A METHOD AND A TOOL FOR ASSESSING IN-ORBIT DEBRIS-RELATED RISK FOR SPACE SYSTEMS

André Elie(1), Romain Kervarc(1), Patrice Carle(1), Stéphanie Prudhomme(1), Scott Kempf(2) , Frank Schaefer(2), Thérèse Donath(1)

(1)ONERA, System Design and Performance Evaluation Department, F-91761 Palaiseau, France.
CP: andre.elie@ onera.fr*
(2)Fraunhofer Ernst-Mach-Institut,Spacecraft Technology Group, Eckerstraße 4, 79104 Freiburg, Germany. CP:scott.kempf@emi.fraunhofer.de*

**CP: Contact Point*

Abstract

This paper addresses a methodology taking space-debris-related risk for Low, Medium and Geostationary Earth Orbit space missions into account, and aims at assessing the collision risk not only as a physical threat supported by a physical spacecraft, but as a hazardous effect on the space system mission. The goal is to develop a tool exploiting such physical simulation results (i.e. effects of sustainable impacts on the spacecraft in case of small debris, cost of the spacecraft avoidance manoeuvres in case of large debris) in a given debris scenario, to compute the repercussion of these effects on the space mission, and to perform comparisons between possible debris scenarios. This work is part of the P²-ROTECT (Prediction, Protection & Reduction of OrbiTal Exposure to Collision Threats) project, initiated in March 2011.

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1. Introduction

The threat posed to space mission by the growing number of space-debris (Figure 1) has been steadily increasing in the recent years to the point that numerical simulations evaluating the growth of these debris in Low Earth Orbit show their number has reached an alarming point. The long-term evolution of the space-debris threat shows a growth in population and a general instability [1]. A need for mission risk assessment tools, able to analyse the long-term debris-environment has appeared, to correctly evaluate the need for space-debris environment improvement policies.

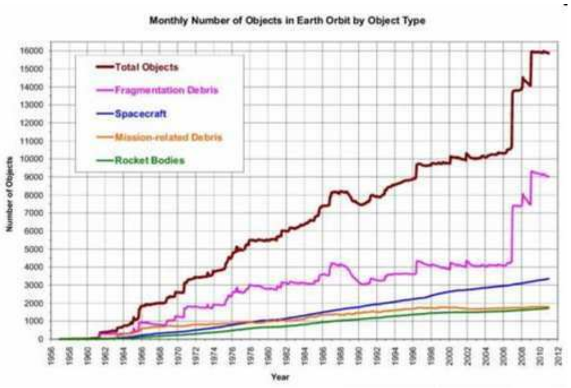


Figure 1. Monthly number of objects in Earth orbit by object type

The P²-ROTECT project aims at providing an efficient evaluation tool of space missions' vulnerability to space debris-related risks for LEO (Low Earth Orbit), MEO (Medium Earth Orbit) and GEO (Geostationary Earth Orbit) space missions. It will focus on analysing both trackable and untrackable debris effects, at spacecraft components level as well as mission functions level. It will further analyse three main ways of reducing space-debris-induced vulnerability:

- a better in-orbit collision prediction may allow for efficient and not damage-inducing avoidance manoeuvres;
- a better overall mission protection, such as reinforced spacecraft components, but also redundant systems between spacecrafts and optimized component positioning for spacecraft design;
- a better debris environment, with the study of effect of space-debris removal campaigns,

Proc. '6th European Conference on Space Debris'
Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013)

regular or punctual, and of the application of space debris mitigation rules.

This paper addresses the innovating method developed in the P²-ROTECT project to assess the vulnerability of a space system in an improved space-debris environment, and describes the tool that has been developed to allow the computation of said vulnerability, SAVESPACE (Space Asset Vulnerability to the Effects of Space Population Avoidance and Collision Evaluator).

The paper is organised as follows. An evaluation of the threat posed by the space-debris situation to space systems is first exposed in Section 2. Section 3 will then propose a detailed explanation of the method developed in the P²-ROTECT project, and the innovations it contains. A description of the SAVESPACE tool and of its workflow is then given in Section 4. Finally, concluding remarks and improvements perspectives are given in the last section of the paper.

2. Space debris threat evaluation

Space debris represent an increasing threat to satellites, as their number has been alarmingly growing in the past years, and have focused public attention because of recent catastrophic events:

- anti-satellite missile launched on 11th January 2007,
- Iridium-33/Cosmos-2251 collision on 10th February 2009,
- etc.

Figure 2 shows the monthly number of objects in orbit around Earth, with calculated previsions until 2030 (pay particular attention to the total curve).

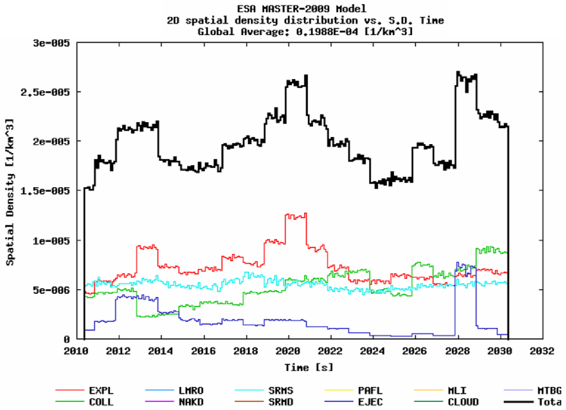


Figure 2. Space debris (source: NASA Orbital Debris Quarterly News, 12(1): 12).

When tackling the debris problem, one sees two classes of problem arise, each provoked by a different class of debris:

- "large" debris are objects trackable from the ground (i.e. roughly of a size larger than a certain size (ranging from 10 cm in LEO1 to 50-100 cm in GEO2 with intermediate sizes in MEO3) which may be listed in a catalogue (about 16,000 such objects are known today). Collisions with such objects are always catastrophic for the spacecraft, but are predictable, which allows manoeuvring to avoid them. However, collision avoidance manoeuvres have several damageful consequences, among which:
    - some functionalities of the spacecraft (such as its payload) are generally unavailable during manoeuvre; thus, each manoeuvre temporarily prevents the system to fulfil its mission;
    - manoeuvres consume propellant, which is also required for station keeping; thus, more frequent manoeuvres reduce the lifetime expectancy of the spacecraft.
- "small" debris untrackable objects (the number of which is evaluated to range in billions) for which the only available knowledge on the ground is a statistical repartition model. Collision with such object is not predictable, but may be less severe if the spacecraft is suitably protected and the size of the object is small enough (typically less than 1 cm). Still, too frequent impacts also have dire consequences for the spacecraft:
    - impacts may accelerate the ageing of spacecraft components and increase their failure rate, thus reducing their performance as time goes by;
    - impacts, if the impacting object is large enough, or if the impacted component is vital enough, may cause the loss of the complete system or at least of one important subfunction.

As the number of debris increase, the consequences are numerous:

- more "large" debris cause more frequent manoeuvres, which are expensive in terms of propellant, thus reducing the lifetime of the spacecraft; moreover, depending on the mission, the payload may be unavailable during manoeuvres;
- more "small" debris cause more frequent impacts, accelerating performance degradation or failure on some functions of the spacecraft;

and these various forms of vulnerability are difficult to compare. Moreover, one could figure out many different solutions to deal with this debris issue, and it is very uneasy to determine which are best, thus making quite difficult to assess the overall effect on the performance of the system: some threats allow the system to protect itself by reacting (large debris), others must be endured (small debris), and man action on the environment may influence the threat level (debris creation or removal). Several solutions exist [8], but their comparison on the long term is difficult, since they may be of very different natures, and have effects on various terms.

3. The P^{2}ROTECT method

3.1 Description

As seen in Section 2, debris in orbit around the Earth may be roughly classified into two categories:

- small debris, which are untrackable and cannot be avoided, but which on the other hand do not necessarily have a very damageable impact on the spacecraft when colliding it;
- large debris, which are trackable and may lead the operators on Earth to have the spacecraft do an avoidance manoeuvre, because of their being likely to destroy the spacecraft if colliding it.

In order to have a comprehensive approach to the issue dealt with here, it is necessary to address the following questions:

1. How is it possible to assess the impact of a collision on the spacecraft? In particular:
    - for small debris, how may the consequence of an accumulation of small impacts be assessed?
    - for large debris, how is it possible to assess several manoeuvre strategies on a long term?
2. How is it possible to compare several possible operational solutions for a given spatial system with respect to the impact of debris collision?

3.2 Method

Here, we focus on the missions that the spatial system is supposed to realise throughout its lifetime. Those two elements are the key points in the methodology exposed here, and are a possible answer to the two questions mentioned above. In the following, by a threat we denote a collision between the considered space system and a debris.

In order to do so, we do not consider the usual static vulnerability notion, but rather a notion of mission vulnerability: we study the mission that the spatial system is expected to realise, and decompose it as a chaining of elementary functions, that are realised by elementary units of the spatial system, and we study the potential losses that can occur at the level of those elementary functions rather than on the elementary units (even if of course both are related).

This notion is supported by the ATLAS method [5, 6]. ATLAS (Analysis by Temporal Logic of Architectures of Systems) is a generic method aimed at assessing the performance of a complex system by exploiting prior knowledge on the individual performances of the agents of the system, as well as an Onera software tool implementing this method. ATLAS relies on modelling the considered system's behaviour by an interval temporal logic (cf. e.g. [4, 2, 3]), thus describing the organisation of the different elementary functions in a logic tree (Figure 3). Performance assessment is difficult in this context, since on the one hand the knowledge on agents may be very heterogeneous, and, on the other hand, the performance of the system does not only depend on that of its agents, but also on the dependency relationships that exist between these agents. ATLAS addresses this issue by focusing on a mission-oriented analysis in which the system is represented as an organisation of functions and resources, upon which a key notion of function availability and resource availability is considered.

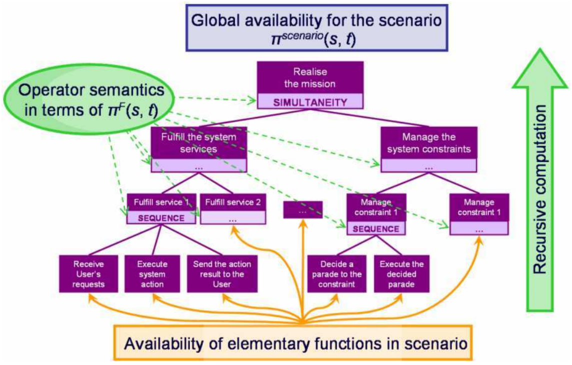


Figure 3. ATLAS: method overview

The main idea of the P^2-ROTECT project consists in using ATLAS as a central integration platform to assess the impact of space debris on the capability of the space system to fulfil its mission (cf. [9, 10, 11]). This organisation is described on Figure 4: space debris impact on the physical components of the system is computed by a dedicated physical simulation software (PIRAT), and then translated using a component redundancy and interaction model (CRIOS) into function availabilities, which are exploitable by ATLAS.

The method allows studying many space systems in a consistent way. The P^2-ROTECT project, indeed, will initially deal with three different space missions: Sentinel-1 (in LEO), Galileo (in MEO), and Meteosat Third Generation (in GEO). All that is needed for the study is:

- a description of the dynamic realisation of the mission, down to functions that are elementary enough for their performance to be deduced from the status of the threatened system (this may be refined from generic space system ATLAS trees [7]);
- a description of how the realisation of threats may influence these elementary performances.

3.3 Assessment of the loss of service

The overall method is described on Figure 4. The mission-oriented analysis consists in describing the mission expected from the system by the user in terms of a dynamic organisation of elementary function, each elementary function being associated to a set of elementary components of the system. In association to this description, the notion of function availability is central in the ATLAS method. It is represented as a conditional probability that a function is achieved at a certain time t provided that it was initiated at a given time s. This is a very minimal representation of a service expected from an agent, and ATLAS relies on the assumption that, for each agent, this representation may be deduced from the prior knowledge of the user: indeed, this function availability must be provided for each elementary function, and will be computed by ATLAS for higher-level functions, including the root function representing the mission. In addition to that, resource consumptions and availabilities are assessed, and used to correct the performance to take resource needs into account.

For each of the elementary functions identified above, we do need a model providing the performance of the function. What we mean here by performance is the probability that the function is achieved at a given time t_f, provided that it started at a given time t_i. We denote this performance as:

$$\pi^F(t_i, t_f).$$

This way, using those models, we need to obtain the following performances:

- a nominal performance, which will serve as the reference;
- a degraded performance in the case where the considered threat occurred (which can be zero if the collision destroys the spacecraft).

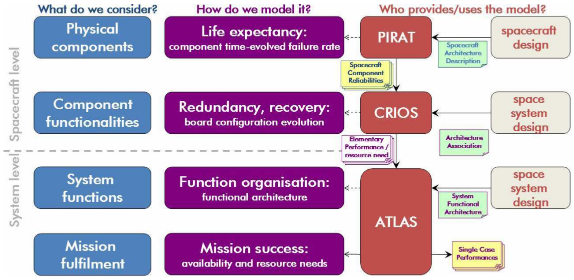


Figure 4. Overall idea of project P²-ROTECT

These performances are computed for each possible solution considered for the studied space system.

3.4 Integration throughout the lifetime of the system

A key point in considering the loss of performance throughout the lifetime of the system is that the realisation or the avoidance of a space-debris may not only have an impact at the time when it happens (e.g. a collision lowers the performance of the collided component, or when an avoidance manoeuvre prevents the realisation of another mission), but also on the long term (e.g. using propellant and thus diminishing the lifetime of the spacecraft).

In order to be able to do comparisons, we consider an integral index over a given scenario: we express the needs associated to each mission function throughout time, and, from the performance in both nominal and degraded cases, we compute a satisfaction index by integrating the performance weighted by the need throughout time. This way, we obtain an unique index, which takes into account both the lowering of performance at the instant of the impact and the consequences on a longer term.

3.5 Three ways for vulnerability reduction

Vulnerability reduction is an issue which the method presented here may be able to address properly. Indeed, there are currently three main trends in prospective ideas for debris exposure reduction:

- *protection*, i.e. better spacecraft internal organisation and armouring;
- *prediction*, i.e. enhancement of ground space situational awareness means (lowering the cataloguing threshold and improving collision prediction);
- *action*, i.e. voluntary alteration of the debris environment.

These three ways each has specific effects on various terms:

- protection implies that, on the short term, impact-related failures will be less frequent;

- prediction implies that more impacts will be avoided by manoeuvre, but on the other hand that manoeuvres may be more adequate, thus making the manoeuvre policies different, which, on the short term, may cause the payload to be unavailable at different times and, on the mid term, may affect the remaining propellant and thus the lifetime of the mission;
- action implies a range of long-term effects.

It is thus very difficult to compare these possibilities, and our integrated method is a good way to commeasure their effects.

4. Framework computation

4.1 Vulnerability index

The final result expected from the SAVESPACE tool is a measure of an overall Vulnerability of the scenario with regards to a reference scenario. This is expressed by an index, defined in Equation 1:

$$V = \int_{ti}^{tf} p^{\mathrm{Int/Ref}}(t+\delta(t)) \times \beta(t) \times (\sigma^{Int}(t,t+\delta(t)) - \sigma^{\mathrm{Ref}}(t,t+\delta(t)))dt \qquad (1)$$

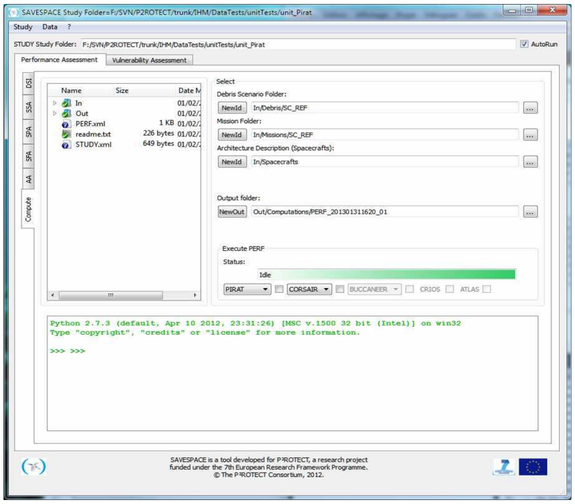
This Equation 1 expresses:

- the difference between the performances of the reference case σ^{Ref} and the case of interest σ^{Int},
- the likelihood of the scenario of interest with regards to the reference scenario $p^{Int/Ref}$,
- each ones of the former calculated on the delay for the need to be satisfied $\delta(t)$ defined by the user,
- pondered by the user defined instantaneous need $\beta(t)$,
- and integrated on the wanted time period for the availability of the capability (t_i, t_f).

Thus, this vulnerability index expresses the availability variation between the two cases, taking into account the user needs and the respective likelihood of the scenario of interest, in the duration of the analysis.

4.2 Performance comparison

The basis of the proposed approach is that the method computes a mission availability value for a specific case of study. This value is not relevant by itself, but needs to be compared to the availability value calculated for a reference scenario. Thus, the user of the SAVESPACE tool needs to define first a reference study, compute the corresponding single case performance by running the tool on it, and then design a second study of interest, describing its space system and the space-debris situation with their relevant evolutions, compute the corresponding single case performance and finally, determine the respective likelihood of those two cases and confront it with the user needs for the mission, using the VALET tool to at last obtain the Vulnerability Index which describes its study.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STUDY Study Folder: F:/SVN/P2ROTECT/trunk/IHM/DataTests/unitTests/unit_Pirat

☑ AutoRun

Name	Size	Date M
In		01/02/
Out		01/02/
PERF.xml	1 KB	01/02/
readme.txt	226 bytes	01/02/
STUDY.xml	649 bytes	01/02/

Debris Scenario Folder: In/Debris/SC_REF

Mission Folder: In/Missions/SC_REF

Architecture Description (Spacecrafts): In/Spacecrafts

Output folder: Out/Computations/PERF_201301311620_01

Status: Idle

PIRAT ☐ CORSAIR ☐ BUCCANEER ☐ CRIOS ☐ ATLAS ☐

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Python 2.7.3 (default, Apr 10 2012, 23:31:26) [MSC v.1500 32 bit (Intel)] on win32
Type "copyright", "credits" or "license" for more information.

>>> >>>
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SAVESPACE is a tool developed for P²ROTECT, a research project funded under the 7th European Research Framework Programme.
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Figure 5. SAVESPACE Graphic User Interface for case study definition

The computation by the SAVESPACE tool of this Vulnerability Index is defined by the user with the help of the SAVESPACE graphic user interface shown on Figure 5.

4.3 Input data

The breakdown of the data needed to process a study is as such (shown in Figure 6):

- the debris knowledge data, separated between trackable and untrackable debris, provides respectively assessments of avoidance effects and of impact effects;
- the spacecraft design data, used with the impact effects data, allows obtaining component liveness data, from which resource availability and function availability assessments can be computed;
- the mission architecture data, in conjunction with the function availability assessment, then produce, with the previously assessed avoidance effects and resource availability, the mission availability data;
- the previously obtained vulnerability data, finally, combined with the mission availability data, delivers the Vulnerability Index.

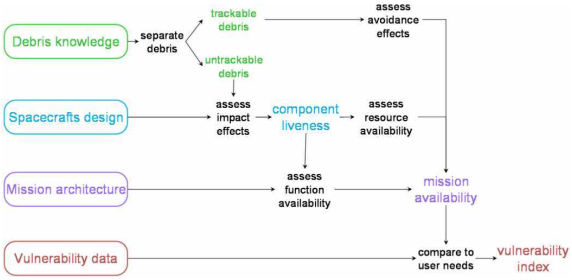

Figure 6. Input data use

4.4 Study workflow

The typical workflow to process a study using the SAVESPACE tool is described on Figure 7.

The user starts a study (blue box on the figure) by logging in the tool, to ensure data traceability, and by creating a new study or loading an existing one.

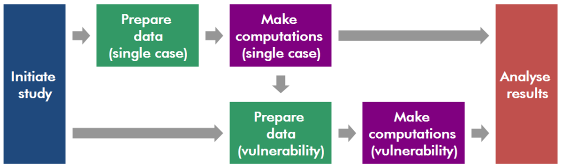

Figure 7. SAVESPACE tool study workflow

The data preparation step (green boxes on the figure) allows transforming the “mission knowledge” into data files compatible with the various pieces of software included in SAVESPACE. To do so, the user can again load existing files and add them to its study, or create new ones by using the ad hoc graphic user interface. A study is constituted of a large number of different files, containing all kinds of data related to the case. The definition of a single case requires access to this information:

- debris scenario information data,
- space situational awareness data,
- a description of the system physical architecture,
- the propellant consumption linked to station keeping data,
- an architecture description for each type of spacecraft in the space system,
- the system functional architecture data,
- and the architecture association that links spacecrafts components to function configurations and their resources.

Once the information for a single case is transmitted to the tool, the calculation for a single case performance can be started by launching the tool and the chaining of codes.

The computation for the Vulnerability Index requires a reference scenario and a scenario of interest, thus two case performance calculations are required before the last step of the process can be launched. For this last step, the tool needs input from the user, in the form of a description of its needs regarding the space system, and a generated file containing the data describing the respective likelihood of the two cases considered. The final step of the calculation can then be started, using a dedicated graphic user interface, to generate the final Vulnerability Index.

5. Conclusion

The P^2-ROTECT project designed a new method for assessing in-orbit debris-related risk for space systems. The method described in this paper is a massive improvement over the usual methods in this matter on several points:

- it takes advantage of the fine physical model for space-debris impact damages assessment at component level,
- it works on multi-scale levels by including the functional architecture of the space system to allow assessing the risk from component level up to mission level,
- it also incorporates the effects of trackable debris encounter risks for the mission,
- it computes a unique vulnerability index, which captures the sensitivity of a proposed solution for risk reduction with regards to a reference scenario.

The global trade-offs analysis that can be assessed from the results of the tool (e.g. Space Surveillance Tracking vs. protection, SST vs. Active Debris Removal, ADR vs. mitigation) will result in a improved knowledge in the possible solutions for the increasing of safety in space.

Several examples, built from actual space systems in LEO, MEO and GEO, have been selected to illustrate the application of the method. The preliminary results for one of these examples are described in another paper [12]. They show that the global trends obtained are correct, and that the tool is able to catch thin sensitivity variations in trade-offs. Further studies will be concluded to strengthen the model and gain confidence in the obtained vulnerability values.

The tool will be further developed along three main improvement paths:

- the physical model used to calculate the damages at component level will be upgraded to take into account the effects of impacts on solar panels that produce damaging electrical arcs;

- the platform overall user environment will be modified to better fit the various categories of users (e.g. a user from the satellite industry will be more interested in the spacecraft protection, thus we intend to offer a specific configuration for assessing the space-debris risk with spacecraft protection improvement in priority; and as well with the national space agencies, insurance companies, …);
- the exploitation of the results returned by the platform will be improved, with tools aimed at better understanding the precise origin of the Vulnerability Index variations, by allowing the exploration of the causal chain.

6. Acknowledgements

The authors would like to thank Onera's “Space System Survivability” research programme team, namely Mrs Catherine Jolly, and Dr. Sylvain Bertrand for their useful comments on that work, as well as the remarkable support we received from Mr Thibault Lang, from Onera’s “Defence and Space System” scientific team, through its relentless use of the platform and its valuable help in its thorough testing.

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