision probability monitoring. Re-assessment during mission extensions or anomalies.

How close is enough to be considered CPO?

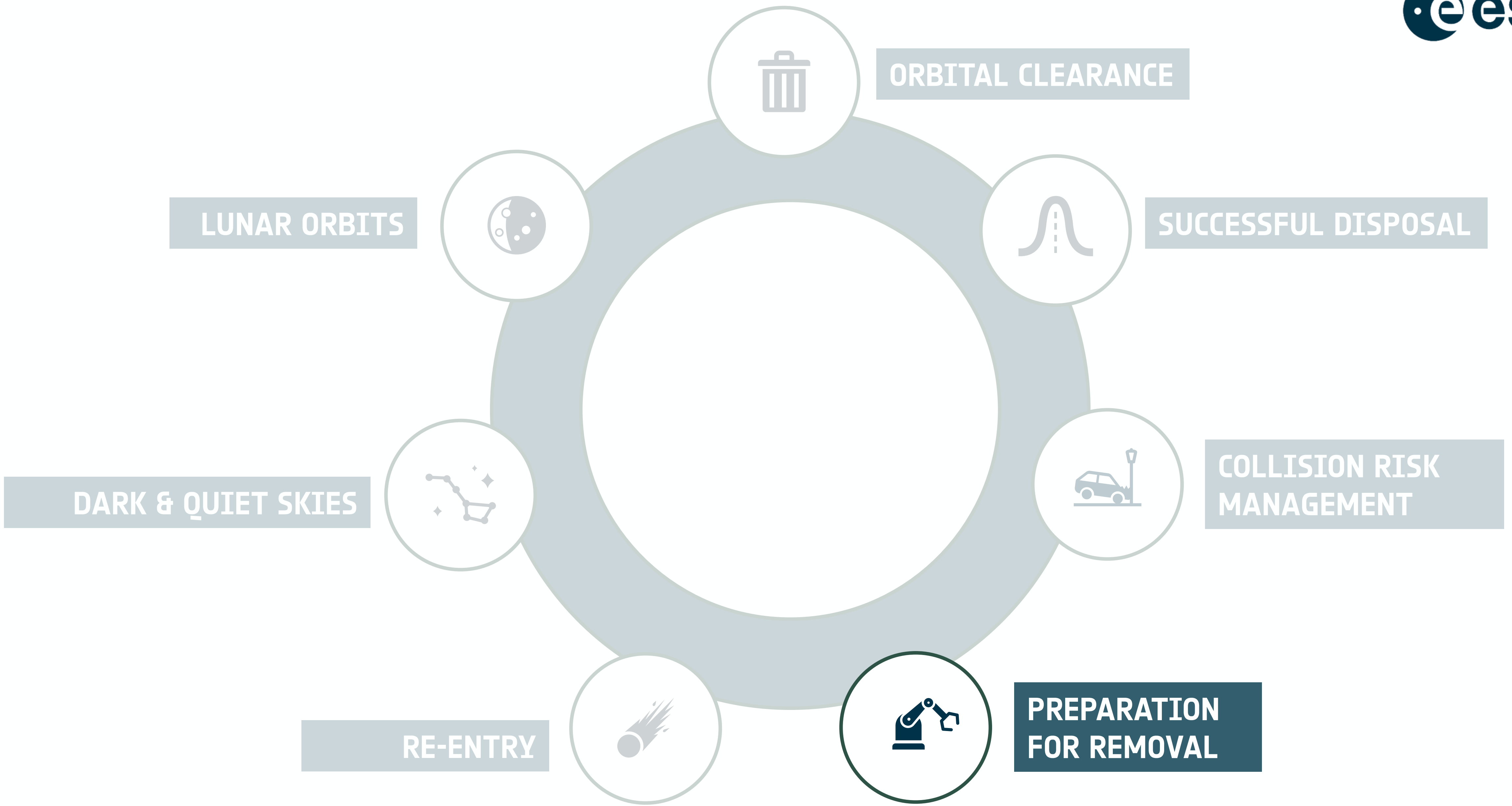
Any mission where the spacecrafts are maintaining a **relative distance** is considered to fall under the category of close proximity operation and formation flying

It is understood that the verification methodology may be significantly different between cases such as

- Active Debris Removal/In-orbit servicing mission
- Satellites with km of separation

For the latter, it can be enough to demonstrate that the time to reach a potential risky conjunction (e.g. after an erroneous manoeuvre) is enough for the ground to react as in the case of collision avoidance manoeuvres with other debris object

CPO: Close-Proximity Operations



ORBITAL CLEARANCE
LUNAR ORBITS
SUCCESSFUL DISPOSAL
DARK & QUIET SKIES
COLLISION RISK MANAGEMENT
RE-ENTRY
PREPARATION FOR REMOVAL

Preparation for removal

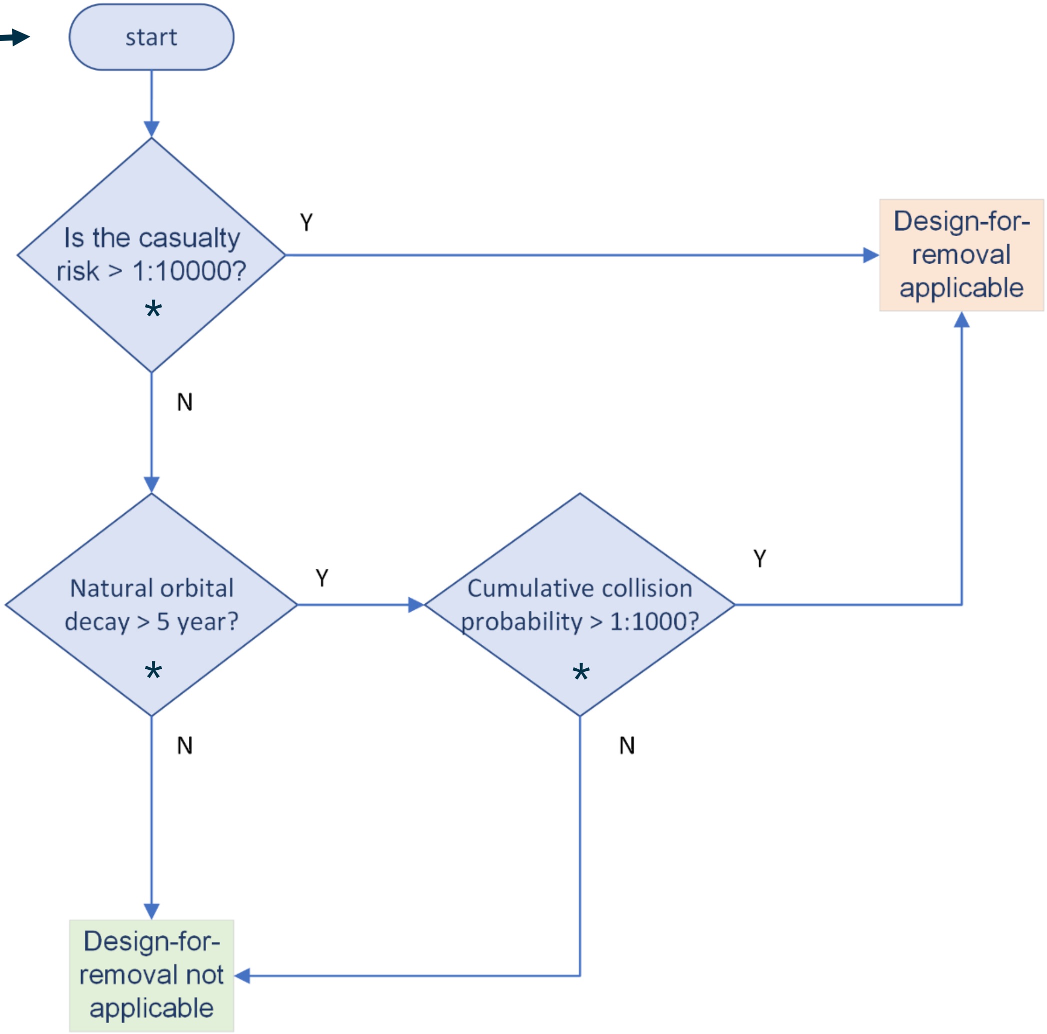
novelty level

GEO: always requested
LEO: requested for high-risk objects

The requirements cover several aspects related to Design-for-Removal (D4R)

- Mechanical **interfaces**
- Support to passive **navigation**
- Assessment of long-term **attitude**
- Attitude reconstruction from ground
- Limiting and damping **angular rates**
- **Operations**
- …

LEO



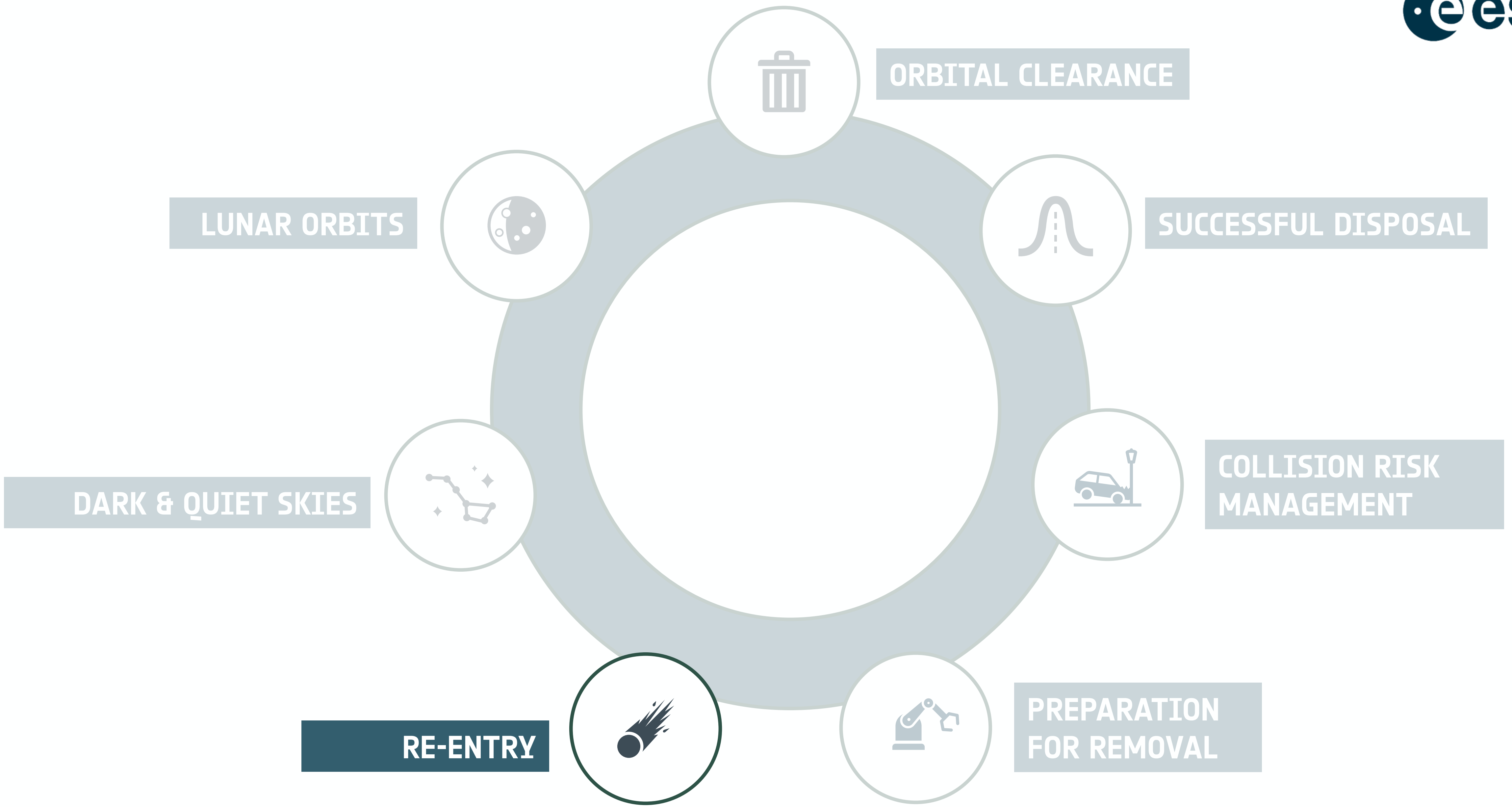
* In case of failure in orbit

FREQUENTLY ASKED QUESTION

Do D4R features make my mission a CPO mission?

Not automatically: the requirements related to Collision risk management for close proximity operations and formation flying (5.3.3.4) do not become applicable only because of the adoption of design-for-removal features

D4R: Design-for-Removal | CPO: Close-Proximity Operations


ORBITAL CLEARANCE
SUCCESSFUL DISPOSAL
COLLISION RISK MANAGEMENT
PREPARATION FOR REMOVAL
RE-ENTRY
DARK & QUIET SKIES
LUNAR ORBITS

Re-entry

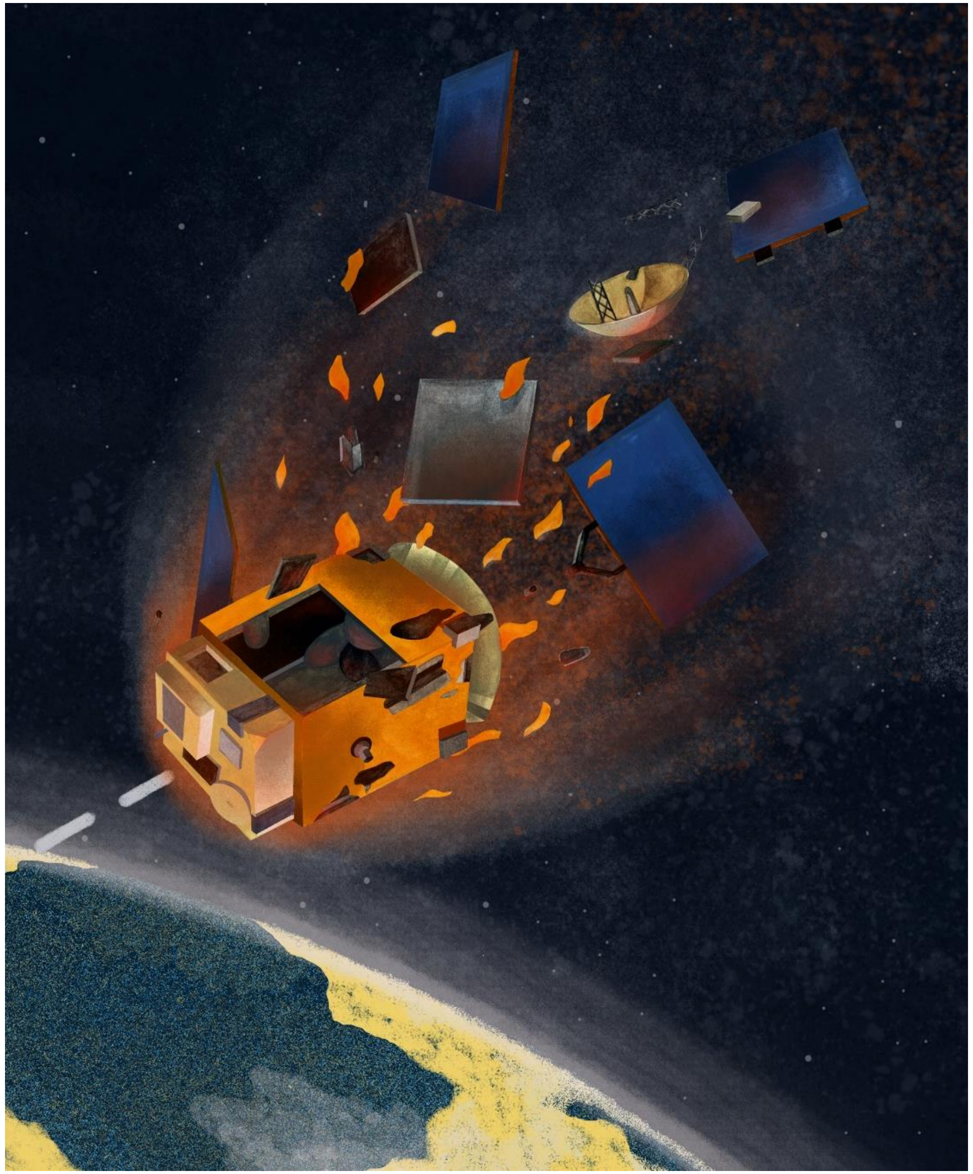
novelty level

The main requirement has not changed:
re-entry casualty risk < 10^{-4}

ESA's Re-entry Safety Requirements (ESSB-ST-U-004) remain applicable

What's new

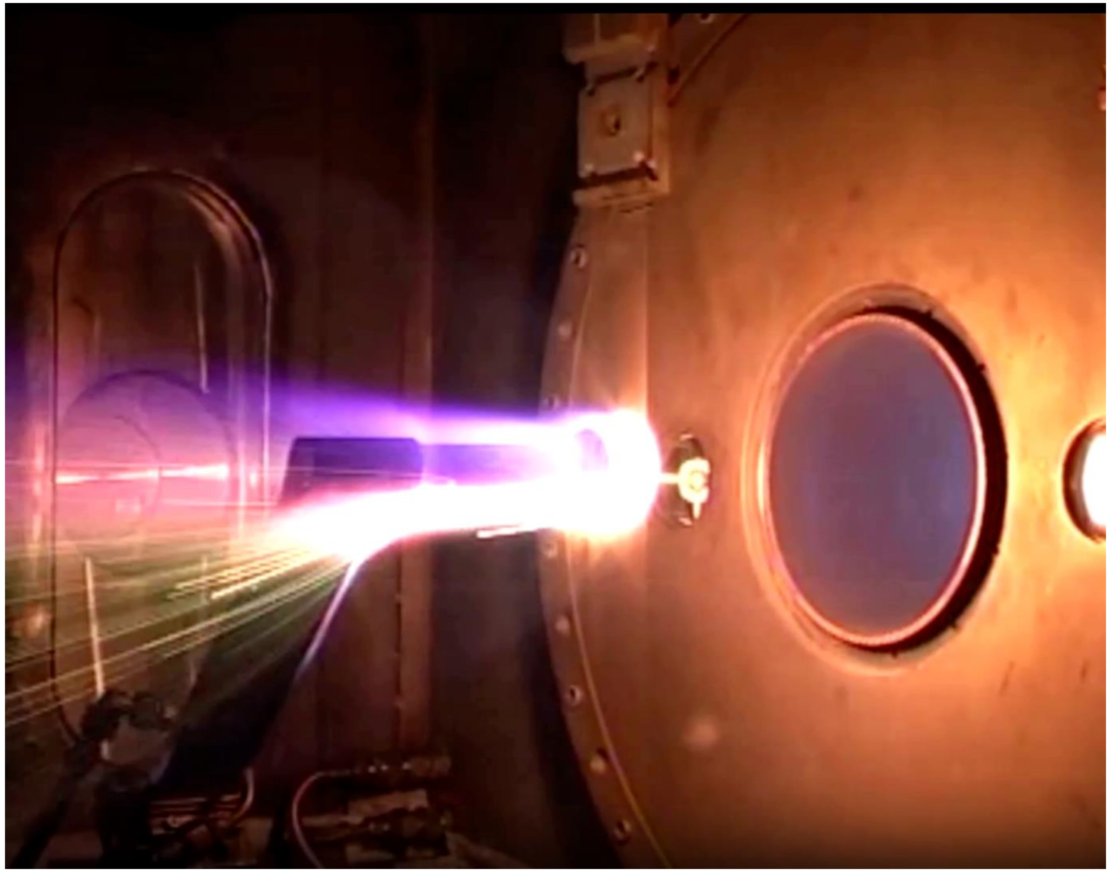
- More stringent requirement for **large constellations** (**10^{-6}**)
- Order of **preference** in how to achieve compliance
  1. Design for demise
  2. Controlled re-entry
  3. Any other approach needs approval



What about design-for-containment?

It requires approval by the approving agent (i.e. ESA's technical authority for space debris mitigation)

It won't be accepted without testing given that current simulation tools are not suitable to verify its efficacy and it is considered an approach for which TRL maturation is needed



FREQUENTLY ASKED QUESTION

Re-entry

novelty level

What's new

Explicit request for a **probabilistic assessment** of the casualty risk

- Uncertainty sources to be considered described in ESA Space Debris Mitigation Compliance Verification Guidelines (ESSB-HB-U-002-Issue 2),
- Modelling guidelines in DIVE - Guidelines for Analysing and Testing the Demise of Man-Made Space Objects During Re-entry (ESA-TECSYE-TN-018311)


esa

estec

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

DOCUMENT

ESA Space Debris Mitigation Compliance Verification Guidelines

Prepared by	ESA Space Debris Mitigation WG
Reference	ESSB-HB-U-002
Issue	2
Revision	0
Date of Issue	14 February 2023
Status	Approved
Document Type	HB
Distribution	ESA

esa

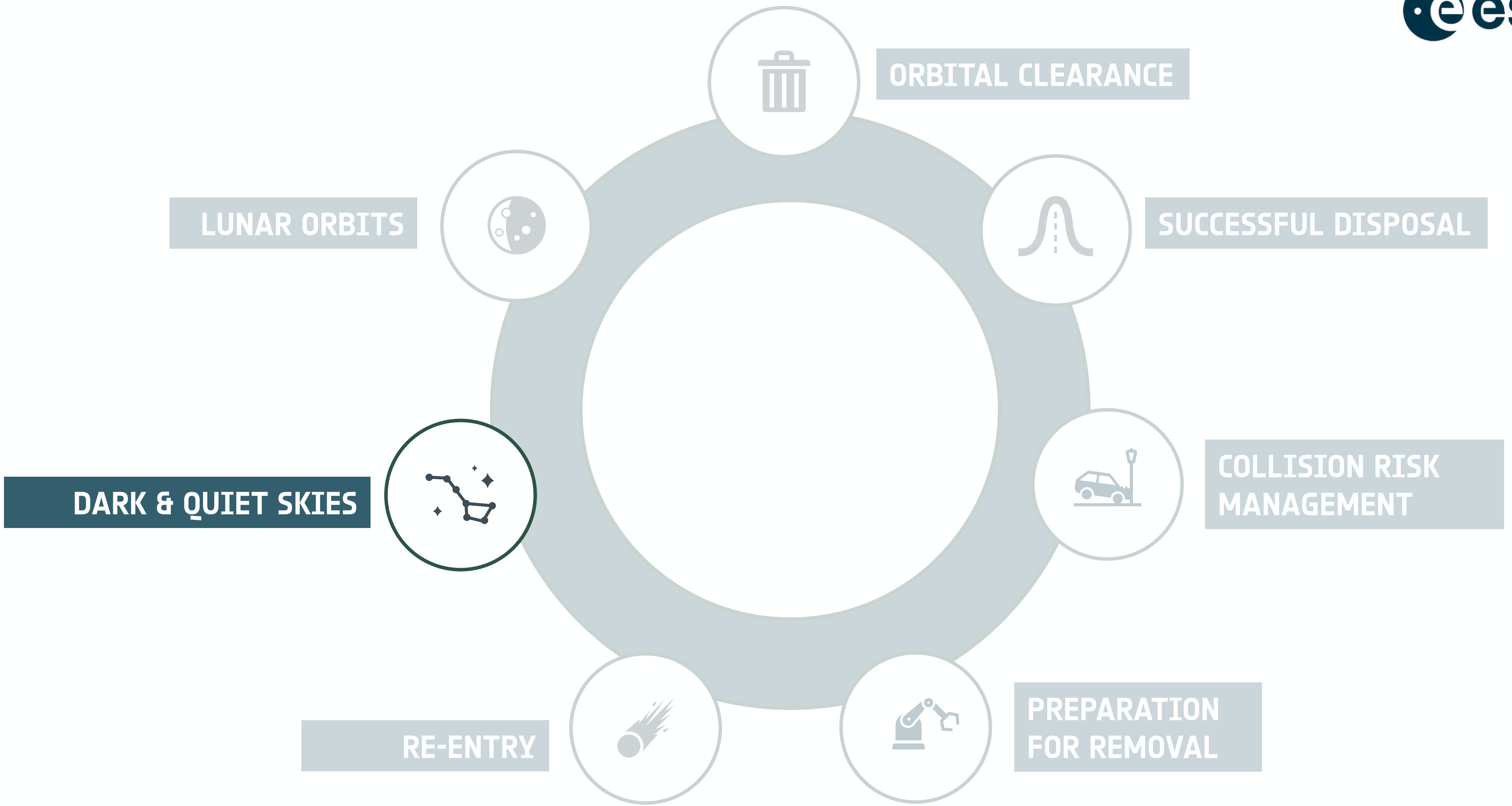
estec

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

TECHNICAL NOTE

DIVE - Guidelines for Analysing and Testing the Demise of Man Made Space Objects During Re-entry

DIVE


ORBITAL CLEARANCE
SUCCESSFUL DISPOSAL
COLLISION RISK MANAGEMENT
PREPARATION FOR REMOVAL
RE-ENTRY
DARK & QUIET SKIES
LUNAR ORBITS

Dark & Quiet Skies

novelty level

5.6.a

The developer of a spacecraft or launch vehicle orbital element in near Earth orbit shall quantify the visual brightness of the design.

Early phases (0-B)

Assess brightness assuming a combination of diffuse and/or specular reflection for primitive shapes (e.g. sphere, cylinder, flat plate).

Diffusive and specular reflection for surfaces is described using physical or empirical models, e.g. ideal Lambertian, or empirical Phong reflection models

ESA tools available (internally only at the moment) for such assessments

Later phases (B-C)

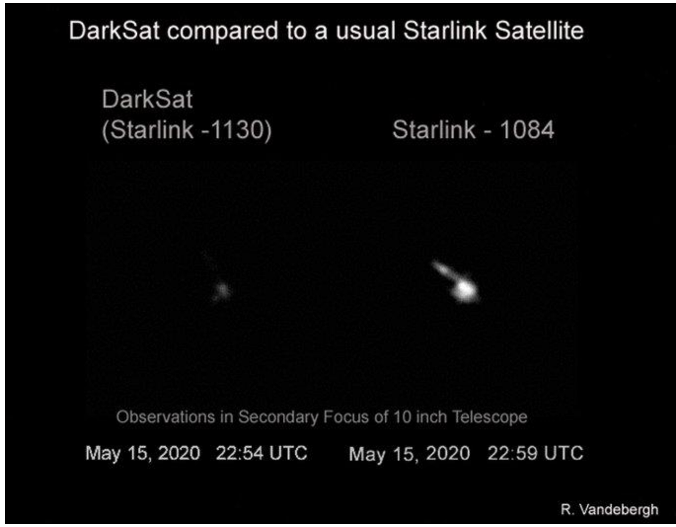
3D geometrical models describe the overall system using exposed subassemblies with different material properties.

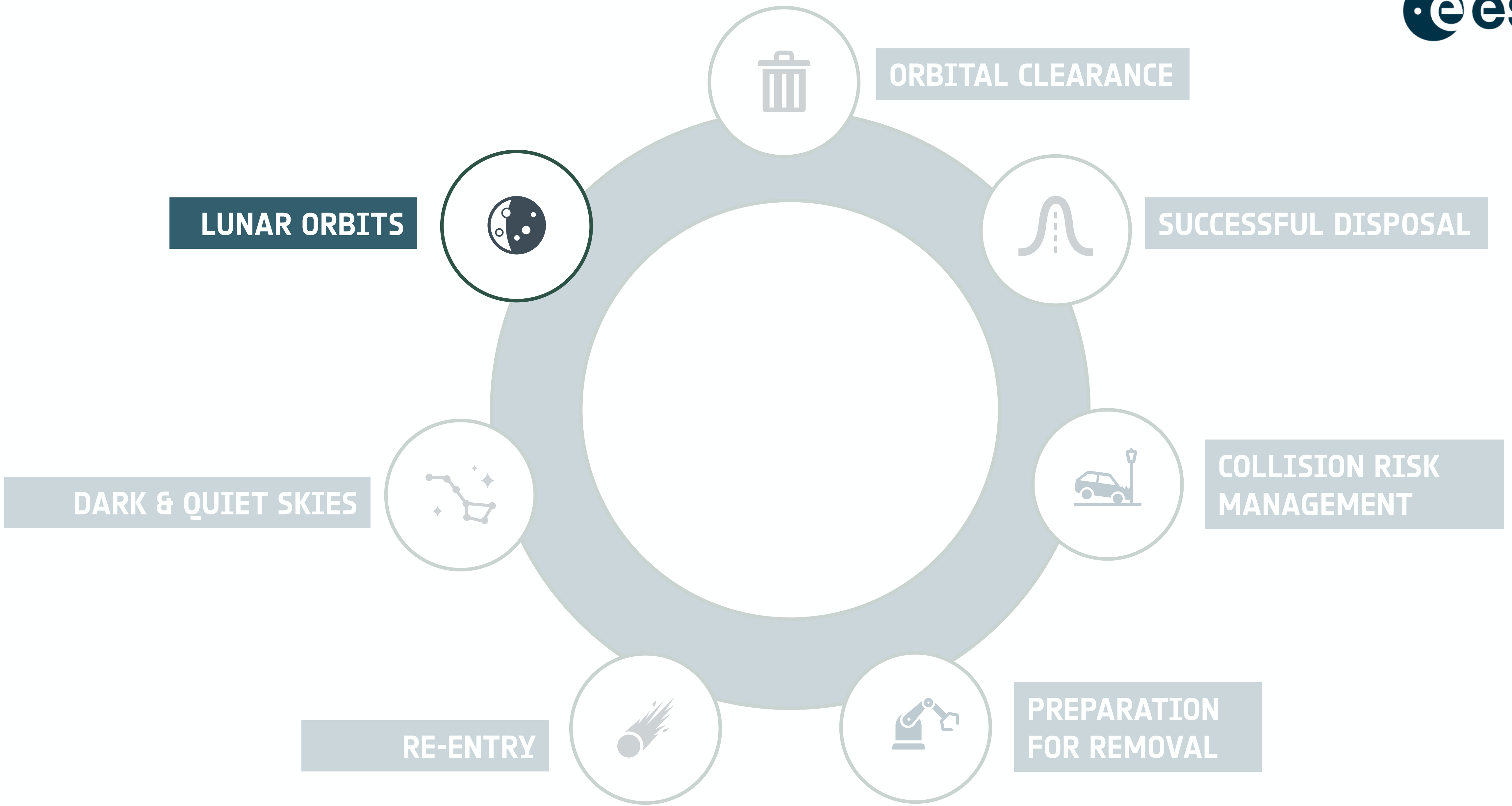
Material properties are described with specular or diffuse reflection models or with more complex bi-directional reflectance distributions (BDRF).

Identify specific conditions that may cause glints / strong reflections

After production (D onwards)

Regularly update the brightness estimate during the qualification phase with measured BDRFs of materials, exposed subassemblies, or the whole system.




ORBITAL CLEARANCE
LUNAR ORBITS
SUCCESSFUL DISPOSAL
DARK & QUIET SKIES
COLLISION RISK MANAGEMENT
RE-ENTRY
PREPARATION FOR REMOVAL

Lunar orbits

No intentional **breakup**

No **release** of space debris during normal operations

Space & ground segment designed to have **ephemerides** available for space traffic coordination

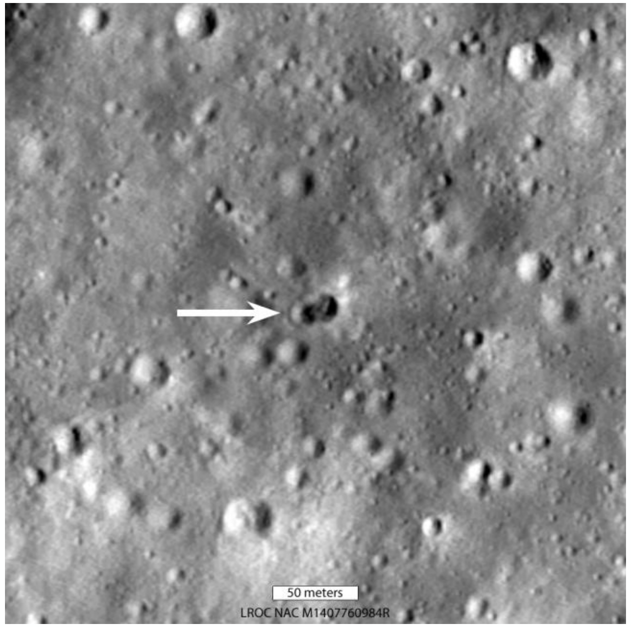
Disposal by one of the following means in order of preference:

1. **Heliocentric** orbit
2. Lunar impact, Earth re-entry, or a Lunar graveyard orbit

The free drift trajectories after disposal of a spacecraft or launch vehicle orbital element in lunar orbit shall be analysed for at least 100 years to evaluate:

1. Probability of **Earth re-entry** and its associated impact area
2. Probability of **Lunar impact** and its associated impact area

Double crater created by the impact of a rocket body on the Moon in March 2022.
Credits: NASA/Goddard/Arizona State University



Lunar orbits - tools

For the propagation of lunar and libration point orbits, the following tools are recommended.
The tools are available in ESA member states through the https://gitlab.space-codev.org/ website.

godot

CUDAjectory

Application
long term propagation of lunar orbits,
e.g. to assess the variation of the orbital elements of the lunar graveyard orbit

Application
parallel computation of large numbers of orbital states
e.g. long-term Earth re-entry risk analysis for spacecraft in libration point orbits

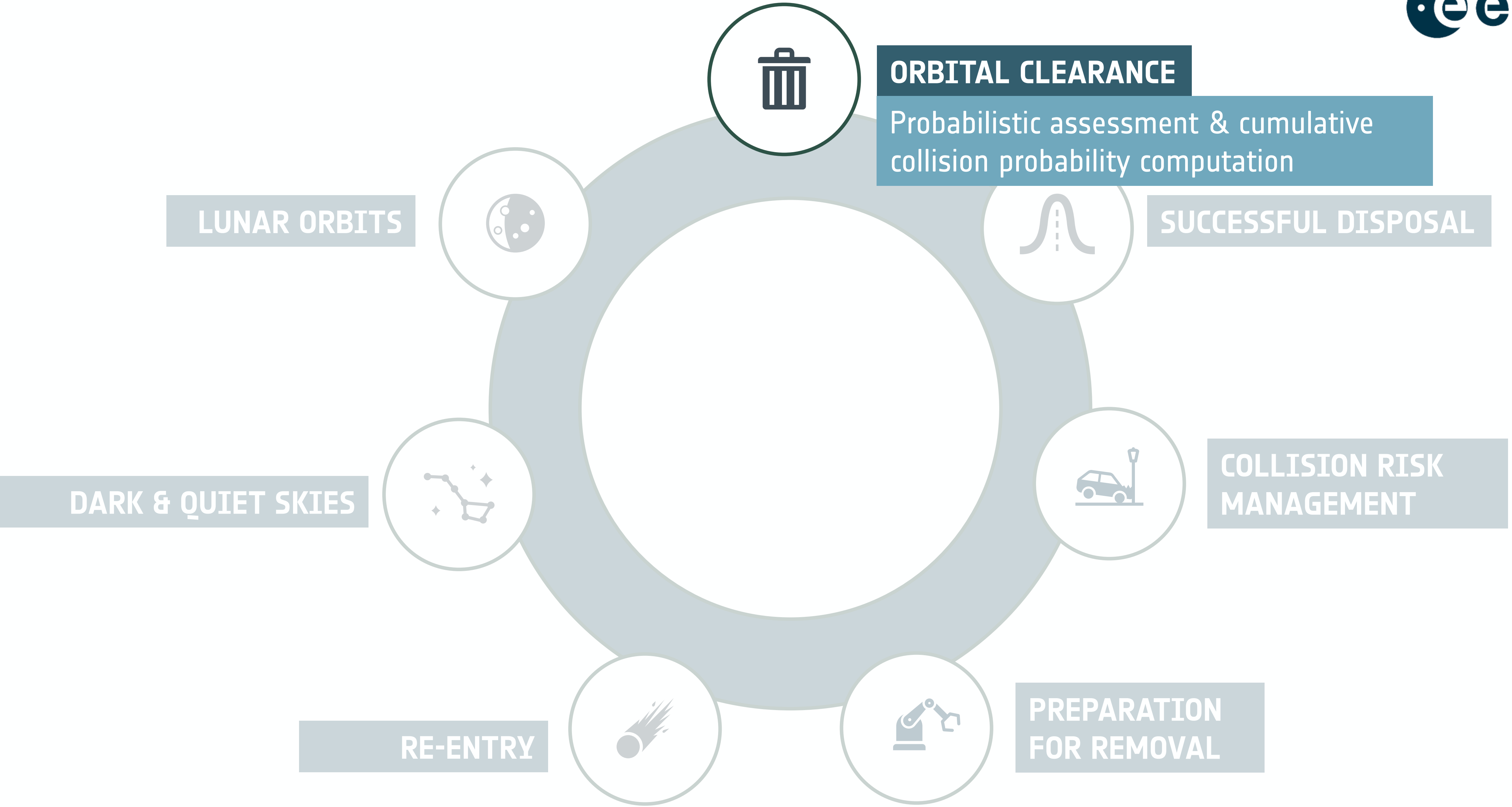
Policy

Requirements

Handbook

Tools

space.debris.mitigation@esa.int


ORBITAL CLEARANCE
Probabilistic assessment & cumulative collision probability computation
LUNAR ORBITS
SUCCESSFUL DISPOSAL
DARK & QUIET SKIES
COLLISION RISK MANAGEMENT
RE-ENTRY
PREPARATION FOR REMOVAL

Orbital lifetime and cumulative collision probability

5.4.2.3.a

LEO protected region clearance
The orbit clearance of a spacecraft or launch vehicle orbital element from the LEO protected region shall satisfy both following conditions:
1) the **orbit lifetime** is less than 5 years […]
2) the **cumulative collision probability** from its end of life until re-entry with space objects larger than 1 cm is below 10^{-3}

6.2

Verification and validation requirements
f) The orbit lifetime of a space object shall be assessed **probabilistically**, including at least the variability by moving the starting point through a **full solar cycle** […]
g) For the orbit lifetime assessment, […] the **50th percentile** for orbit with eccentricity below 0,3 at end of life […]

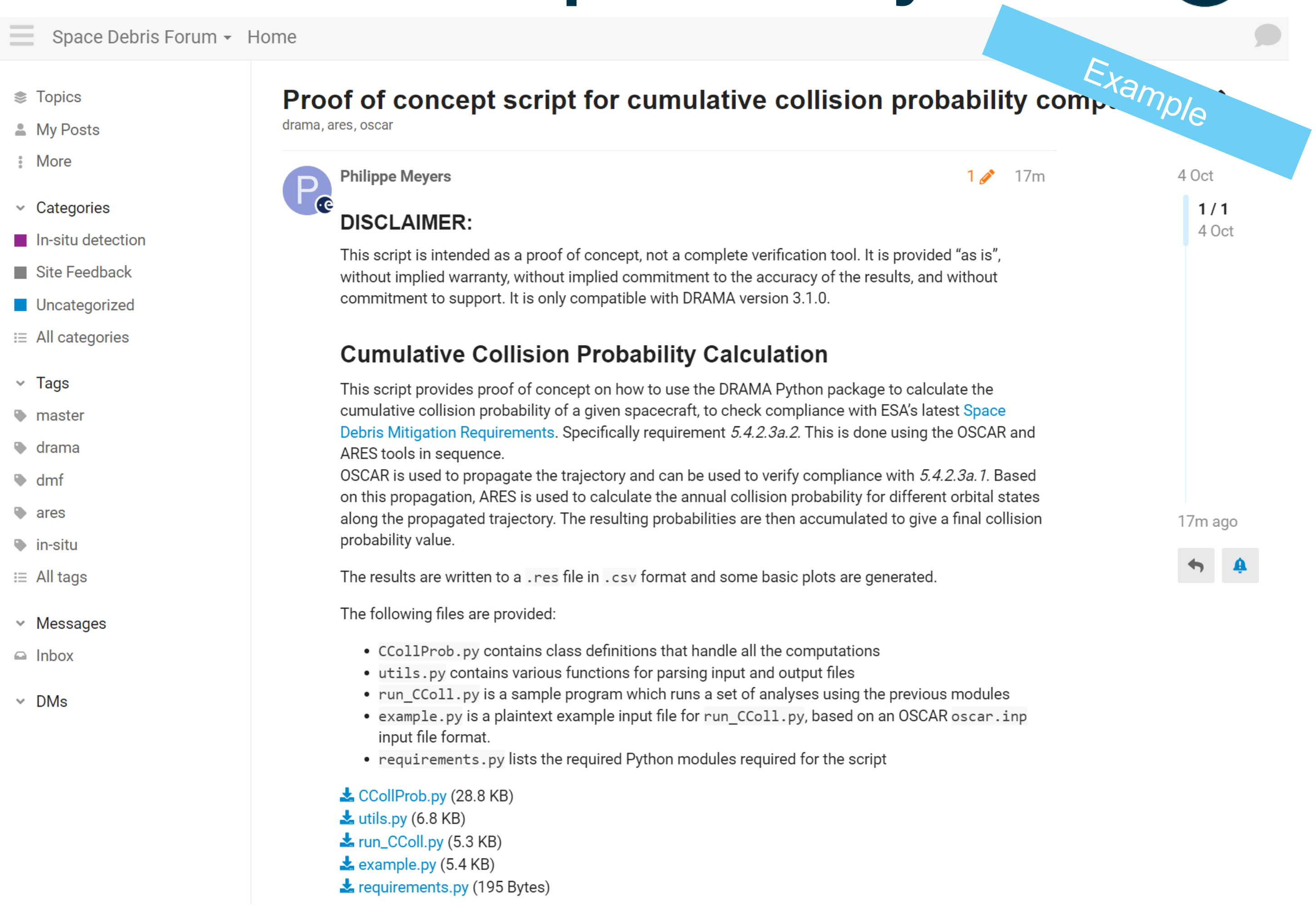
Helper scripts available to support verification for orbital clearance and cumulative collision probability requirements

Computation of:

- Disposal trajectory for different **target lifetimes** and **disposal epochs** (aid probabilistic assessment)
- Associated **cumulative collision probability**

Orbital lifetime and cumulative collision probability

Where?



https://debris-forum.sdo.esoc.esa.int/

DRAMA python package

pyDRAMA

Search docs

CONTENTS:

- Installation
- Getting started
- Known issues
- Module Reference
  - ARES
  - MIDAS
  - OSCAR
  - SARA
- Examples
- Developer Module Reference

drama.ares.run(*config=None, dependent_variables=[], project=None, save_output_dirs=None, parallel=True, ncpus=None, timeout=None, keep_output_files='summary', spell_check=True, **kwargs*)

Runs (parametric) ARES analysis and return the results.

Parameters:
- **config** (*dict or list*) –
  The (parametric) ARES run configuration. If a dictionary is provided it must be of the following format (lists are used for parametric analyses):

```
{
    'epoch': datetime or list,
    'sma': float or list,
    'ecc': float or list,
    'inc': float or list,
    'raan': float or list,
    'aop': float or list,
    'spacecraft_radius': float or list,
    'mass': float or list,
    'functionality': int or list,
    'particle_size_min': float or list,
    'particle_size_max': float or list,
    'EMR_switch': int or list,
    'uncertainty_type': int or list,
    'uncertainty_along': float or list,
    'uncertainty_cross': float or list,
    'uncertainty_radial': float or list,
    'lead_time': float or list,
}
```

OSCAR for disposal trajectory computation

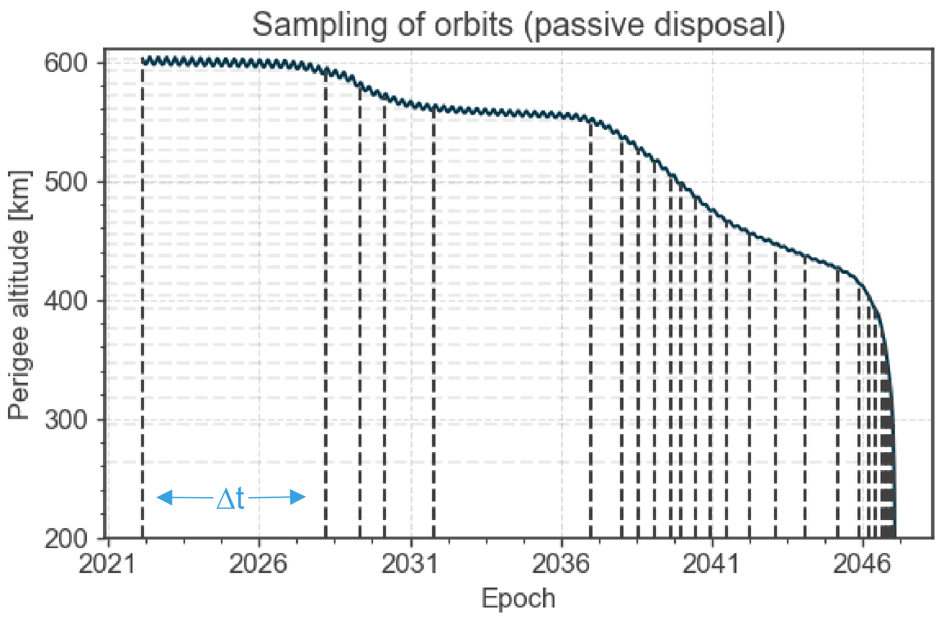
ARES for cumulative collision probability computation

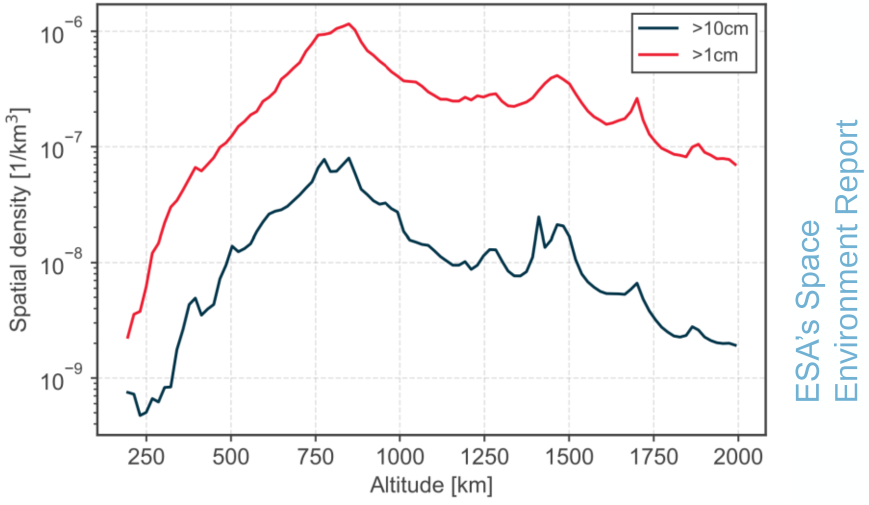
https://sdup.esoc.esa.int/drama/python_package_docs/index.html

Space Debris User Portal (esa.int) · Tools · DRAMA

Cumulative collision probability computation

1. OSCAR for disposal trajectory computation
2. Discretise trajectory: steps of 10 km in perigee altitude (LEO)





1 cm calibrated population (no forecast)

3. ARES annual collision probability (ACP) over each slice
4. Scale to slice duration (Δt) and aggregate probabilities

Orbital clearance: script inputs

- OSCAR input file (from DRAMA GUI or template)

Spacecraft parameters	• Mass • Cross-sectional area **Including appendages** e.g. solar panels
Disposal options	• Free drift or delayed de-orbit • **Target lifetime** configurable e.g. [1.5, 3, 5] years in script
Begin date	• End of operation epoch • Varied forward over solar cycle (yearly steps)
Initial orbit	• Starting orbit of disposal
Solar activity scenario	• May be performed with different solar activity models

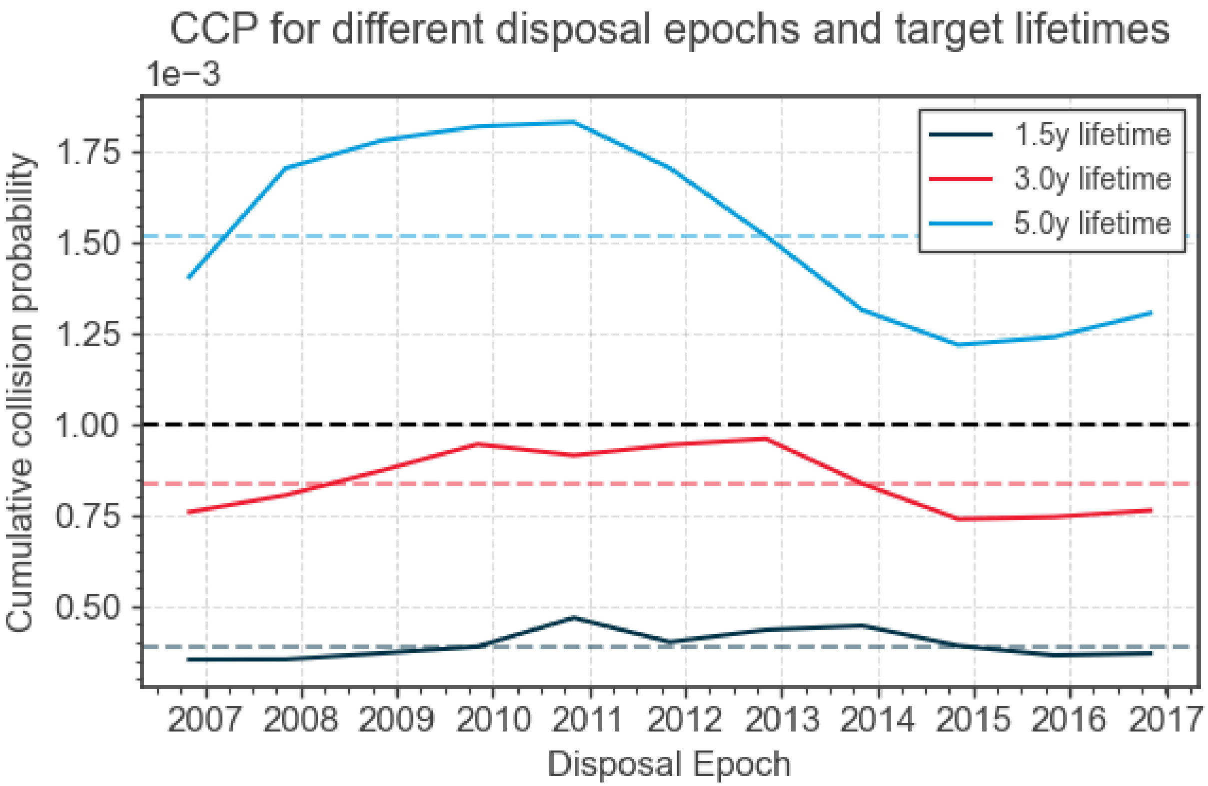
- Runs in a parallelised fashion

6.2

Verification and validation requirements

e) […] The cumulative collision probability is computed considering the complete space object geometry, **including appendages**, unless it is demonstrated that specific appendages can be hit by objects larger than 1 cm without generating space debris.

Orbital clearance: script outputs

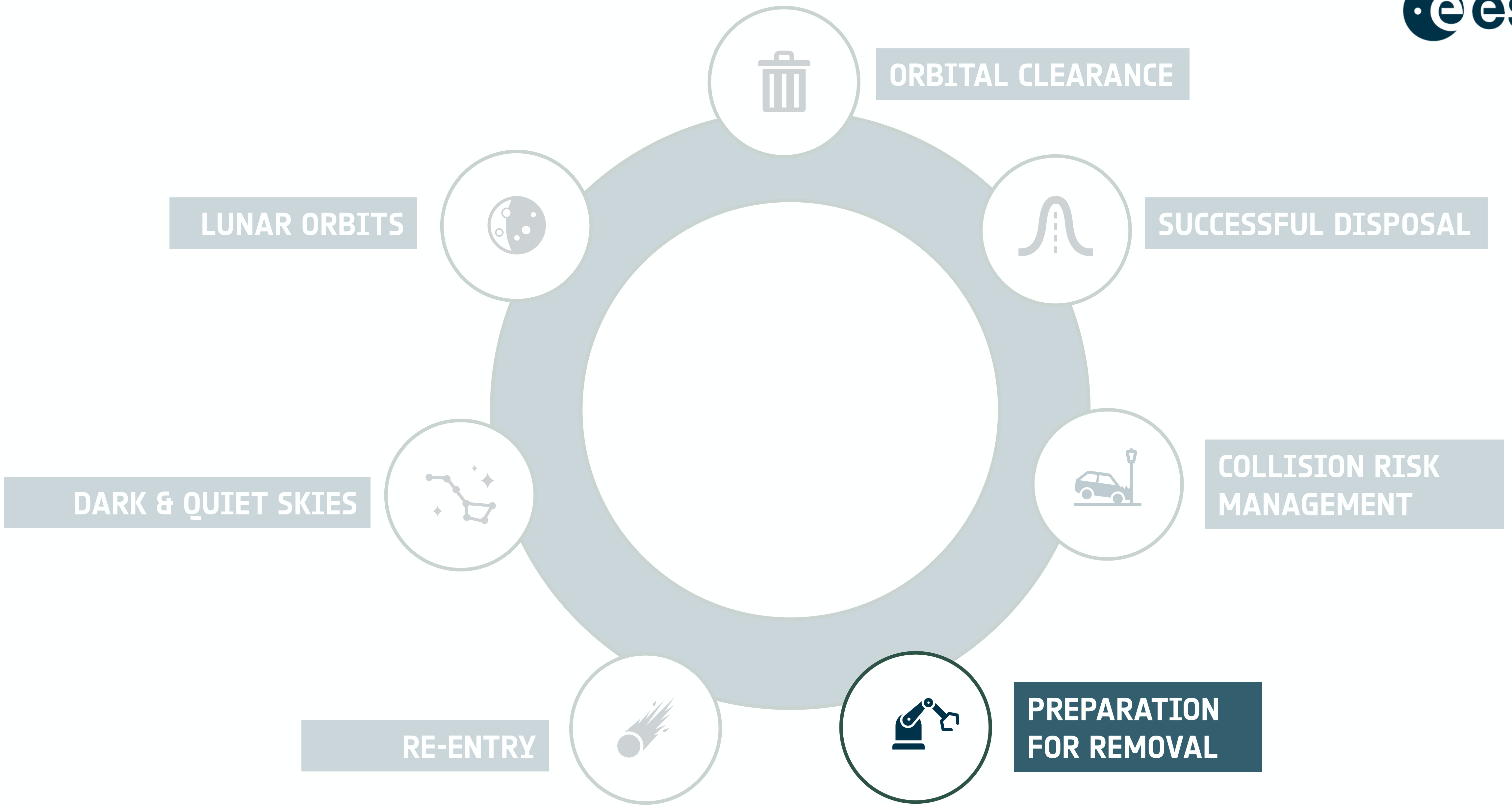


5-year lifetime would not be compliant with cumulative probability requirement

Median value of sampled trajectories
(or trajectory closest to median computed lifetime)

Vary disposal epoch over solar cycle →

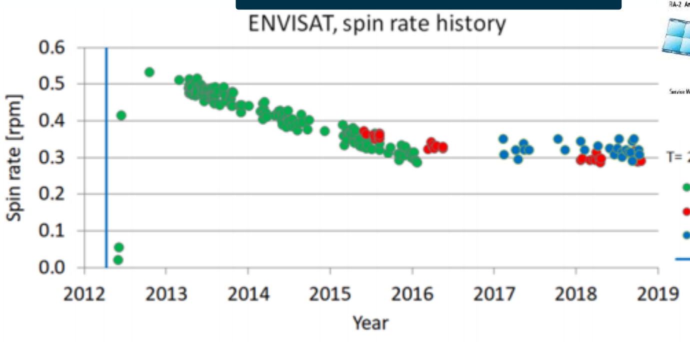
CCP: Cumulative Collision Probability

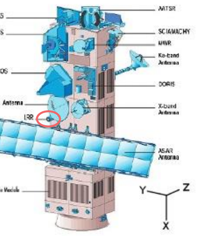

ORBITAL CLEARANCE
SUCCESSFUL DISPOSAL
COLLISION RISK MANAGEMENT
PREPARATION FOR REMOVAL
RE-ENTRY
DARK & QUIET SKIES
LUNAR ORBITS

Why Design-for-Removal is needed?

Active Debris Removal (ADR) is challenging, but crucial to maintain a sustainable orbital environment

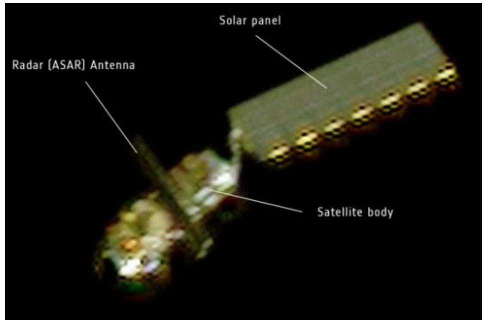
Debris object spin



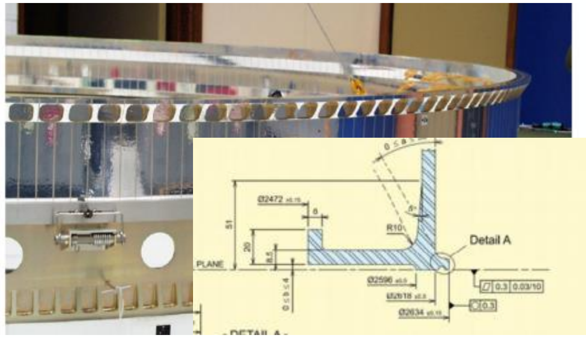


ENVISAT Retroreflector

Debris object not designed for capture



Missing capture interfaces



To enable ADR, we need to prepare the satellites to be removed → Design for Removal (D4R)

D4R implies dedicated modifications to cover certain **functions,** in order to ease removal by external servicer and decrease associated risks and costs

The most optimal approach is to find a **standard D4R solution (or standard D4R interface)** for all missions → only one servicer design

What is a standard D4R interface?

A standard D4R solution or interface shall cover different functions:

- Capture
- Relative navigation for rendezvous
- Attitude reconstruction from ground — LEO
- Detumbling — LEO

Debris removal service description

Cooperative

- The satellite is operational but unable to perform the end-of-life functions with respect to removal from orbit.

Uncooperative

- The satellite is non-operational (either completely or with respect to attitude control) and tumbling.

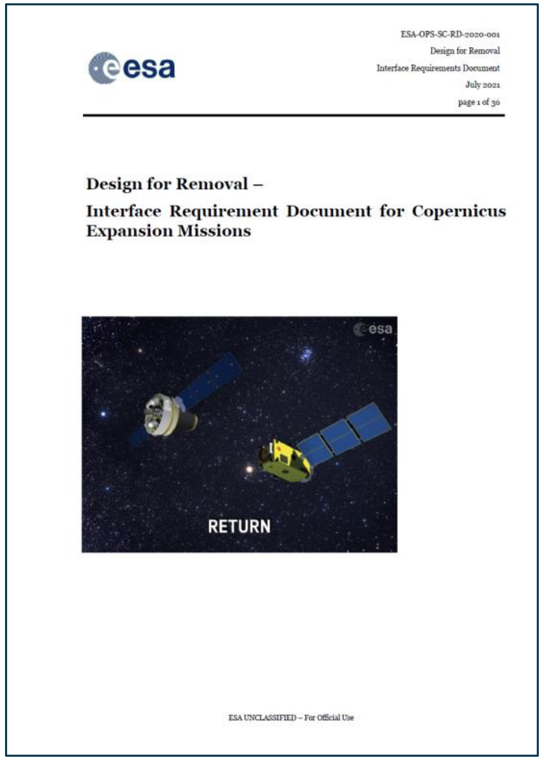
For **cooperative scenario** and prepared targets, it is assumed the target:

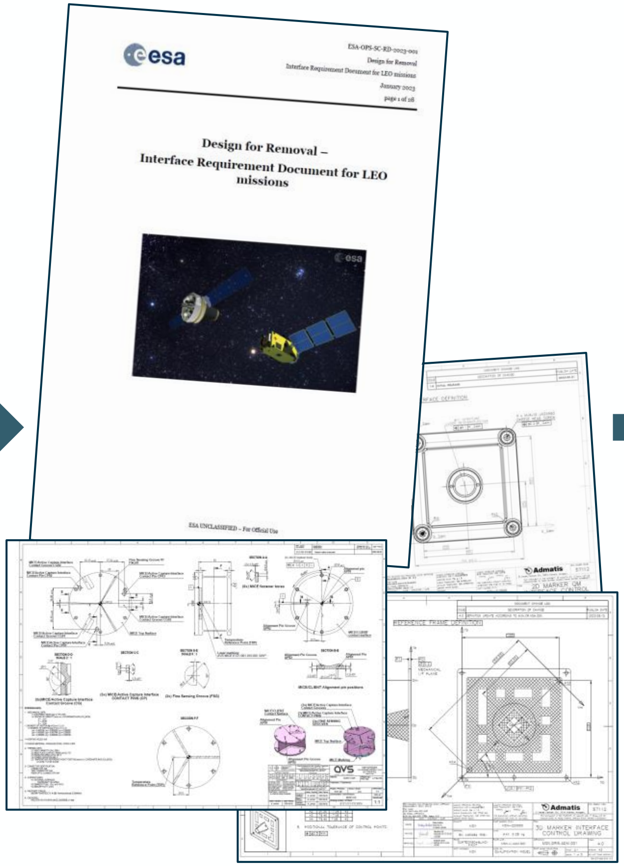
- Is prepared for capture (e.g. dedicated mechanical capture interface, rendezvous markers / navigation supports implemented)
- Can provide telemetry to the mission control centre of the debris removal service provider
- Capable to perform attitude control
- Will not hinder the capture process (e.g. thrust during the final moment before capture).

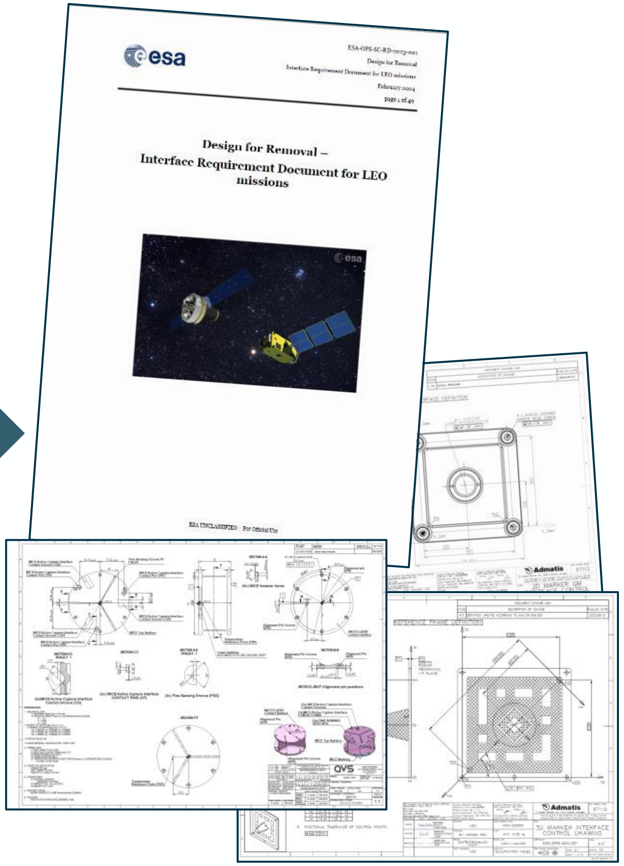
For **uncooperative scenario** and prepared targets, it is assumed the target is:

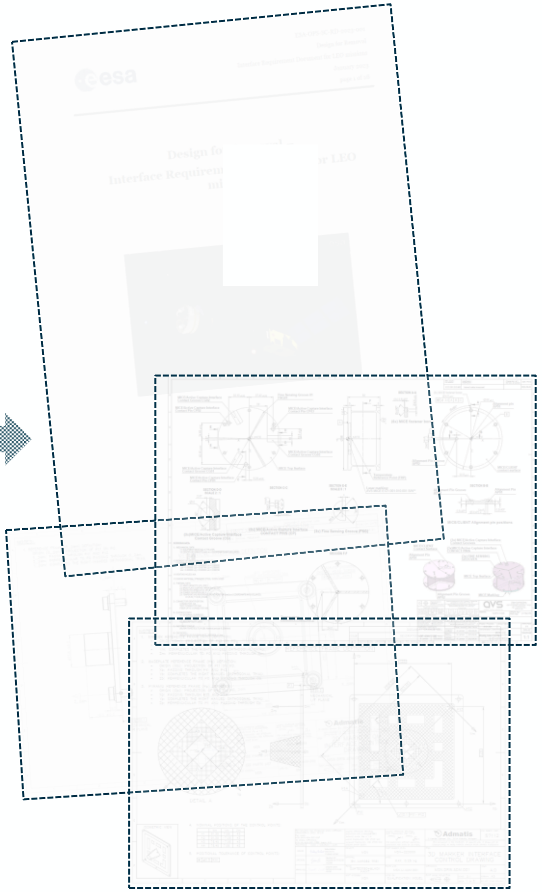
- Prepared for capture (e.g. dedicated mechanical capture interface, rendezvous markers / navigation supports implemented)
- Unable to provide telemetry on the status, all information on target status based on observations from ground
- Characterisation of tumbling motion shall be done in orbit by the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

D4R Interface Requirements Document









First D4R IRD for Copernicus Expansion Missions released in 2020	First D4R IRD for LEO missions released in 2023 MICE, 2D marker and 3D marker ICDs	Second D4R IRD for LEO missions released in 2024 MICE, 2D marker and 3D marker ICDs	Future D4R IRD data-package releases for other applications
Applicable for Copernicus only	Applicable for LEO missions performing a controlled re-entry	Applicable for LEO missions performing controlled or uncontrolled re-entry	

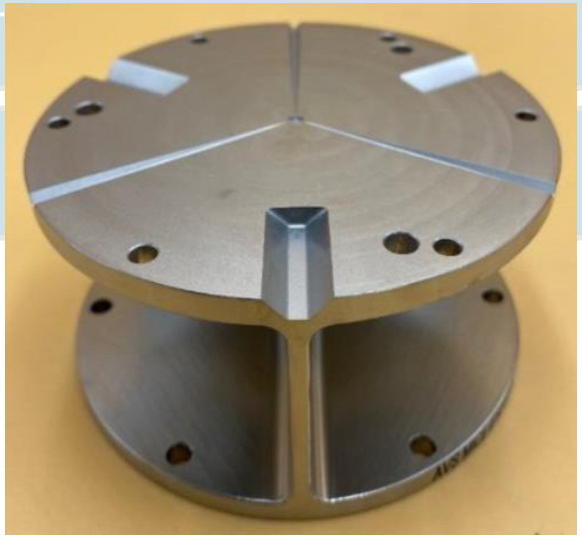
D4R Technologies - Capture

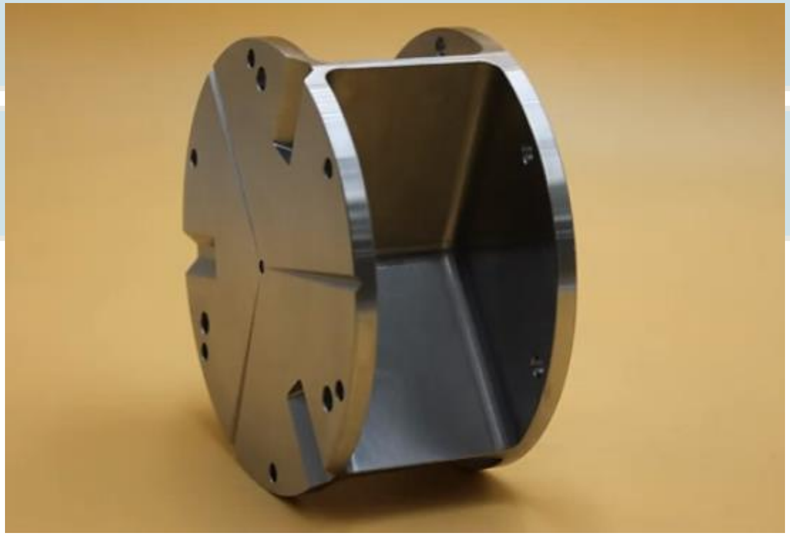
Capture

Relative navigation for rendezvous

Attitude reconstruction from gr

Detumbling





MICE – Mechanical Interface for Capture at EOL

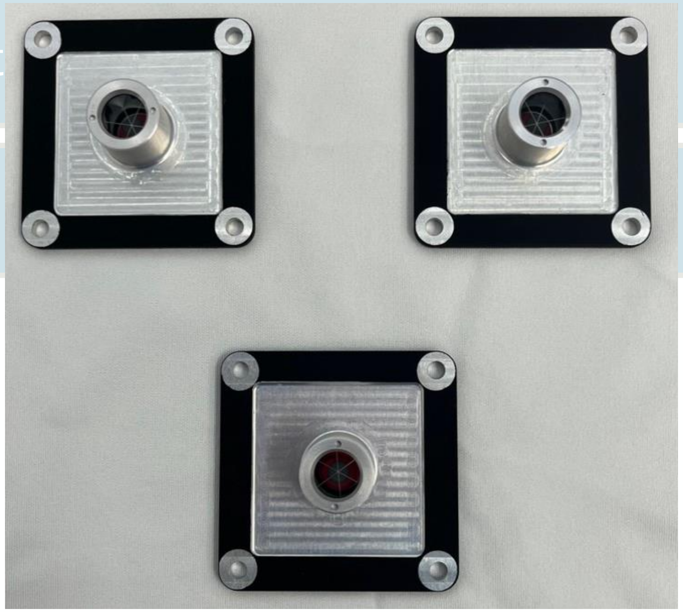
D4R Technologies – Relative Navigation and attitude reconstruction

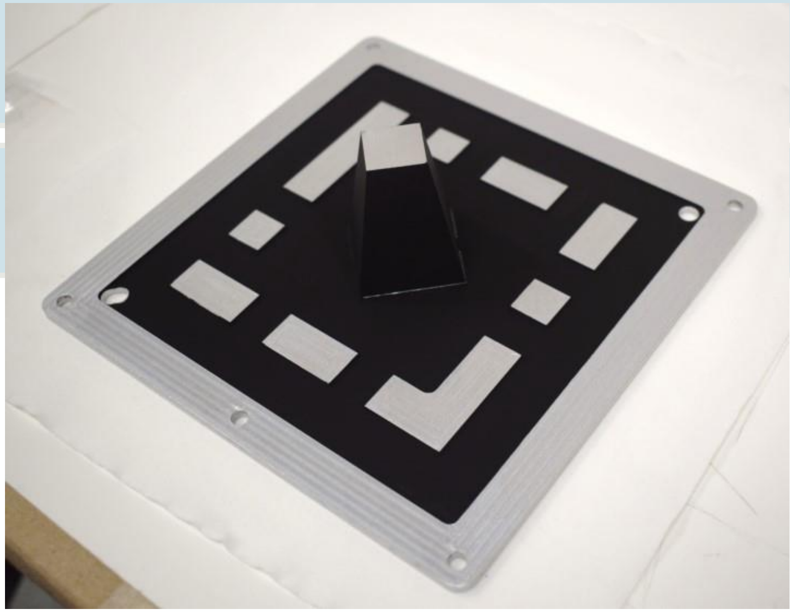
Capture

Relative navigation for rendezvous

Attitude reconst

Detumbling





MSN – Markers to Support Navigation

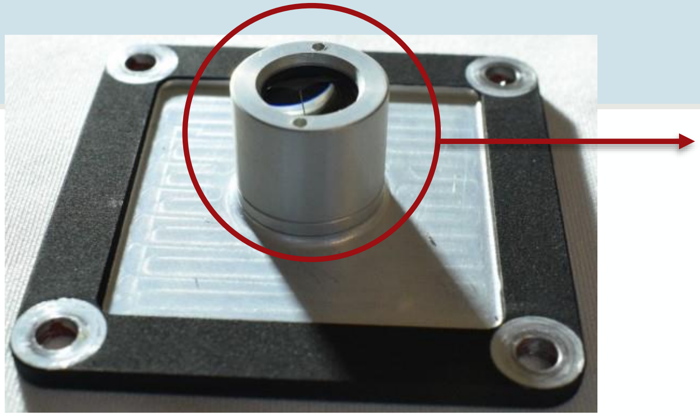
D4R Technologies – Relative Navigation and attitude reconstruction

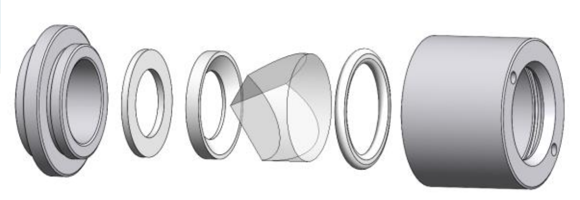
Capture

Relative navigation for rendezvous

Attitude reconstruction from ground

Detumbling





LRRs – Laser Retro-Reflectors (embedded on 2D Markers)

D4R Technology – Detumbling

Capture

Relative navigation for rendezvous

Attitude reconstruction from ground

Detumbling

Short-circuited magnetorquers

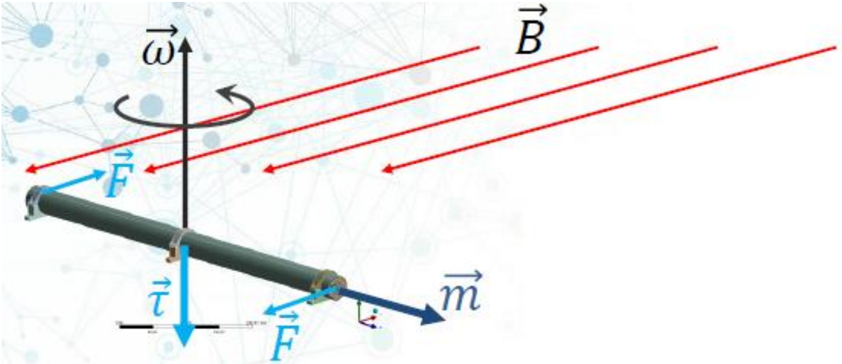
Stabilisation of tumbling motion

Short-circuited magnetorquer

Patent Reference:
213130EP TE/BD

Idea: a short-circuited magnetorquer can still produce a torque helping detumbling…

1. a rotating satellite in LEO sees a time-dependent magnetic field created inside the magnetorquer
2. the magnetic flux variation produces an electromotive force at the magnetorquer terminals
3. an induced current is generated on the coil wire
4. resulting in the magnetorquer magnetic moment and generated torque
5. the dissipation of rotational kinetic energy is achieved through Joule effect inside the magnetorquer



Magnetic moment induced by changes in magnetic flux

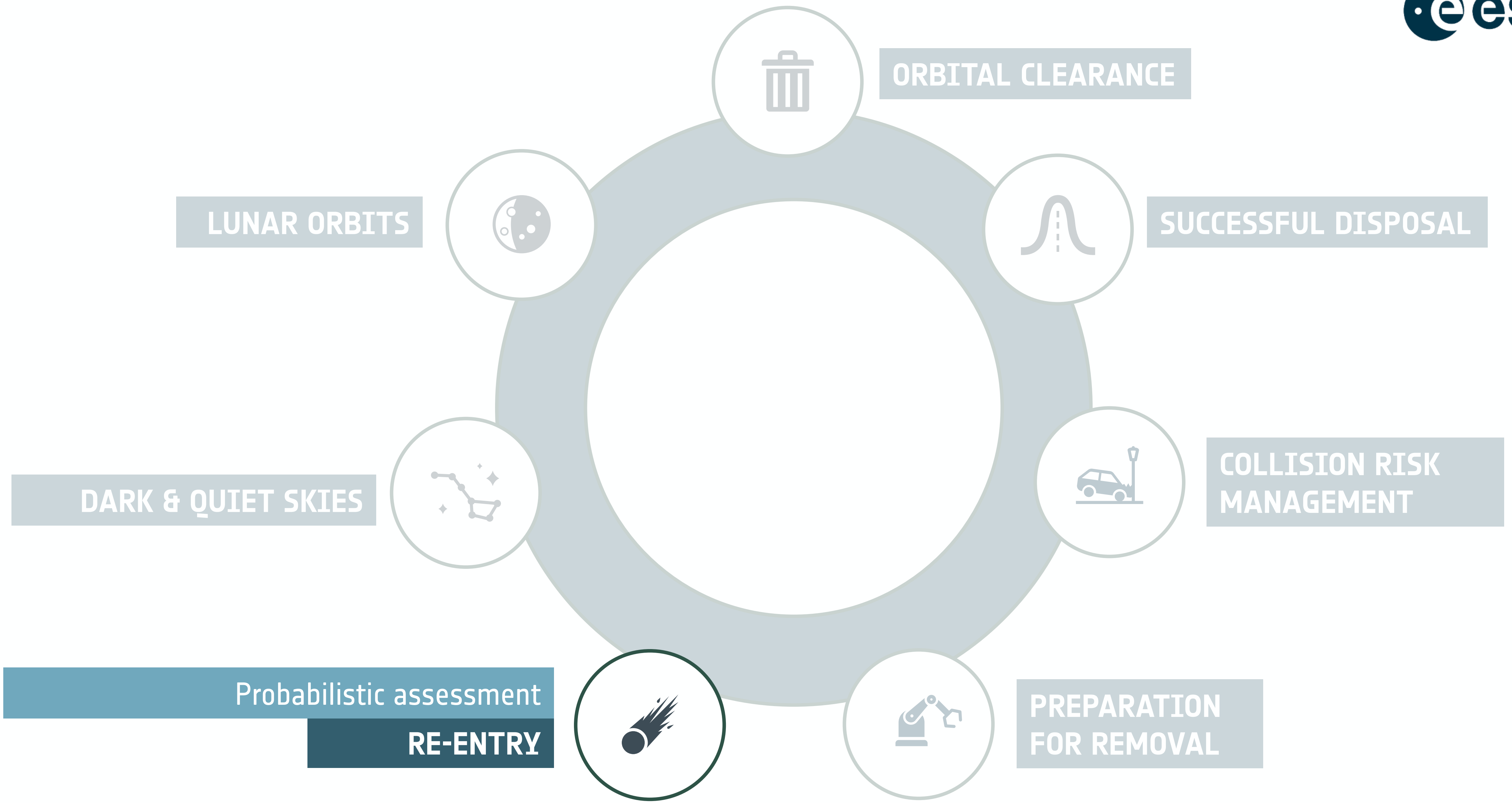
Proof of concept of short-circuit triggering system (left)
and short-circuited magnetorquer (right)

How can we design for the cooperative scenario?

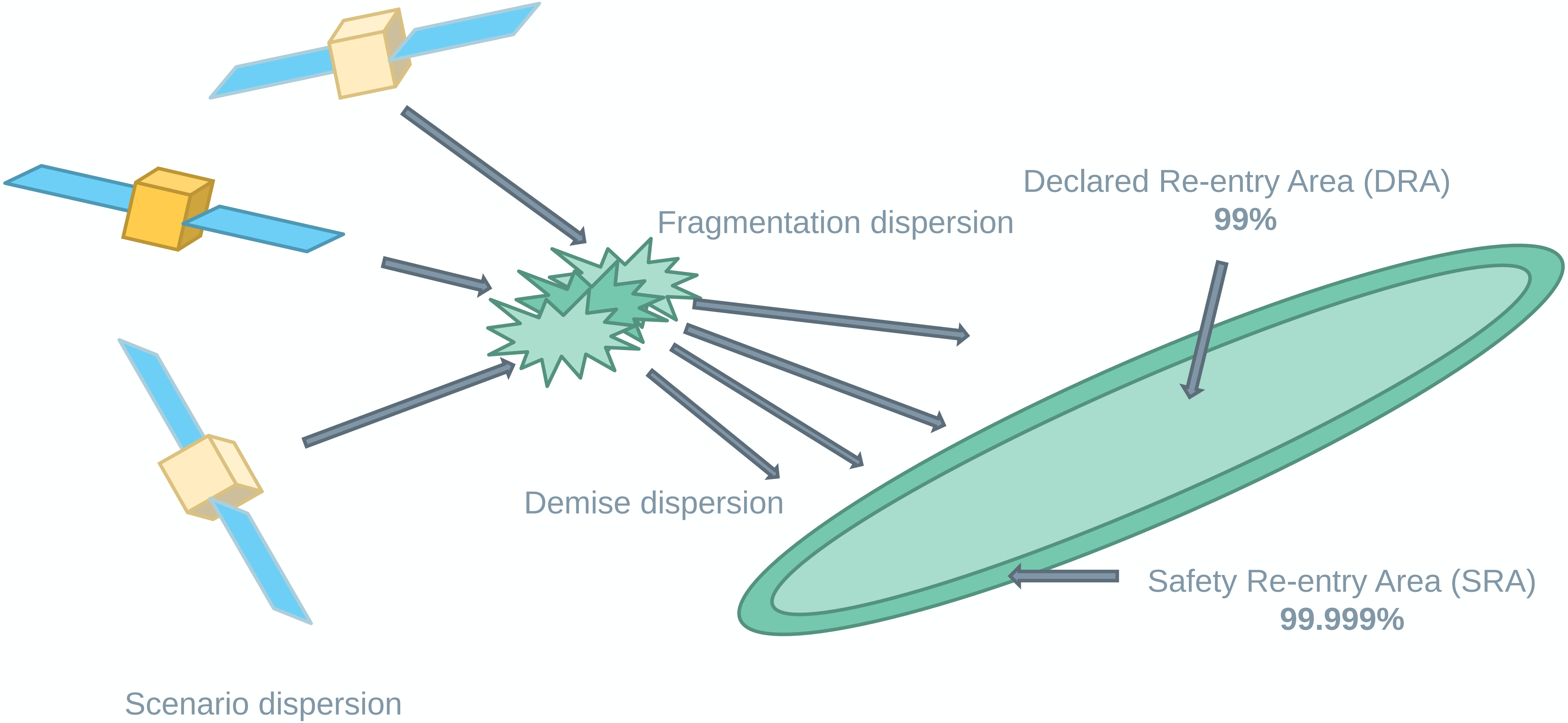
…given that no service is currently readily available in LEO?

We understand that this is a gradual process, so a first step is to design a Safe Mode compatible with capture i.e.

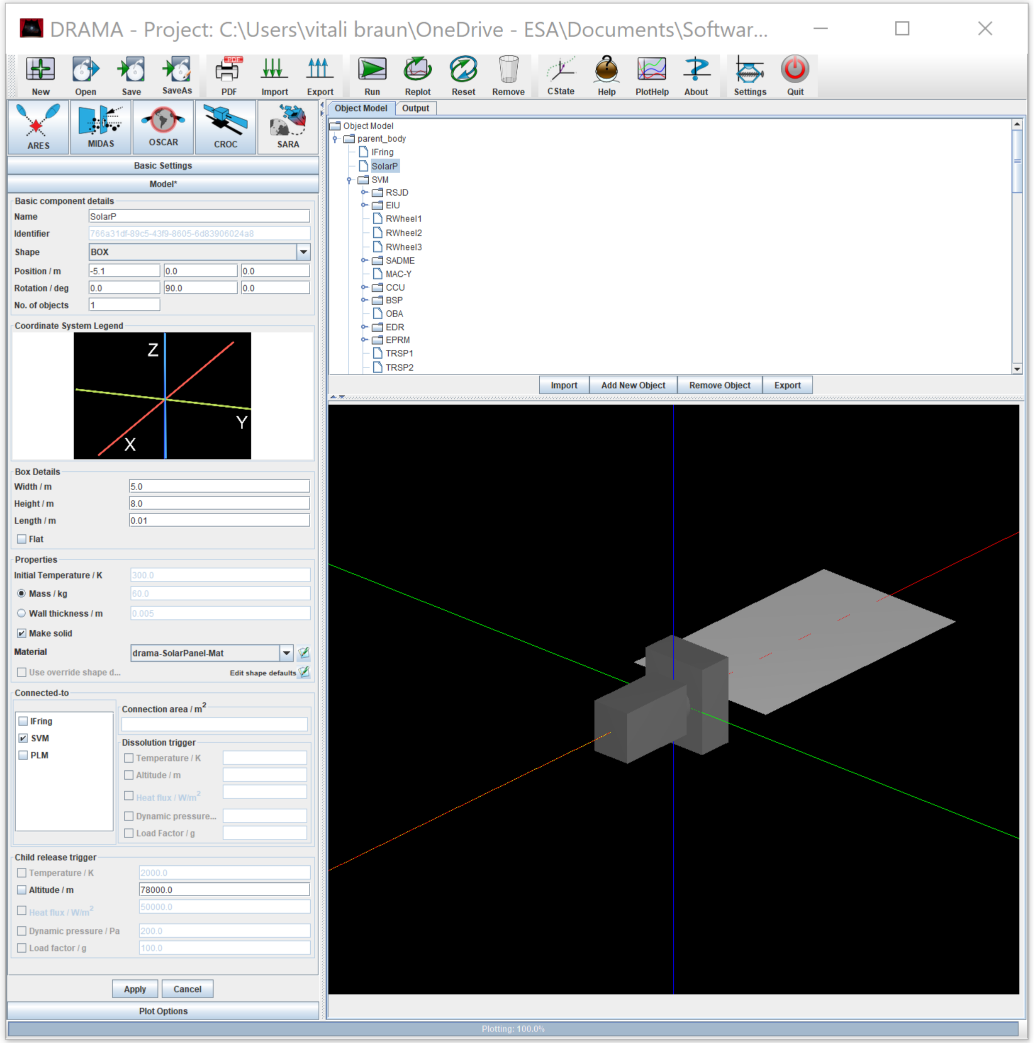
- stable angular rates
- prevention of AOCS from reacting against capture
- orientation of appendages to ensure access to the mechanical capture interface

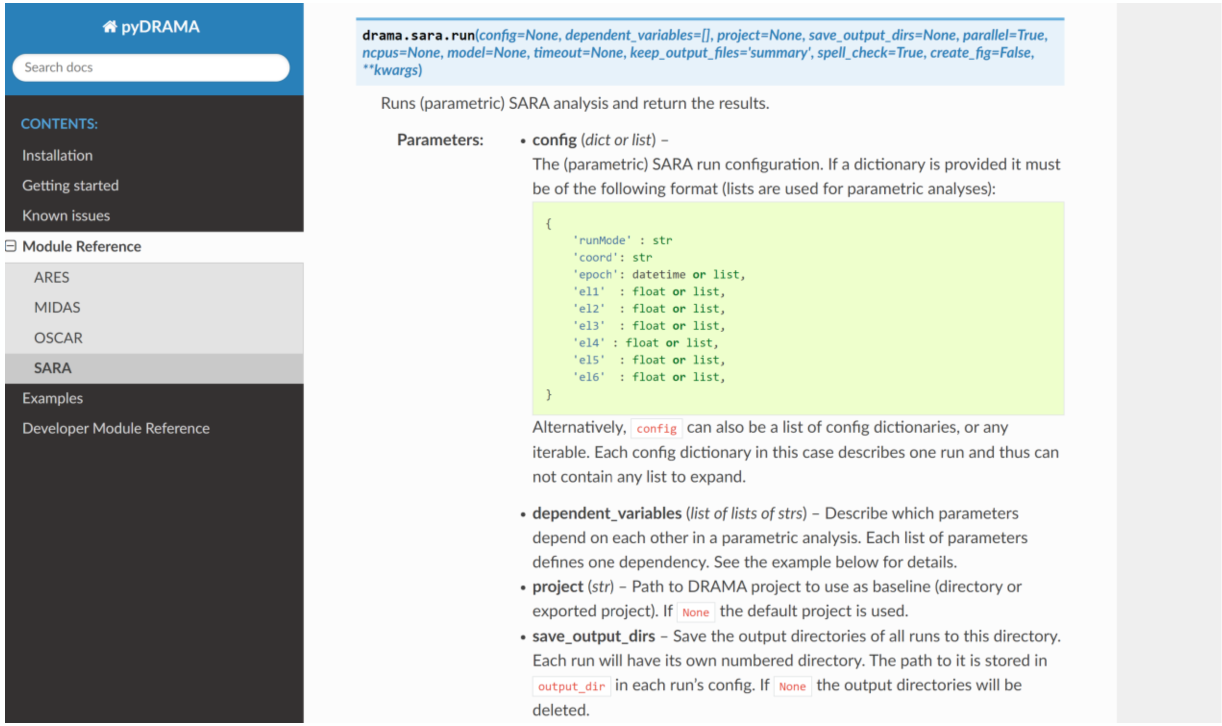

ORBITAL CLEARANCE
SUCCESSFUL DISPOSAL
COLLISION RISK MANAGEMENT
PREPARATION FOR REMOVAL
Probabilistic assessment
RE-ENTRY
DARK & QUIET SKIES
LUNAR ORBITS

Probabilistic Assessment of Re-entry Risk



DRAMA 3.1.0 and Python Package





https://sdup.esoc.esa.int/

Space Debris User Forum

Space Debris Forum ▾ Home

- Topics
- My Posts
- More

Categories
- In-situ detection
- Site Feedback
- Uncategorized
- All categories

Tags
- dmf
- master
- drama
- in-situ
- All tags

Example Scripts for Performing Monte Carlo Analyses using SARA

Daniele Bella May '23

Calculating the SRA and DRA (Safety and Declared Reentry Areas) for a mission, as well as the on-ground casualty risk, is an important part of a controlled reentry's safety analysis. One of the ways that it can be computed is through the use of a Monte Carlo simulation.

Though the DRAMA GUI provides a "Monte Carlo Analysis" mode, this is in reality a parametric analysis, without randomised parameters. However, it is possible to use DRAMA for "true" randomised Monte Carlo analyses using the DRAMA python package and some scripting. In order to show how this could be performed, and how each of the major parameters of a SARA run can be randomised, we created a set of example scripts. These were designed to be used as a reference and/or starting point during the development of more complex and comprehensive calculations; they are thus heavily commented and feature simplified algorithms, for the sake of understandability. They can and should be expanded upon based on the needs of your analysis, in order to encompass other parameters or to make use of more rigorous but more complex methods.

In fact, if you have any suggestions for improvements, or want to share your experience in tailoring them to a mission's needs, don't hesitate to reply to this post! Everyone can then learn from it, and in future it even helps us provide better examples and tools.

What the example scripts cover

- Opening a nominal example SARA project
- Creating an arbitrary number of randomised inputs, including uncertainty on a deorbit burn
- Compiling these inputs into the format required for SARA
- Running SARA in a parallel fashion for each case
- Parsing the results, calculating the overall casualty risk
- Using the location of the fragments, using a simplified and conservative algorithm to calculate the SRA and DRA

These are all the necessary files:

SARA_MC_script.py (10.3 KB)
SARA_MC_helpers.py (20.0 KB)
example_project.dpz (3.8 MB)

May 2023

1 / 1
May 2023

May 2023

https://debris-forum.sdo.esoc.esa.int/

Main code

```python
if __name__ == "__main__":
    # Load the base model
    base_model = sara.get_model(project=PROJECT)
    # Load the base config
    base_config = sara.get_basic_config(project=PROJECT)

    # Generate the list of randomised configs, models and project_paths
    configs = create_config_from_burn(
        base_config, START_ORBIT_STATE, DELTA_V, n=NUM_RUNS
    )
    models = randomise_model(base_model, n=NUM_RUNS)
    project_paths = randomise_project_xml(PROJECT, n=NUM_RUNS)

    # Get inputs in the correct format for multiprocessing
    func_inputs = []
    for i in range(NUM_RUNS):
        func_inputs.append([models[i], configs[i], project_paths[i], i])

    print("Created config, running SARA...")
    with Pool(NCPUS) as p:
        p.starmap(run_sara, func_inputs)

    # Parse the result
    parsed_reentry_result = parse_reentry_results_xml("output")
    parsed_risk_result = parse_risk_results_xml("output")

    # We now have the locations of every single fragment! We can use this however we like.
    # For example, we could use it to calculate the SRA and DRA from the impacts. Here is a
    # very simplified function
    ra_df = calc_reentry_area(parsed_reentry_result, [0.99, 0.9999])

    # Calculate the total 2D casualty risk for the whole simulation
    tot_casualty_risk = 1 - np.prod(
        1 - parsed_risk_result["totalCasualty2D"] / NUM_RUNS
    )
    print(f"The computed casualty risk is {tot_casualty_risk}")

    ## Plot the data
    SRA_boundary = ra_df[ra_df["Threshold"] == 0.99]
    SRA_boundary = pd.concat([SRA_boundary, SRA_boundary])
```

- Load nominal model and conditions from DRAMA project
- **Create N runs with independently randomised parameters**
    1. Randomise orbit and final burn
    2. Randomise the SARA model properties
    3. Randomise material properties
- Run SARA in a parallelised fashion
- Parse outputs
- Calculate SRA and DRA
- Calculate Overall (averaged) casualty risk
- Plots

1. Initial conditions in stochastic simulations

Example scenario uncertainties available in ESSB-HB-U-002:

Table D-1: Approach for initial conditions for stochastic simulations

Re-entry type	Orbit type	Initial Conditions	Uncertainties
Uncontrolled	Decaying circular orbit	Altitude: 130 km x 130 km Semi-major axis: 6501 km	Argument of perigee with uniform distribution across an
Uncontrolled	Targ circu		
Controlled	Targ circu		
Uncontrolled or controlled	High eccer or inter		

D.2.2.1 Uncertainties for nominal controlled or off-nominal uncontrolled re-entry

The re-entry casualty risk analysis is performed for each relevant mission scenario with sufficient confidence to cover all re-entry uncertainties:

- Nominal case, e.g. controlled or uncontrolled re-entry.
- Off-nominal cases, e.g. degraded controlled re-entry and uncontrolled re-entry due to failures prior to enter the nominal case.

The uncertainties for the nominal and off-nominal cases are identified and taken into account depending on the space system design and operations.

For example, the following dispersion parameters have been considered for the ESA ATV controlled re-entries:

a. Position at last boost ignition: ±3 km

b. Burn Start Time: ±5 s

c. Delta-v realisation dispersion: Gaussian, 1σ (e.g. ±5 %)

ESA UNCLASSIFIED – For Official Use

esa

estec

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands

T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

DOCUMENT

ESA Space Debris Mitigation Compliance Verification Guidelines

Prepared by	ESA Space Debris Mitigation WG
Reference	ESSB-HB-U-002
Issue	2
Revision	0
Date of Issue	14 February 2023
Status	Approved
Document Type	HB
Distribution	ESA

...but should be tailored to your mission

1. Initial conditions in stochastic simulations

```python
# Position uncertainty
######################

# Create random unit directions to have noise be in
dir_array = np.random.uniform(low=-1, high=1, size=(n, 3))
dir_array_norm = np.linalg.norm(dir_array, axis=1)
dir_array = dir_array / np.tile(dir_array_norm, (3, 1)).T

# Scale this random direction by a random scale
pos_scale_arr = np.random.uniform(low=0, high=pos_uncert, size=(n))
pos_noise_arr = dir_array * np.tile(pos_scale_arr, (3, 1)).T

# Manoeuvre uncertainty
#######################

# Apply uncertainty to the delta-V scale
delta_v_thrust_scale = np.random.uniform(
    low=1 + thrust_uncert_bounds[0], high=1 + thrust_uncert_bounds[1], size=(n)
)
delta_v_scale = np.random.normal(1, delta_v_sigma, size=(n))

# Calculate randomisation of delta-V direction; creating a new coordinate system to be able
# to apply random angles

# Need any vector that isn't collinear with the delta-v vector, and not ill-conditioned
# coord_const_vec = [1, 0, 0] if all(np.cross([1, 0, 0], delta_v)) == 0 else [0, 1, 0]
coord_const_vec = np.zeros((3))
coord_const_vec[np.argmin(np.abs(delta_v))] = 1

# Generate unit vectors of coordinate system
delta_v_arr = np.array(delta_v)
x_vec = np.expand_dims(
    np.cross(coord_const_vec, delta_v_arr)
    / np.linalg.norm(np.cross(coord_const_vec, delta_v_arr)),
    -1,
)
y_vec = np.expand_dims(
    np.cross(x_vec[:, 0], delta_v_arr)
    / np.linalg.norm(np.cross(coord_const_vec, delta_v_arr)),
    -1,
)
z_vec = np.expand_dims(delta_v_arr / np.linalg.norm(delta_v_arr), -1)
```

Example script uses **ATV example** from the handbook

- Position dispersion (uniform)
- Delta-v dispersion (Gaussian)
- Randomised angle deviations for thrust vector

Set of initial conditions can come from **mission analysis**

```python
# Generate random angles to rotate the thrust by
angle_rots = np.deg2rad(np.random.normal(0, delta_v_angle_sigma, size=(n, 2)))
angle_vects = (
    x_vec @ np.expand_dims(np.sin(angle_rots[:, 0]) * np.cos(angle_rots[:, 1]), 0)
    + y_vec @ np.expand_dims(np.sin(angle_rots[:, 0]) * np.sin(angle_rots[:, 1]), 0)
    + z_vec @ np.expand_dims(np.cos(angle_rots[:, 0]), 0)
)

delta_v_randomised = (
    angle_vects * delta_v_scale * delta_v_thrust_scale * np.linalg.norm(delta_v)
).T
```

1. Nominal Initial conditions: script input

Note: Script does not use the initial conditions present in the DRAMA project

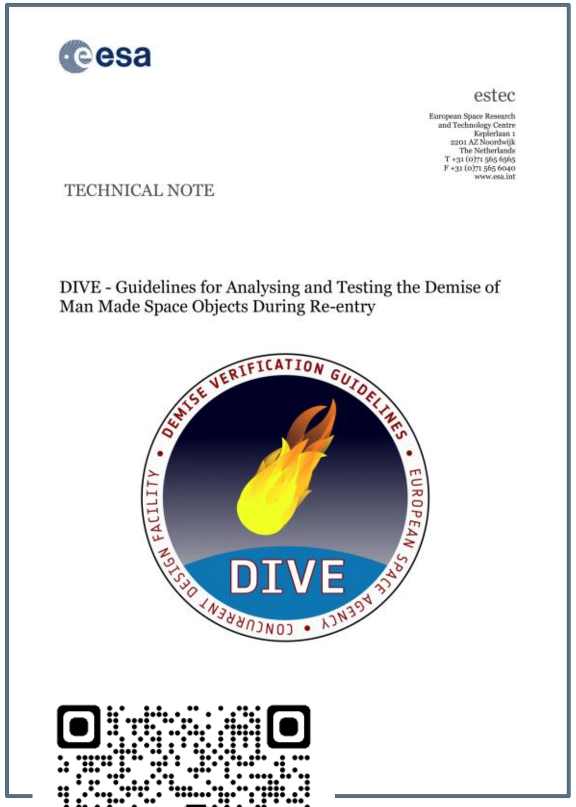
```
PROJECT = "example_project.dpz"
NUM_RUNS = 100
NCPUS = 2

# Initial orbital state, at but before the final burn. Cartesian elements ECI 2000:
# [x, y, z, dx/dt, dy/dt, dz/dt], units in km and km/s
START_ORBIT_STATE = [
    6472.6,
    491.8,
    -58.0,
    -0.5766527384119823,
    7.719100561002604,
    1.3687058837186878,
]

# Delta V to apply, same coordinate system:
# [dx/dt, dy/dt, dz/dt], km/s
DELTA_V = [0.00365274, -0.04910056, -0.00870588]
```

- Set Initial nominal state (before burn)
- Applied (nominal) delta-v of final burn

2. Model dispersions (DIVE – ESA-TECSYE-TN-018311)

```
num_el = len(orig_model.el)
num_cn = len(orig_model.cn)
num_inc = len(orig_model.inc)

# Elements
##########

# Global aerodynamic scaling (drag and heat flux), due to density uncertainty
glob_drag_factor = np.random.normal(loc=1, scale=glob_drag_unc_sigma, size=(n))
glob_heat_factor = np.random.normal(loc=1, scale=glob_heat_unc, size=(n))

# Individual element drag offset
drag_factor = np.random.uniform(1 - drag_unc, 1 + drag_unc, size=(n, num_el))
heat_factor = np.random.uniform(1 - heat_unc, 1 + heat_unc, size=(n, num_el))

# Mass uncertainty
mass_factor = np.random.normal(loc=1, scale=mass_unc_sigma, size=(n, num_el))

# Connectors
############

height_offset_cn = np.random.uniform(
    -height_unc_cn, height_unc_cn, size=(n, num_cn)
)
temp_offset_cn = np.random.uniform(-temp_unc_cn, temp_unc_cn, size=(n, num_cn))
pres_factor_cn = np.random.uniform(
    1 - pres_unc_cn, 1 + pres_unc_cn, size=(n, num_cn)
)

# Inclusions
############
height_factor_inc = np.random.normal(
    loc=1, scale=height_unc_inc_sigma, size=(n, num_inc)
)
```

- Object-wise global drag and mass uncertainty
- Connectors breakup altitude uncertainty (also pressure, temperature)
- Inclusions breakup altitude uncertainty


esa

estec

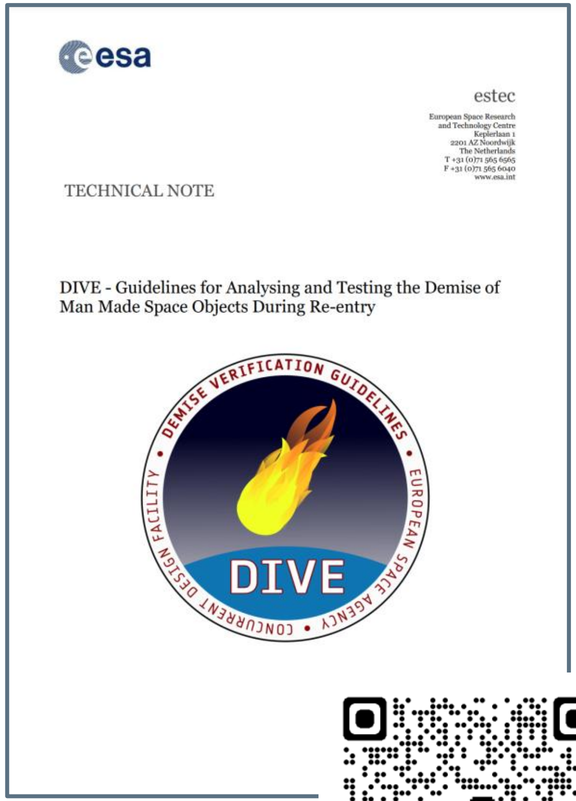
European Space Research and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

TECHNICAL NOTE

DIVE - Guidelines for Analysing and Testing the Demise of Man Made Space Objects During Re-entry

3. Material dispersions (DIVE – ESA-TECSYE-TN-018311)

```python
# Generate the random numbers for the MC run
alloy_melt_offset = np.random.uniform(
    -alloy_melt_unc, alloy_melt_unc, size=(n, num_materials)
)
oxidised_emissivity_factor = np.random.triangular(
    left=1 - oxidised_emissivity_unc_factor,
    mode=1,
    right=1 + oxidised_emissivity_unc_factor,
    size=(n, num_materials),
)
heat_cap_factor = np.random.normal(
    loc=1, scale=heat_cap_sigma, size=(n, num_materials)
)
latent_melt_factor = np.random.normal(
    loc=1, scale=latent_melt_sigma, size=(n, num_materials)
)
```


esa

estec

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

TECHNICAL NOTE

DIVE - Guidelines for Analysing and Testing the Demise of Man Made Space Objects During Re-entry

Monte Carlo Guidelines: How many samples?

ESSB-HB-U-002: Appendix M.2

The Monte Carlo analysis should be executed until **convergence of the percentiles**, and not solely be based on a maximum number of samples.

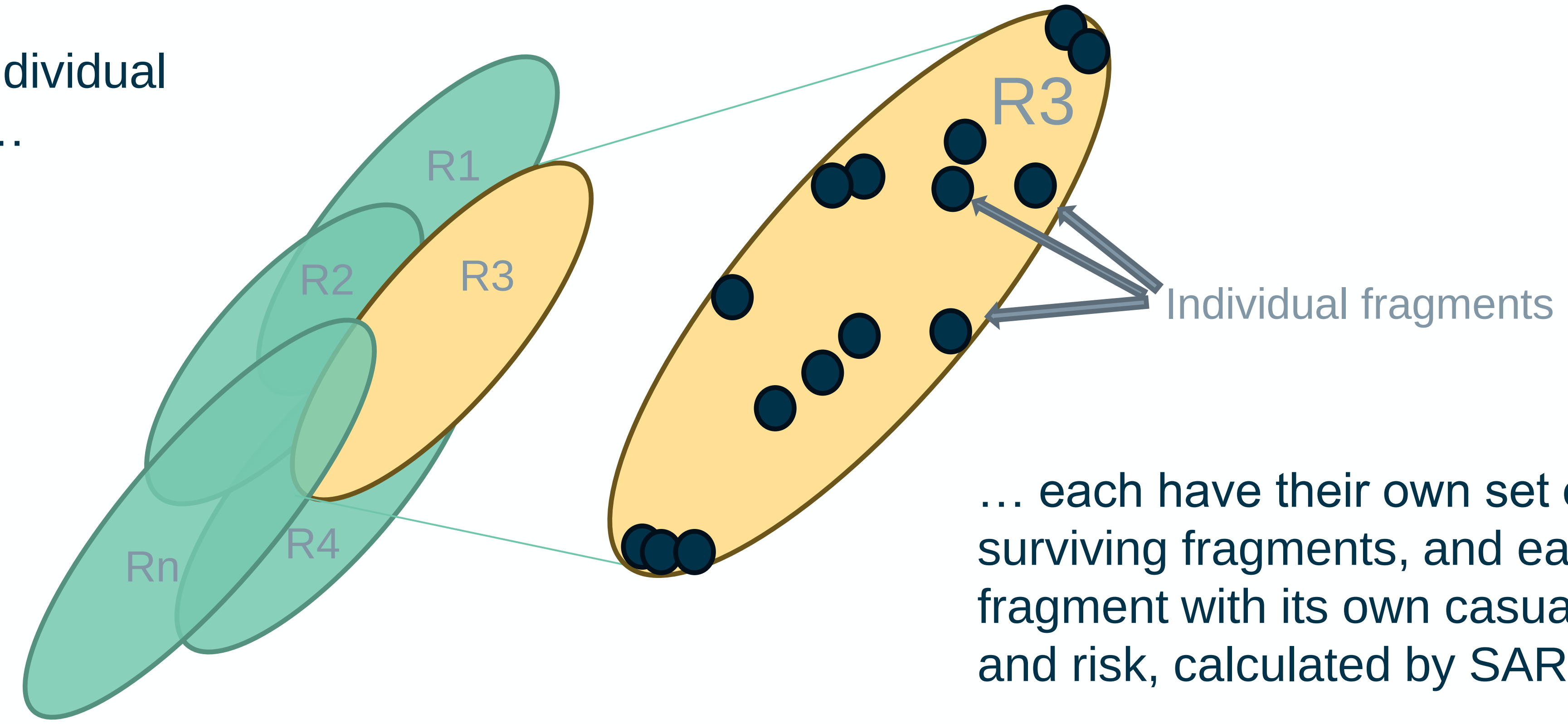
Example Criteria

- *The 95% confidence interval in the mean value of the total landed mass is within 2.5% of the current value.*
- *The 95% confidence interval in the mean value of the number of landed fragments is within 5% of the current value.*
- *The 95% confidence interval in the mean value of the landed mass of each individual component is within either 0.2kg or 10% of the current estimate for all components which land in 1% of simulations.*

The recommended minimum number of runs is **2000.**

Then run SARA… and analyse the results

We now have the individual results of each run…



… each have their own set of surviving fragments, and each fragment with its own casualty area and risk, calculated by SARA

Calculating the total (averaged) risk from here is very straightforward

```
# Calculate the total 2D casualty risk for the whole simulation
tot_casualty_risk = 1 - np.prod(
    1 - parsed_risk_result["totalCasualty2D"] / NUM_RUNS
)
```

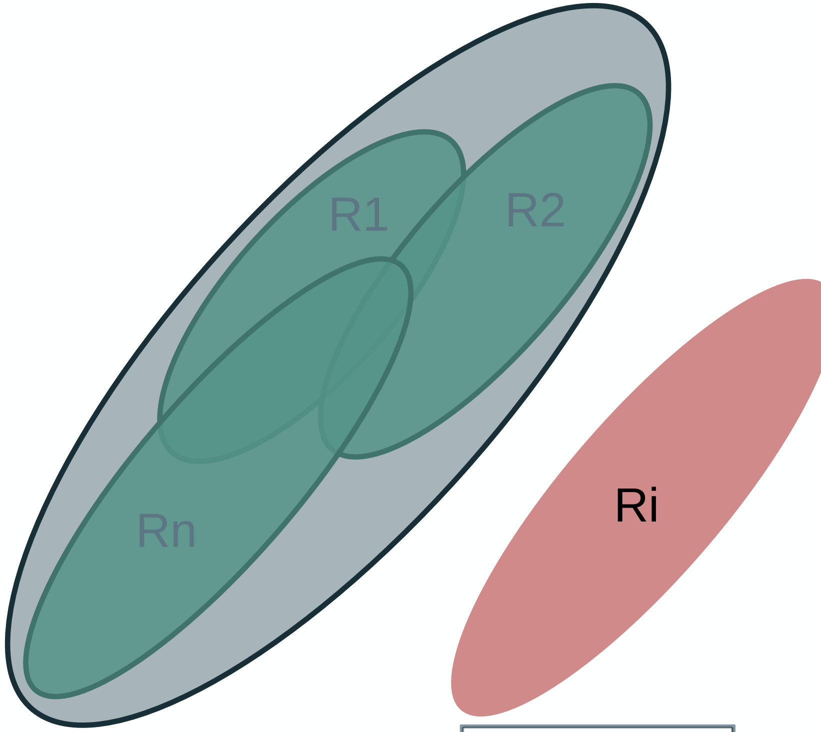
Results: Calculate DRA/SRA

D.2.13 Declared Re-entry Area (DRA) and Safety Re-entry Area (SRA)

The Declared Re-entry Area (DRA) and the Safety Re-entry Area (SRA) are computed following several simulation runs (Monte Carlo), which are based on the dispersions of the relevant variables to cover all uncertainties of the model (see section D.2.2), where the amount of runs yield stable confidence intervals (see Figure D-7):

a. The Declared Re-entry Area (DRA) delimits the area where the debris are enclosed with a probability of 99% given the delivery accuracy.

b. The Safety Re-entry Area (SRA) delimits the area where the debris are enclosed with a probability of 99,999% given the delivery accuracy.

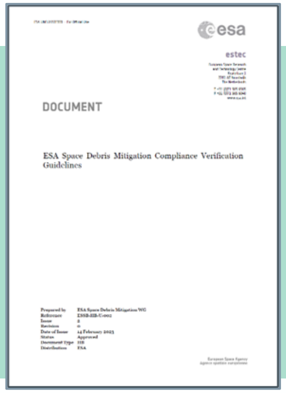


Optimisation Problem - many ways of calculating this

Important Note:

- 99/99.999% of **runs**
- **NOT** 99/99.999% of the **fragments**

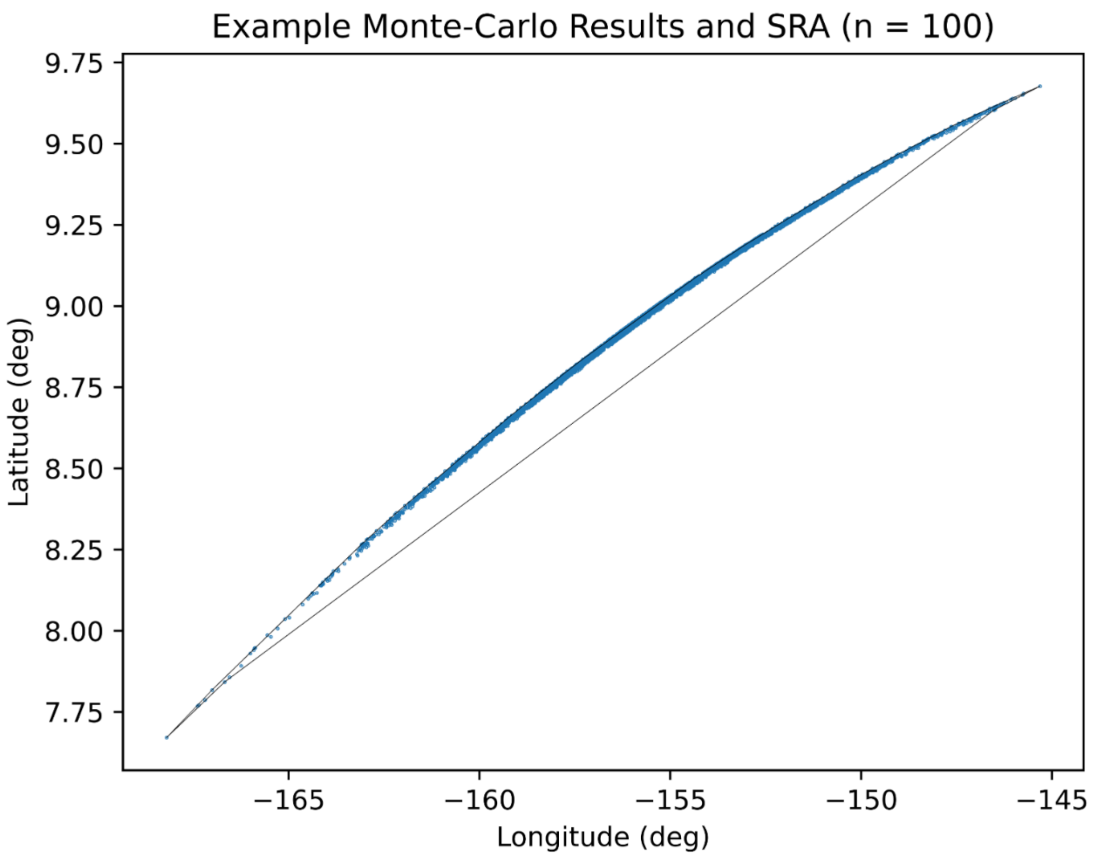
Not respecting this can lead to certain components being systematically excluded



Example Implementation and result: SRA

```python
def calc_reentry_area(
    objects_df: pd.DataFrame, thresh_list: List[float] = [0.99]
) -> pd.DataFrame:
    """Example of what you can do once you have all the impacting fragments. This function
    calculates the reentry area (convex hull) that includes a certain percentage of the runs.

    This will NOT give anything near the optimum result, and is just meant as an example; better
    algorithms should be implemented in practice.

    :param objects_df: Dataframe containing the final properties of the impacting objects, as
    returned by parse_reentry_results_xml()
    :type objects_df: pd.DataFrame
    :param thresh_list: List of threshold percentages for which to calculate the reentry  area,
    defaults to [0.99]
    :type thresh_list: List[float], optional
    :return: Dataframe containing the latitude and longitude of the vertices of the reentry areas
    for each threshold
    :rtype: pd.DataFrame
    """
    pts_df = objects_df[["longitude", "latitude", "run"]].copy(deep=True)

    # Convert the location of fragments to cartesian coordinates in order to get rid of disconuities
    x, y, z = EarthLocation.from_geodetic(
        lon=pts_df["longitude"], lat=pts_df["latitude"]
    ).to_geocentric()
    pts_df["x"], pts_df["y"], pts_df["z"] = (x.value, y.value, z.value)

    run_ids = pd.unique(pts_df["run"])
    runs_df = pd.DataFrame(columns=["Run", "x", "y", "z", "pts_index"])
    for i, run in enumerate(run_ids):
        # Find the mean latitude and longitde of each run
        run_points = pts_df[pts_df["run"] == run]
        mean_point = EarthLocation.from_geocentric(
            run_points["x"].sum() * u.m,
            run_points["y"].sum() * u.m,
            run_points["z"].sum() * u.m,
        ).to_geodetic()
        mean_point = EarthLocation.from_geodetic(lon=mean_point.lon, lat=mean_point.lat)
```

Convex hull approach used



Space Debris User Forum

Space Debris Forum ▾ Home

- Topics
- My Posts
- More

Categories

- In-situ detection
- Site Feedback
- Uncategorized
- All categories

Tags

- dmf
- master
- drama
- in-situ
- All tags

Example Scripts for Performing Monte Carlo Analyses using SARA

Daniele Bella May '23

Calculating the SRA and DRA (Safety and Declared Reentry Areas) for a mission, as well as the on-ground casualty risk, is an important part of a controlled reentry's safety analysis. One of the ways that it can be computed is through the use of a Monte Carlo simulation.

Though the DRAMA GUI provides a "Monte Carlo Analysis" mode, this is in reality a parametric analysis, without randomised parameters. However, it is possible to use DRAMA for "true" randomised Monte Carlo analyses using the DRAMA python package and some scripting. In order to show how this could be performed, and how each of the major parameters of a SARA run can be randomised, we created a set of example scripts. These were designed to be used as a reference and/or starting point during the development of more complex and comprehensive calculations; they are thus heavily commented and feature simplified algorithms, for the sake of understandability. They can and should be expanded upon based on the needs of your analysis, in order to encompass other parameters or to make use of more rigorous but more complex methods.

In fact, if you have any suggestions for improvements, or want to share your experience in tailoring them to a mission's needs, don't hesitate to reply to this post! Everyone can then learn from it, and in future it even helps us provide better examples and tools.

What the example scripts cover

- Opening a nominal example SARA project
- Creating an arbitrary number of randomised inputs, including uncertainty on a deorbit burn
- Compiling these inputs into the format required for SARA
- Running SARA in a parallel fashion for each case
- Parsing the results, calculating the overall casualty risk
- Using the location of the fragments, using a simplified and conservative algorithm to calculate the SRA and DRA

These are all the necessary files:

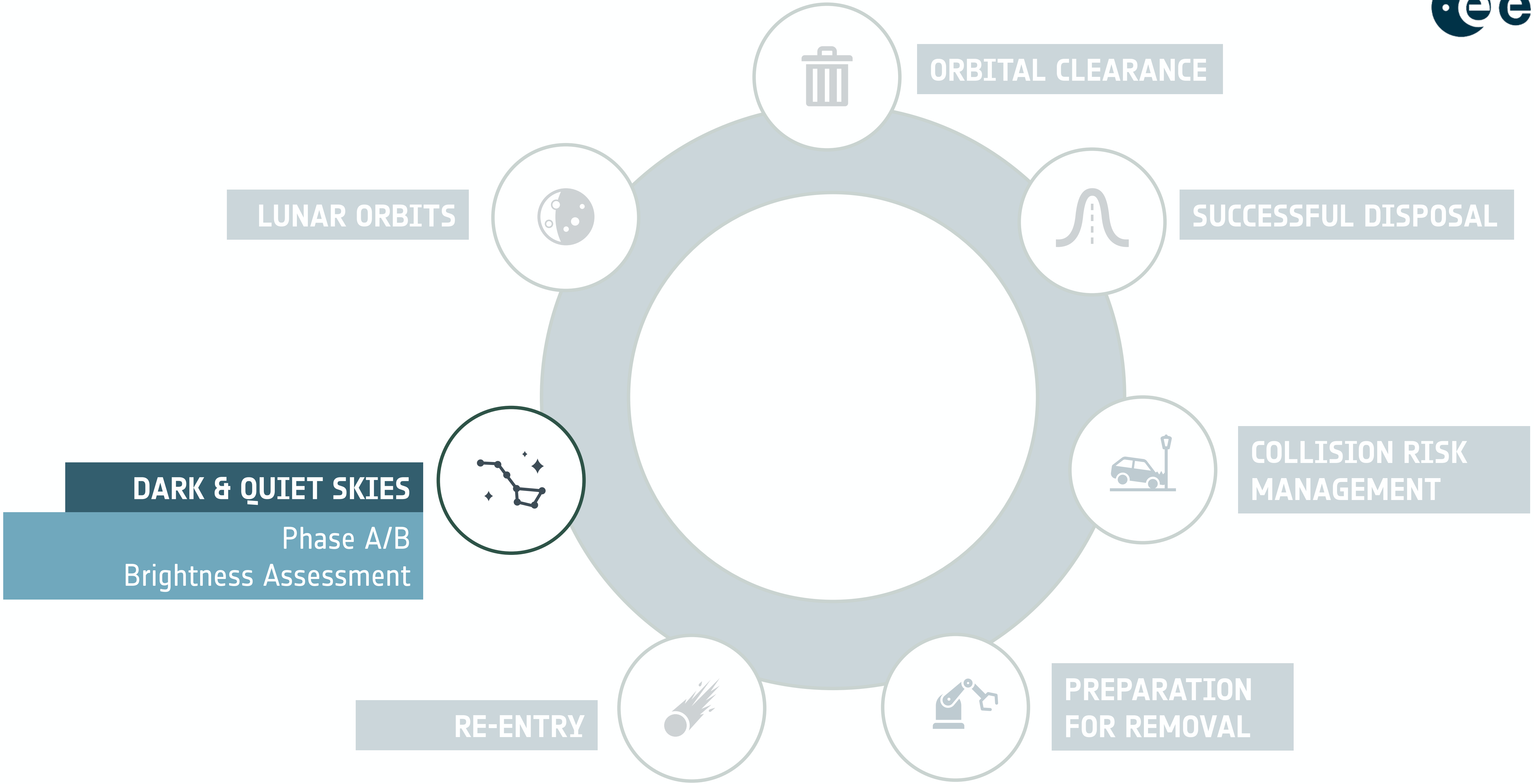
SARA_MC_script.py (10.3 KB)
SARA_MC_helpers.py (20.0 KB)
example_project.dpz (3.8 MB)

May 2023

1 / 1
May 2023

May 2023

https://debris-forum.sdo.esoc.esa.int/


ORBITAL CLEARANCE
LUNAR ORBITS
SUCCESSFUL DISPOSAL
DARK & QUIET SKIES
Phase A/B
Brightness Assessment
COLLISION RISK
MANAGEMENT
RE-ENTRY
PREPARATION
FOR REMOVAL

Phase A/B Requirements– Visual Brightness

ESSB-ST-U-007 Issue 1 5.6.a

The developer of a spacecraft or launch vehicle orbital element in near Earth orbit shall quantify the **visual** brightness of the design.

Early phases (0-B)

Assess brightness assuming a combination of diffuse and/or specular reflection for **primitive shapes** (e.g. **sphere**, cylinder, flat plate).

Diffusive and specular reflection for surfaces is described using physical or empirical models, e.g. ideal **Lambertian**, or empirical Phong reflection models

ESA Space Debris Mitigation Compliance Verification Guidelines

The apparent magnitude of a satellite can be computed from the irradiance ratio of the satellite with respect to the solar illumination irradiance $\boldsymbol{E_{sun}}$ and the apparent magnitude of the Sun $\boldsymbol{m_{sun}}$ at Earth distance.

$$m_{sat} = m_{sun} - 2.5\log\left(\frac{E_{sat}}{E_{sun}}\right) + x\chi$$

Satellite Brightness

Atmospheric Extinction

Need to determine:

1. Geometric set-up
2. Reflectance model
3. Atmospheric extinction

1. Geometric Set-Up

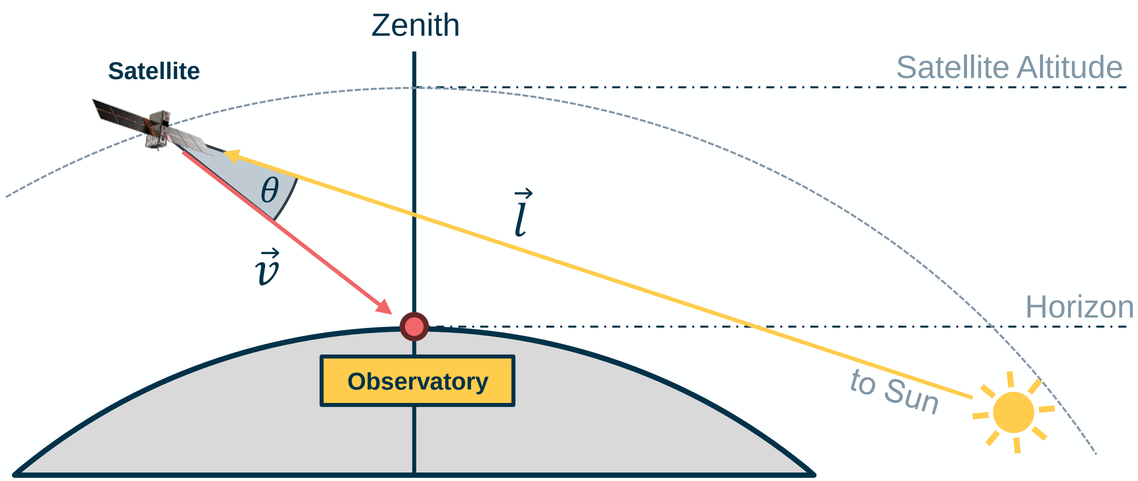
The geometric set-up of the **satellite**, the **Sun**, and an **observer** is required. These are used to construct:

- The sun-to-satellite vector $\vec{l}$
- The satellite-to-observer vector $\vec{v}$

The angle between these vectors is the phase angle θ (see following slides).

The vector to zenith from the observer is also required to calculate airmass (see following slides).

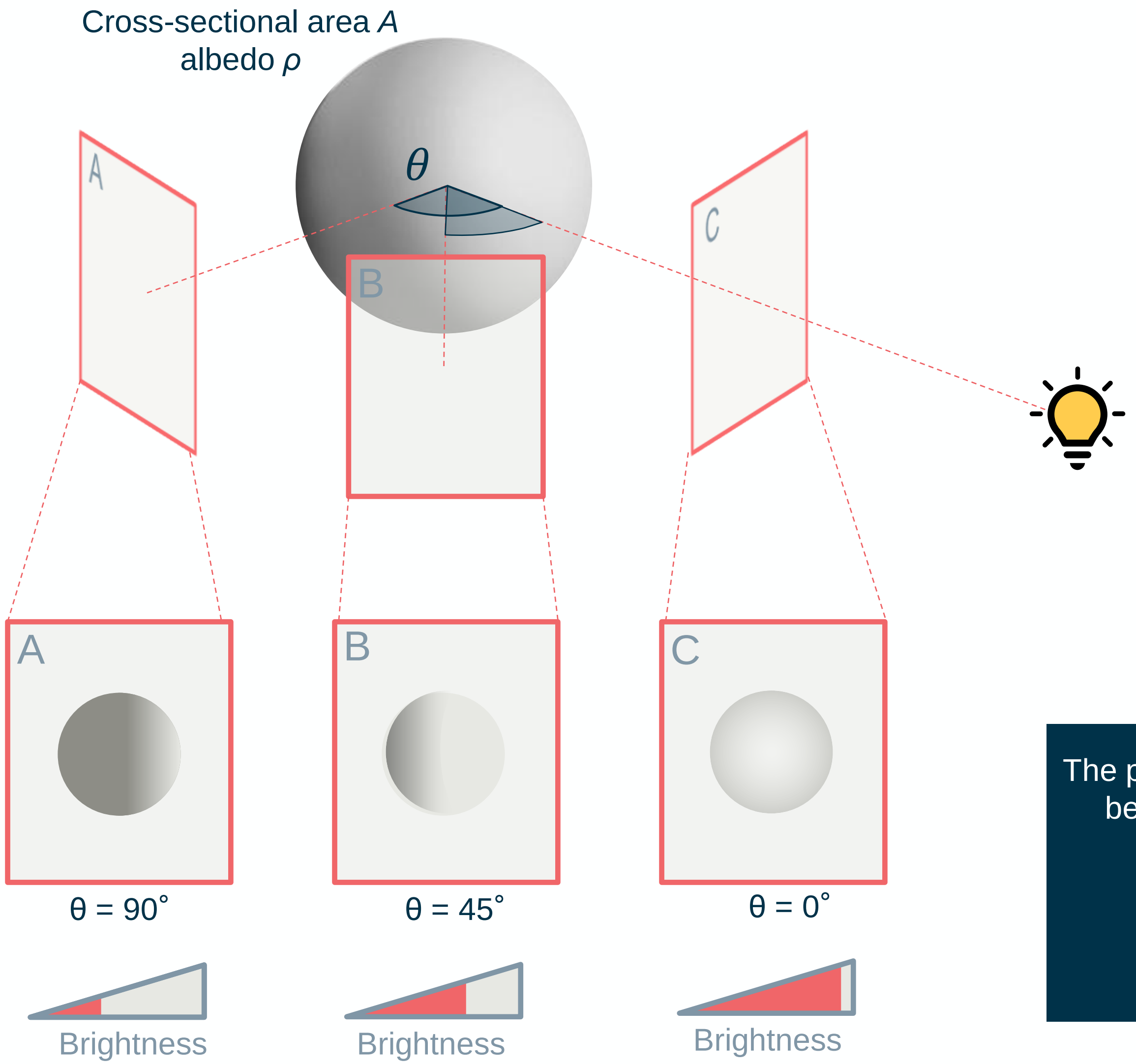
The brightness will be at a maximum when θ is closest to 0° and $|\vec{v}|$ is minimised, subject to the constraint that the satellite is not in eclipse.



$\vec{l}$ satellite-to-sun vector

$\vec{v}$ satellite-to-observer vector

2. Simple Reflectance Model – Lambertian Sphere



Lambertian reflectance is the property that defines an ideal diffusely reflecting surface. The apparent brightness of a Lambertian surface to an observer is the same regardless of the observer's angle of view. For an illuminated **Lambertian sphere**, the **observed brightness only varies with phase angle θ.**

$$E_{sat} = E_{sun} \frac{f_r\left(\vec{l}, \vec{v}\right)}{d^2}$$

$$f_r\left(\vec{l}, \vec{v}\right) = \rho \, A \, \frac{1}{\pi}\left(\sin\theta + (\pi - \theta)\cos\theta\right)$$

The phase angle θ is the angle between illumination and observation vectors

$$\theta = \cos^{-1}\frac{\vec{l} \cdot \vec{v}}{\left\|\vec{l}\right\| \, \|\vec{v}\|}$$

$$0° \leq \theta \leq 180°$$

E_{sat}	satellite emission
E_{sun}	Solar illumination irradiance
d	distance from observer-satellite
ρ	geometric albedo
θ	phase angle
A	cross-sectional area
$\vec{l}$	satellite-to-sun vector
$\vec{v}$	satellite-to-observer vector

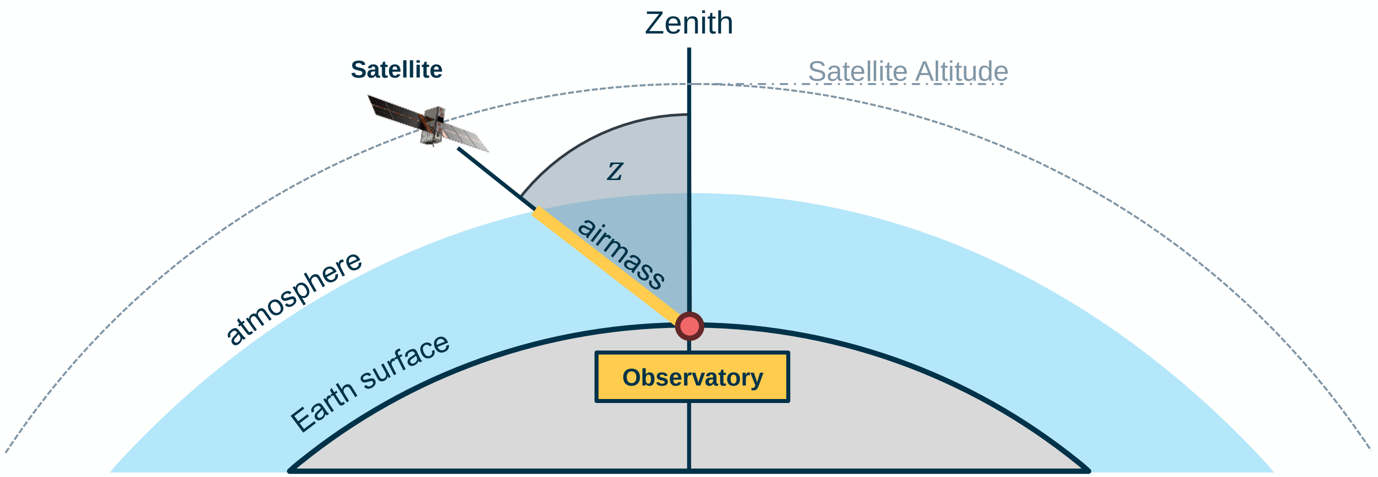
3. Modelling Extinction

Some light is absorbed and scattered by the atmosphere, reducing the brightness of a satellite when viewed from ground. This is referred to as extinction.

$$\text{Extinction} = x\chi = \frac{0.12}{\cos z}$$

$\chi = {}^{1}/_{\cos z}$ is the airmass, which is the quantity of atmosphere crossed by the observed light, normalized to zenith.

$x \simeq 0.12$ mag/airmass is a typical value at visible wavelengths[1]



z = Zenith angle

[1] Patat, F., et al. "Optical atmospheric extinction over Cerro Paranal." Astronomy & Astrophysics 527 (2011): A91.

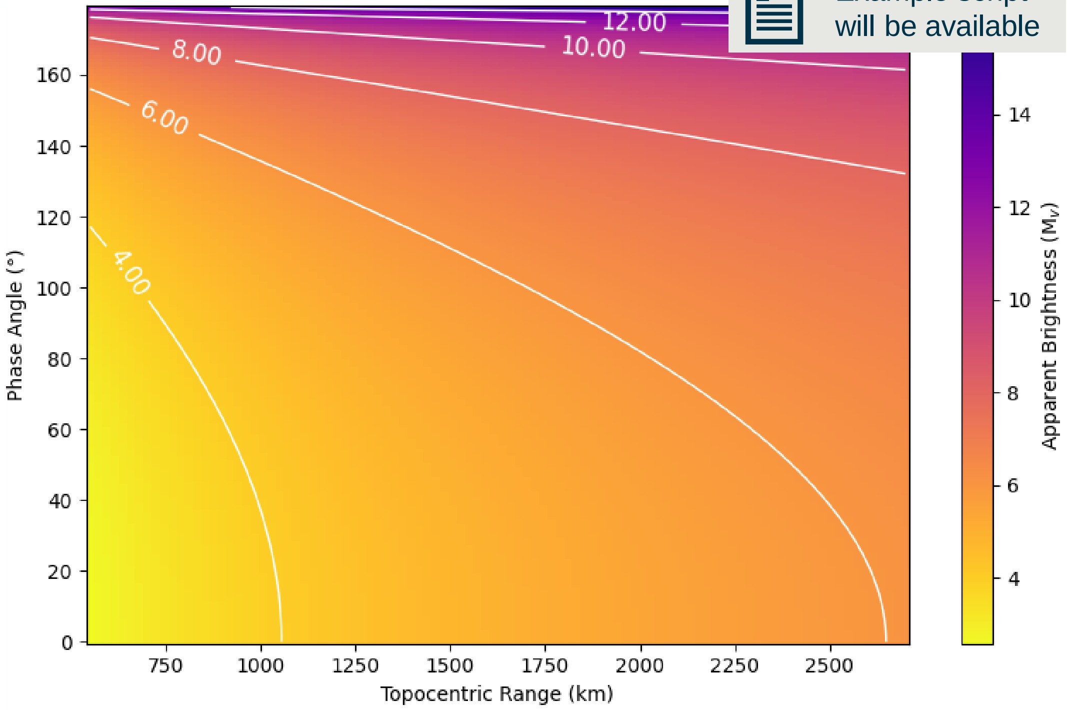
Assessment Steps

With a simple Lambertian sphere as a reflectance model and a defined geometrical set-up the brightness can be calculated by hand using the equations given or implemented in a script.

Modelling Process:

1. Estimate satellite cross-sectional area
   - Can use e.g. DRAMA CROC
2. Estimate/assume geometric albedo
3. Calculate geometries
   - Satellite position
   - Observatory position
   - Sun position
4. Calculate phase angle θ
5. Calculate satellite brightness
6. Calculate extinction
7. Calculate final magnitude
8. Document results

Example script will be available



Results for a satellite with cross-sectional area 7m^2 and assumed geometric albedo of 0.25. Satellite in circular orbit at an altitude of 550km, with corresponding minimum and maximum topocentric ranges.

Next steps

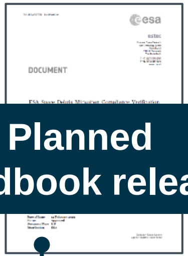
NOW

Question time

Questions that could not be answered now will be followed up

Dedicated clarification sessions can be requested

Clean Space Days



Planned Handbook release

drama

DRAMA and MASTER population release

October 2024 | November 2024 | December 2024 | January 2025 | February 2025 | March 2025 | April 2025

MILAN 2024 iac 75th

Policy

Handbook

Requirements

Tools

space.debris.mitigation@esa.int