CONSIDERATION OF SPACE DEBRIS ISSUES IN EARLY SPACECRAFT DESIGN PHASES

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ABSTRACT

The ever increasing number of space debris objects – in particular in the orbital region between 600 km and 1000 km – causes growing concern and subsequently measures to avoid a mission degradation or even the loss of mission due to particle impacts. Standards have been developed to cope with the aspects of the space debris problem (e.g. ISO 24113 [11]) such as the mitigation of the generation of further space debris objects and the evaluation of the re-entry risk.

Measures to consider the a.m. aspects need to be applied as early as possible in the spacecraft design process to ensure a cost and time efficient implementation. Some aspects such as shielding layout, material selection, structural integrity, design for demise, which could have a significant impact on the design and the configuration of the spacecraft structure, are discussed.

Software tools such as ESA's ESABASE2 and DRAMA tools as well as NASA's DAS2.0 software to analyse the vulnerability of a spacecraft and to support the assessment of the compliance with standards are presented.

1. THE PROBLEM

Since the beginning of the space age the number of man-made objects orbiting the Earth has increased to about 17,000. This includes all spacecraft and orbital debris in the trackable size range of more than about 10 cm in diameter.

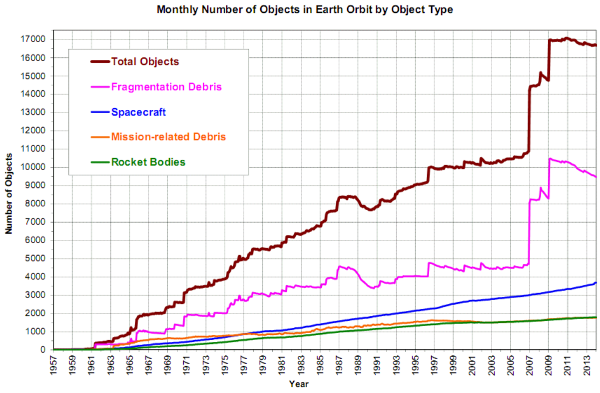


Figure 1. Evolution of the trackable space debris population [15]

Fig. 1 shows that in particular two events had a considerable impact on the catalogued objects population: the Fengyun 1-C anti-satellite test in 2007 and the Iridium 33 and Cosmos 2251 collision, which was the first collision between two intact satellites. Both events occurred in an altitude band of around 800 km, particularly increasing the space debris threat in this already highly populated region.

However, the object numbers visible in Fig. 1 are considering a very small portion of the space debris population only, since the predominant majority of particles is smaller than 10 cm.

Fig. 2 shows the cumulative particle flux as a function of the particle size on a circular orbit in an altitude of 800 km. It can be seen that space debris particles are the dominant source.

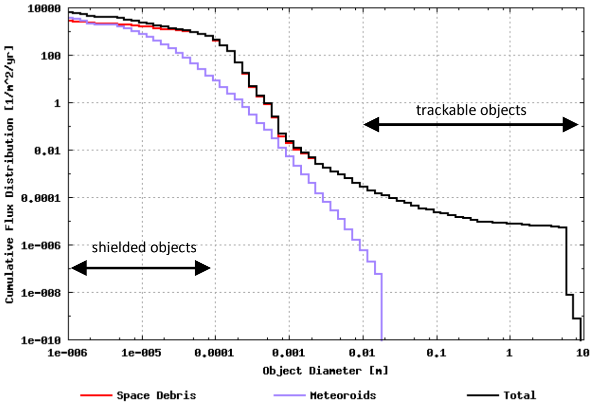


Figure 2. Cumulative particle flux in 800 km altitude as a function of the particle size (MASTER-2009 model)

Besides the dependency of the particle flux from the object size, Fig. 2 indicates that the most interesting size regime with respect to the risk posed to a spacecraft is the sub-millimetre to centimetre size range. Smaller particles in the micron size range usually cannot cause non-negligibly damage, while the statistical probability of a collision with trackable objects is relatively insignificant and has to be addressed by deterministic means with the aim to perform collision avoidance manoeuvres, if a certain collision probability is predicted.

Particles in the sub-millimetre to centimetre diameter range are of main concern for spacecraft operators, since they pose a non-negligible risk to LEO spacecraft, in particular in the most crowded, but also most frequently used regions such as Sun-synchronous orbits in the 600 km to 1000 km altitude range.

Even relatively small particles feature a high to very high potential to cause severe damage, as can be seen in the examples given in Fig. 3.

The image on the left hand side shows the impact of a sub-millimetre-sized particle on the solar panel of the Hubble Space Telescope, while on the right hand side the impact of a millimetre-sized particle on the radiator of the Space Shuttle is shown.

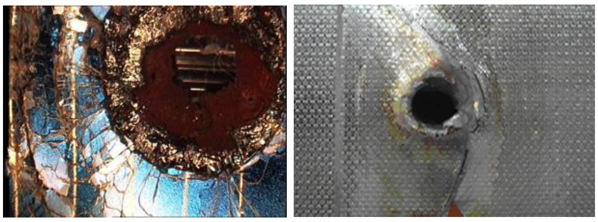


Figure 3. Impact features (images: ESA (left), NASA (right))

Although the current situation is already causing some concern and needs to be considered in the spacecraft design, it has to be expected that it will become even worse in the future. Several simulations of the debris population evolution were performed by means of different analysis tools, different assumptions on the driving parameters (e.g. the collision rate of large objects) and different institutions [13]. The general result is that in case of no further in-orbit explosions and a 90% compliance with the commonly adopted mitigation measures, the LEO debris population will grow by about 30% within the next 200 years. The most affected altitude band is in the 800 km to 1000 km range, where the main reason for this growth are catastrophic collisions between large non-manoeuvrable spacecraft (e.g. Envisat) in this most crowded region.

ESA's Clean Space initiative addresses these problems in its branches 3 "Space debris mitigation" and 4 "Technologies for space debris remediation" and supports potential solutions such as the active removal of objects [10].

2. STANDARDS AND REQUIREMENTS

As a consequence of the growing concern with respect to the space debris environment and the threats posed to satellite missions, a number of guidelines and standards have been established, e.g.:

- European Code of Conduct for Space Debris Mitigation [2]
- IADC Guidelines for Space Debris Mitigation [3]
- United Nations Space Debris Mitigation Guidelines [5]
- ESA Requirements on Space Debris Mitigation for Agency Projects [1]; to be applied to future procurements of space systems since April 2008
- ISO 24113 "Space Debris Mitigation Requirements" and subordinated standards [11] [12]

Based on the guidelines, which state 'what' has to be done with respect to debris mitigation, the standards provide a set of instructions 'how' the measures defined in the guidelines have to be implemented.

The existing guidelines, requirements and standards are covering - amongst others - the following aspects:

- mitigation of the generation of additional space debris,
- prevention of break-ups,
- collision avoidance,
- re-entry risk limitation,
- disposal of objects (spacecraft and launch stages) outside the protected regions (Fig. 4),
- survivability assessment against space debris and meteoroids.

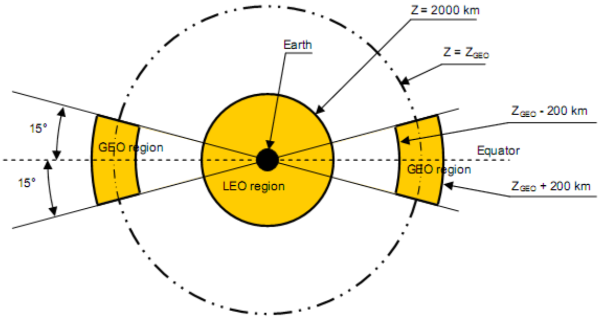


Figure 4. Protected regions [3]

For ESA missions, a Space Debris Mitigation Document has to be established, which shall address amongst others the design and operational measures to be taken to comply with the respective requirements [1].

In particular the European Code of Conduct for Space Debris Mitigation explicitly names spacecraft and mission design measures and requires to perform a debris impact risk assessment as part of these measures, which shall be included in the Space Debris Mitigation Document.

While the achievement of the required mission survivability is mainly in the interest of the spacecraft operators, the other requirements such as prevention of break-ups or re-entry safety address the global interest to protect the space environment and life on Earth.

Usually, for each mission additional requirements are established to address the impact risk and potential damage, stating that the spacecraft must withstand the space debris and meteoroid environment during their operational life with a certain probability, e.g. 96% for unmanned missions or 98.85% for manned missions (here: pressurised modules of the ISS). For some special experiments or components, the probability can be even higher, e.g. 99.99% for hazardous external payloads of the ISS.

3. MEASURES

For each of the three main fields covered by the guidelines and standards – debris mitigation on orbit, re-entry risk limitation and mission safety – suitable measures can be applied to ensure compliance of the space project. Some of these measures are discussed in the following sub-sections.

3.1 On-Orbit Debris Mitigation

The main goal of on-orbit debris mitigation is to avoid the generation of additional space debris objects. Here it is distinguished between objects released during nominal operations and debris clouds generated by unintentional or intentional spacecraft explosions or collisions.

In order to avoid the release of more objects than necessary into space during nominal operations, some measures are the limitation of pyrotechnics or that instrument covers shall not be disposed into space.

To avoid the generation of debris clouds with both large and small debris particles, it has to be ensured that no intentional break-ups are performed or that these are at least limited to exceptional cases (e.g. to disintegrate a satellite before its uncontrolled re-entry to minimise the on-ground risk). An unintentional disintegration of a spacecraft (e.g. explosion of batteries or tanks) has to be avoided. This can be achieved by a passivation (venting of tanks, instrument switch-off, etc.) after the end of the operational mission.

3.2 Re-entry Risk Limitation

The objective of the re-entry risk limitation is to avoid on-ground hazards, more precisely, the limitation of the on-ground casualty.

This can be achieved, if the use of components is avoided, which would survive the re-entry. In case this is not possible (e.g. if large optical instruments are required), the standards require a controlled re-entry. If a controlled re-entry is planned, it is required that those sub-systems, which are needed to perform the controlled re-entry (AOCS including tank, thrusters, star-trackers, electronics, etc.) shall survive the mission with a certain probability. The assessment, whether the latter can be achieved with the given spacecraft structural design is a mission safety task (cp. section 3.3).

Measures to be foreseen in particular in case of an uncontrolled re-entry usually have a significant impact on the spacecraft's structure: The so called "design for demise", i.e. a design, which enables a full disintegration and burn-up during re-entry, requires a suitable arrangement of the spacecraft's components and material selection. As both the component location and the material properties also affect the spacecraft's vulnerability to space debris impacts, a trade-off between re-entry safety and mission safety related requirements will have to be performed, at least in critical cases.

3.3 Mission Safety

The term "mission safety" covers all aspects of the satellite's vulnerability and survivability during its entire mission. The goal of the related requirements is to avoid the loss of the mission (in a sense that the mission goals cannot be achieved) due to space debris impacts or collisions with other large objects.

While the collision hazard can barely be tackled by structural design measures, there are several means to reduce the vulnerability, which have to be implemented through the structural design of the spacecraft. For space debris and mission safety experts it is obvious that mission critical or vulnerable sub-systems shall not be placed at locations with a high debris impact rate, unless a sufficient shielding can be provided. In some cases a change of the satellite's or experiment's orientation could reduce its vulnerability considerably. Mostly however a properly designed shielding configuration is the preferred measure to ensure the required probability of no failure (PNF).

The selection of the best shielding option is usually based on detailed analyses of the available alternatives. A non-exhaustive list of the shielding configurations and shield parameters, which could be varied, is given in the following:

- wall thickness in case of (single wall) housings,
- application of so called "Whipple shields" (Fig. 5), consisting of an outer "bumper", which destroys the impacting particle and creates a cloud of smaller particles, which are not able to penetrate the rear wall,

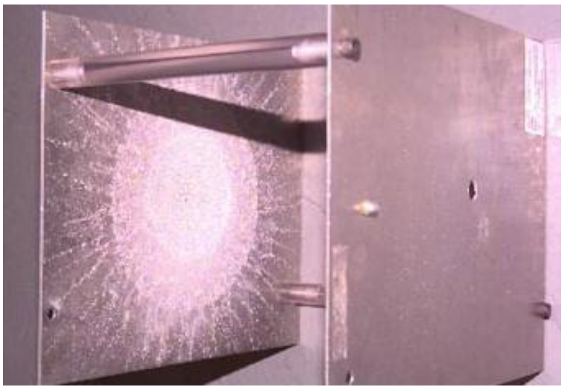


Figure 5. Whipple shield (credits: NASA)

- application of advanced multi-layer bumper and/or stuffed Whipple shields,
- thicknesses, spacing and material of bumper and rear walls,
- material used for the stuffing (e.g. Nextel, Kevlar, etc.)
- cover sheet thicknesses, core thickness and cover sheet material in case of sandwich panels.

In case of the ATV for example, several shielding configurations have been studied and the optimal configuration with respect to shielding effectiveness and mass impact was identified. The shield optimisation was performed with ESA's ESABASE/Debris software (cp. section 5.3).

In summary, it must be concluded that most of the debris mitigation requirements and the named measures are more or less related to the spacecraft design with a potentially considerable impact on its structure and subsequently on its mass. An additional finding of the above said is that there are conflicting functional mission requirements and space debris mitigation requirements.

4. THE SOLUTION

Due to its potentially enormous impact on a satellite's structural design, space debris mitigation measures as outlined above should be considered as early as possible to avoid effort and cost for major design changes in later project phases. It is recommended to perform a first assessment of space debris mitigation and spacecraft vulnerability aspects in Phase A, or Phase B at the latest. As outlined in section 5, some analysis tools are available, which are suitable for a first fast and effective evaluation of the compliance with debris mitigation and vulnerability requirements. With emerging spacecraft design, these analyses should be repeated – also in view of the evolution of the space debris population and the respective environment models during the space project development.

Although the mentioned tools mostly use simplified models suitable for engineering purposes, the preparation of the required input, the selection of appropriate models and in particular the interpretation of the results requires expert knowledge, which is not always available in a space project consortium. However, support can efficiently be given by experts, who are familiar with the requirements, with the application of the space debris mitigation guidelines and with the application of the respective analysis tools.

5. AVAILABLE TOOLS

5.1 DRAMA

ESA’s Debris Risk Assessment and Mitigation Analysis software DRAMA [9] provides the capabilities to make a first assessment of the compliance of a space project with the debris mitigation guidelines of the European Code of Conduct [2]. For the assessment of the different aspects of space debris mitigation separate tools are available.

The Assessment of Event Statistics tool ARES computes the annual collision probability of the respective spacecraft/mission and to assess the number of collision avoidance manoeuvres as well as the propellant mass needed to perform these manoeuvres. These calculations require several user defined settings, such as the spacecraft’s orbit uncertainty, the accepted collision probability level, and the number of revolutions before the manoeuvre takes place.

An assessment of the effects of smaller space debris particles in the size range from 100 µm to 5 cm is performed by the MASTER (-based) Impact Flux and Damage Assessment tool MIDAS. The calculation of the impact flux can be performed for a sphere, a randomly tumbling plate of user defined cross-section or for up to ten oriented surfaces. Besides the impact flux computation, the probability of penetration of a given wall configuration can be assessed.

With OSCAR, the Orbital Spacecraft Active Removal tool, the user can assess the remaining orbital lifetime of a satellite at the end of its mission and the measures to be taken to comply with the 25-year rule, which states that a spacecraft is allowed only to stay within the protected regions (Fig. 4) for maximum 25 years [3][4]. Under consideration of the de-orbit or re-orbit start year and realistic projections of the solar activity, different options such as direct or delayed de-orbit using chemical or electrical propulsion systems and the use of drag-augmentation devices can be analysed.

SARA, the (Re-entry) Survival and Risk Analysis tool is used to simulate the re-entry of a satellite under consideration of its components and the shape and material characteristics of these components. It is analysed, which objects will survive the re-entry and impact on the Earth’s surface. The resulting casualty probability - which in most guidelines shall be below 10^{-4} - is computed and the ground track of the re-entering objects indicates the impact locations on an Earth map.

It must be noted that the models and tools used in DRAMA could offer a rather rough indication of the compliance with the mitigation guidelines. In case the results are close to a non-compliance, it is recommended to perform detailed analyses with more sophisticated tools, e.g. ESABASE2/Debris instead of MIDAS.

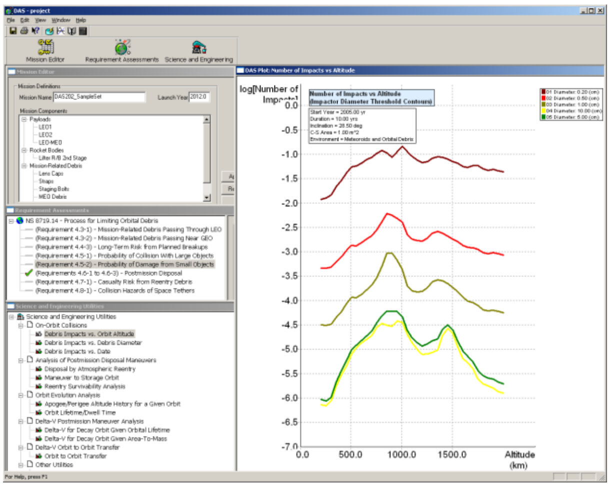
5.2 DAS2.0

NASA’s Debris Assessment Software checks the compliance of a space project with the NASA standard NASA-STD-8719.14 “Process for Limiting Orbital Debris” [4]. To enable the analyses, the user has to specify the mission and the spacecraft characteristics, e.g. the orbit, the mission duration, the satellite components and their materials. The subsequent requirements compliance analyses reveals, whether the mission is in line with the debris mitigation guidelines. To support the measures to be taken, if this should not be the case, DAS2.0 provides a so called “science and engineering” module, which allows to evaluate various mitigation measures to achieve compliance with the requirements. This includes

- limitation of on-orbit collisions,
- analysis of an atmospheric re-entry,
- evaluation of manoeuvres to an appropriate storage orbit (e.g. required delta-v),
- re-entry survivability analysis.

Moreover, some utilities are integrated into DAS2.0, which allow to

- display the debris environment characteristics (example: Fig. 6: no. of impacts vs. altitude),



Mission Name: DAS202_SampleSet
Launch Year: 2012.0

Start Year = 2005.00 yr
Duration = 10.00 yrs
Inclination = 28.50 deg
C-S Area = 1.00 m^2
Environment = Meteoroids and Orbital Debris

Figure 6. DAS2.0 science and engineering module

- convert orbital data (e.g. two-line elements to Keplerian elements),

- compute the cross-sectional area of a spacecraft, which has been modelled via the mission editor.

The compliance analyses provided by DAS2.0 cover - amongst others - the following requirements:

- Limitation of the number and orbital lifetime of objects released during nominal operation in LEO and GEO.
- Limitation of the long-term impact on the debris environment by planned break-ups.
- Post-mission disposal in LEO and GEO regions.
- Casualty risk resulting from uncontrolled Re-entries.
- Mitigation of the collision hazard of space tethers.

Some requirements are slightly different from those of the European standards (e.g. handling of planned break-ups).

Clear requirements exist with respect to collisions with large objects and the damage caused by small objects:

- The collision probability with objects larger than 10 cm shall be less than 0.001.
- The probability of a disabling collision with small debris shall be less than 0.01, which is applicable to those sub-systems only, which are required for post-mission disposal manoeuvres.

The analyses for the latter requirements are performed on the basis of NASA's orbital debris engineering model ORDEM2000, which is rather outdated. A new model - ORDEM3.0 - was recently released by NASA, but has not yet been integrated into DAS.

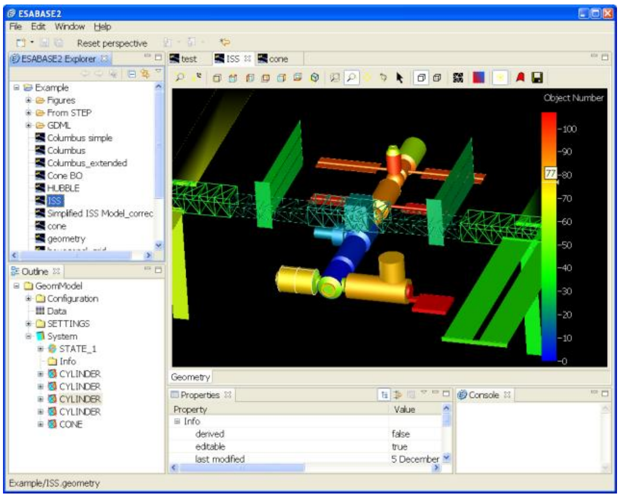
Moreover, DAS2.0 is not covering all of the NASA debris mitigation requirements (e.g. the limitation of the risk posed on other spacecraft by an accidental explosion or the limitation of the short-term risk posed by planned breakups) and therefore, additional analysis tools are needed to evaluate the compliance with these requirements.

5.3 ESABASE2/Debris

ESA's standard space environment analysis tool ESABASE2 [6][8] with its "Debris" application addresses the following requirements of the guidelines and standards named in section 2:

- space debris and meteoroid impact risk assessment,
- assessment of the survivability of those spacecraft components required for re-orbiting,
- survivability assessment for those spacecraft components, which are required for a controlled re-entry,
- implementation of design measures to improve the spacecraft's vulnerability (e.g. shielding design, arrangement of critical components).

A screenshot of the ESABASE2 graphical user interface is shown in Fig. 7.



Property	Value
Info	
derived	false
editable	true
last modified	5 December

Figure 7. ESABASE2 graphical user interface

Meteoroid and orbital debris analyses are performed on 3-dimensional spacecraft models, which can be generated and edited within ESABASE2. For this purpose, a comprehensive set of geometric primitives is available, Boolean operations (intersection, union, subtraction) between the geometrical objects can be performed and a replication of objects is possible to generate grids of objects. The import of CAD models provided in the STEP AP203/214 format allows to make use of existing models.

Beside its Debris application, ESABASE2 integrates other space environment analysis solvers (e.g. for contamination and outgassing analysis - COMOVA) and provides interfaces to external tools through its data exchange facilities.

ESABASE2/Debris integrates the latest available environment models, e.g. MASTER-2009 (ESA's Meteoroid and Space Debris Terrestrial Environment Reference Model) and MEM (NASA's Meteoroid Engineering Model) to ensure state-of-the-art predictions of the impact risk.

To assess the damage caused by impacting objects, particle/wall interaction models are required. In case of ESABASE2/Debris a comprehensive set of pre-defined damage and failure equations can be applied depending on user defined damage criteria. The tool also offers the possibility to modify the ballistic limit equations (BLE) according to the user's needs.

If a BLE shall be applied, which cannot be described by the parametric formulation used in ESABASE2, any user defined BLE can be specified via a so called "User Subroutine", which can be linked to ESABASE2/Debris.

Further modelling capabilities of ESABASE2 include kinematics and pointing of the entire spacecraft and of single spacecraft components (e.g. the solar generator) and the consideration of secondary ejecta, i.e. impacts of particles generated during an impact.

Moreover, the ESABASE2 framework offers various results representation and display options: 3-dimensional and 2-dimensional visualisation and diagrams as well as tabled results output.

The analysis capabilities of ESABASE2/Debris are ranging from a simple assessment of the vulnerability of the outer walls/panels of a spacecraft to a complex analysis of the survivability of complete sub-systems (e.g. the sub-systems required for a controlled re-entry).
In all cases the impact flux (impacts per square metres and year) on a 3D representation of the spacecraft model is calculated, based on the selected environment models. An example of the results is shown in Fig. 8.

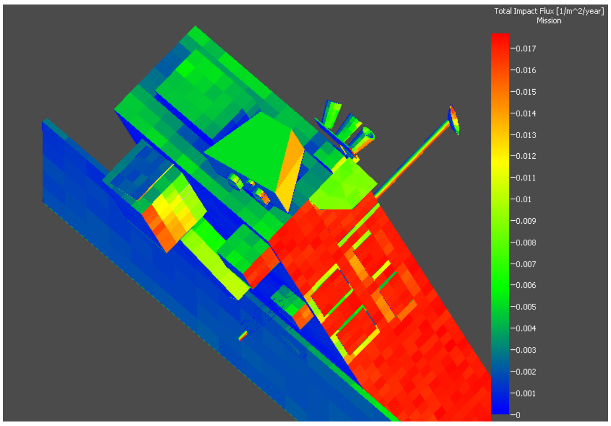


Figure 8. Impact flux results

It can be seen at once, which surfaces of the spacecraft are mostly affected by the space debris and meteoroid environment. Based on the impact flux, the damage caused by impacts can be assessed under consideration of suitable damage laws (particle wall interaction models), and subsequently, the probability of failures and the percentage of the damaged surface area is calculated.
The results of such analyses clearly indicate weaknesses of the spacecraft design and enable the enhancement of the design as well as the optimisation of the shielding configuration. For example, susceptible components pointing in flight direction shall be protected by appropriate structures, which provide sufficient shielding.

6. CONCLUSIONS

Space debris mitigation measures are required for each space mission to adhere to applicable standards and to ensure that the spacecraft is able to withstand the space debris environment for the mission duration.
Measures to comply with the space debris mitigation standards and mission safety related requirements shall be envisaged as early as possibly in the design of the spacecraft structure to avoid expensive re-designs.
A set of engineering tools is available to support the selection and evaluation of needed measures (e.g. shielding, material selection, etc.)
Support to the consideration of space debris related requirements and to the application of the respective tools can be given by experts who provide comprehensive expertise in the field of mission safety.

7. REFERENCES

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