ASSESSING DEBRIS MITIGATION EFFICIENCY USING RISK-ORIENTED CRITERIA: APPLICATION TO LEO EUROPEAN MISSION

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ABSTRACT

This paper addresses the first results of the application of a generic methodology developed to assess the risk of space missions due to the threat of space debris. This work is performed as part of the 30 months P²-ROTECT project (Prediction, Protection & Reduction of OrbiTal Exposure to Collision Threats) that was initiated in March 2011 within the EU seventh framework programme. The method is briefly presented through the vulnerability assessment of the mission of a "SENTINEL-1 type" sub system. Different mitigation scenarios are considered and their efficiencies quantified using the risk-oriented criteria. Numerical results are presented and analysed to illustrate the proposed approach.

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1 INTRODUCTION

Recent numerical simulations on the evolution of orbital debris population in low-Earth orbit indicate that the population has reached an alarming point where the environment is unstable and population growth is inevitable [1]. Remedial measures to be enforced play thus a major role to reduce space mission risk and ensure sustainable space activities. Models of long-term debris environment evolution [2] coupled together with mission risk assessment tools should become particularly useful in assessing the most effective mitigation and remediation measures.

This paper addresses the first results of the application of a generic methodology developed to assess the risk of space missions under different mitigation policies.

Contrarily to many studies, which focus on the vulnerability of the physical system by itself or one of its components [3], the proposed approach considers the risk at a mission level, and aims at evaluating it over the mission lifetime. Therefore, the influence of permanent effects as well as transient effects of a threat may be taken into account and analysed, thus allowing a more comprehensive assessment of the effects of the mitigation policies. The method is based on the evaluation of a vulnerability index [4], which defines a risk of mission performance degradation due to effects of both trackable and untrackable space debris on a complex space system.

The paper is organized as follows. The study case that will be used to illustrate the method is presented in the next section. In section 3, the method for performance evaluation is presented and the different mitigation scenarios described. Section 4 is devoted to vulnerability definition and assessment for the considered study case under the different mitigation policies. The efficiency of each mitigation is also discussed in this section. Concluding remarks are given in the last section of the paper.

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2 STUDY CASE

2.1 Mission characteristics and space system

One of the P²-ROTECT objectives is the evaluation of the vulnerability of a "SENTINEL-1 type" (S1) mission over its lifetime due to the space debris threat. S1 is a near polar sun-synchronous orbiting satellite system for the continuation of Synthetic Aperture Radar operational applications. S1 is a C-band imaging radar mission to provide an all-weather day-and-night supply of imagery for GMES user services[1]. The satellite is supposed operational at January 1st 2013.

A simplified approach is considered here by focusing on the mission of a sub system of the satellite, namely the Attitude and Orbit Control System (AOCS). Note that the method remains unchanged by addressing the mission of a sub system of the satellite or that of the entire space segment. The mission or the global service defined for the AOCS is "provide attitude and orbit control" to the satellite over the its lifetime (supposed to be 7.25 years) starting at January 1st 2013.

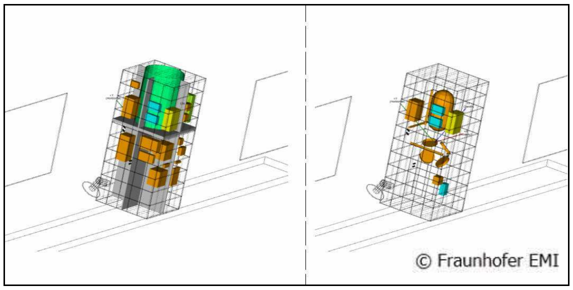


Figure 1. : Left, internal modelled S1-type components. Right, internal AOCS active components.

2.2 Definition of the threat

Among all the phenomena that can impact the realization of the mission by the space system, the threat of space debris is considered in this paper. For the considered Low Earth Orbit (LEO), the population of space objects can indeed have a non-negligible effects on the mission performance. These effects have been separated into two categories, according whether the space objects can be tracked (catalogued) or not.

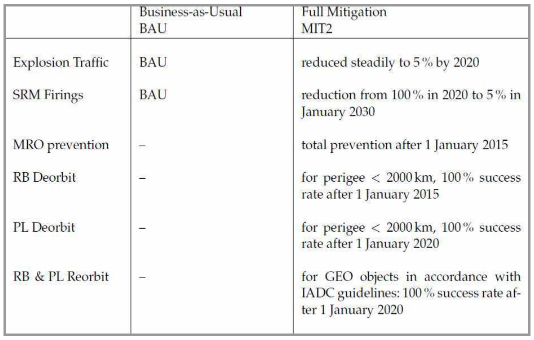
For space objects of size large enough, detection and tracking can be achieved by space situational awareness (SSA) systems. A catalogue of two line elements corresponding to these objects can hence be updated and their trajectories can be predicted. It is hence possible to assess collisions risks with respect to operational satellites and to decide of avoidance manoeuvres in case of high risks conjunctions [5] [6] [7]. During manoeuvre phases, it can be assumed that some services contributing to the mission would not able to be performed (for instance one can assume that "acquiring data" would not be performed due to difficulties to stabilize the line of sight of the sensor) . In addition, reaction to trackable space objects would also impact the physical resources of the satellite, since extra propellant consumption would be required.

For smaller space objects, no conjunction assessment can be predicted and the space system cannot protect itself from potential impacts. Physical components of the satellite can be directly degraded after impact or after cumulated impacts inducing a potential decrease of the global performance of the service.

Both effects are taken into account in this methodology.

2.3 Major working hypothesis

- It is assumed that the AOCS can't ensure its principal mission during avoidance manoeuvres.
- The two debris flux prediction scenarios used in this study are those implemented in MASTER-2009 (developed by ESA). The mitigation policies enforced for each model are listed on Fig. 2.
- Active Debris Removal (ADR) or Event Cloud effects are not modelled in this study.
- Lethal untrackable debris (size ~ 1cm) for which a collision with the satellite entails the lost of the mission are not considered here.
- Only SSA related mitigations and mitigations policies enforced in MASTER-2009 debris flux scenarios are considered.
- Only failure probabilities of internal components are evaluated. The other components are assumed invulnerable to the debris impact.



	Business-as-Usual BAU	Full Mitigation MIT2
Explosion Traffic	BAU	reduced steadily to 5 % by 2020
SRM Firings	BAU	reduction from 100 % in 2020 to 5 % in January 2030
MRO prevention	–	total prevention after 1 January 2015
RB Deorbit	–	for perigee < 2000 km, 100 % success rate after 1 January 2015
PL Deorbit	–	for perigee < 2000 km, 100 % success rate after 1 January 2020
RB & PL Reorbit	–	for GEO objects in accordance with IADC guidelines: 100 % success rate after 1 January 2020

Figure 2. : BAU and MIT2 traffic scenarios from MASTER-2009

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[1] http://www.esa.int/Our_Activities/Observing_the_Earth/GMES/Sentinel-1

3 PERFORMANCE EVALUATION

A probabilistic approach has been chosen to define the notion of performance. The evaluation of the mission performance consists hence in the computation of the probability of success of the mission, with respect to time.

There exist many approaches that can be used to evaluate the performances of systems in a stochastic framework [8]: Bayesian networks, Markov chains, Monte Carlo simulations, etc. The approach used here is the ATLAS methodology developed by ONERA [9].

3.1 Modelling: Architectures association

A very simple and generic way of describing a service or function is to consider that a service consists in answering an order given at some instant within a specific answer delay, which leads to the following performance notion:

$$\pi^F(s,t)$$

which represents the probability of success that function F provides at time t an answer to an order received at time s.

To compute the performance of the mission, one needs to decompose the global service offered by the AOCS in elementary services by the means of temporal logic (simultaneity: SIM; Sequence: SEQ). This decomposition results in a functional tree from which the "leaves" are the elementary functions of the last level of ramification as described on Fig. 3.

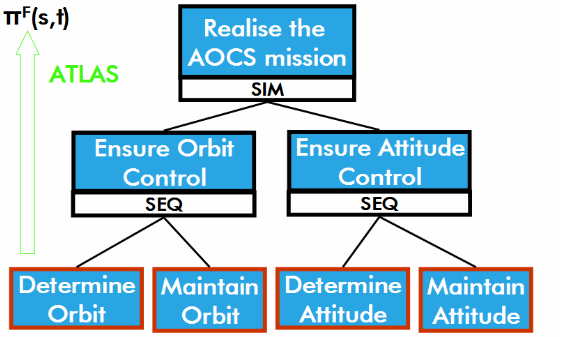


Figure 3. :Functional tree representing a generic AOCS mission. Red contours define the elementary functions

Using this modelling, the probability of success of the mission can be recursively computed from the probability of success of each elementary function, along the functional tree.

It is of course possible, for a given leaf of this tree, to go into further detail by developing it until reaching elementary functions specific to the mission. In agreement with the macroscopic level of the study, no more refinement is applied.

Several physical solutions can satisfy the generic elementary functions of this tree. The one plugged here is inspired from the architecture used for S1. An example of association of a function with a physical architecture of components is represented on Fig. 4. The physical architecture is described by the means of boolen logic that define all the possible configurations of the system to fulfil the function. In nominal mode, regardless the debris threat, the performance of each function is given by the ability of the system in each configuration to satisfy the function. These information are provided by the manufacturer of the system.

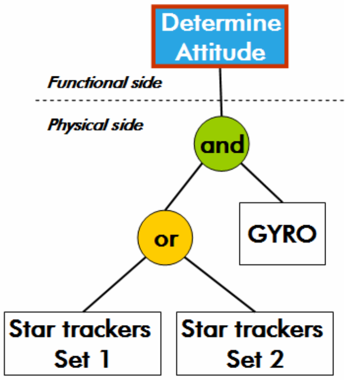


Figure 4. : Example of architectures association with a redundancy for star trackers

For the need of this study, the nominal performances of each possible system configuration have been generated under two main assumptions. The system reacts instantaneously with a probability of success following a linear decrease over the simulation time ranging from 1 to 0.9999. Naturally, it is possible to consider more realistic performances reflecting the behaviour of the system.

3.2 Resources

Each component, or group of components, is associated to one or several resources. A resource defines a physical quantity that is “produced” by a component, or “required” by it to work properly. If a resource availability becomes below a given threshold, defined by the needs of it by other physical components, then the system cannot fulfil its mission anymore. The probability of success of the mission will consequently become zero.

Two resources are taken into consideration in this study:

- Electrical power;
- Propellant;

Because the electrical power is generated by solar panels that are external components and thus invulnerable to the debris in this study (cf. 2.3) , this resource availability is given by a deterministic model that includes an estimation of a decrease over time due to the combined effects of the space weather and debris impacts. It is supposed that the system is well designed and consequently the electrical power availability is still greater than the components need.

Regarding propellant, a simple deterministic approach is taken in this study by considering a fixed mean number of in-plane and out-of-plane orbit manoeuvres per year. These data reflect a simplified approach of the manoeuvres sequences that enable to know the propellant consumption for maintaining the orbit.

Attitude manoeuvres are ensured by reaction wheels. They are electrical actuators that do not require any propellant. The desaturation of the accumulated angular momentum of the reaction wheels is not taken into account in this study.

Anti-collision manoeuvres are probabilistic and managed internally. When an avoidance manoeuvre is decided, the cost model is used to provide an order of magnitude of the speed increment, and hence propellant consumption, necessary for the satellite to avoid a trackable space debris in collision course according to an acceptable safety distance of 10 km, a propagated track accuracy from SSA systems and the delay between the instant of initiation of the avoidance manoeuvre and the estimated instant of impact (scenario dependent).

3.3 Untrackable debris effects on the performance

Impacts of untrackable debris will potentially damage the components realising the function, yielding to a decrease of the probabilities to be in configurations of the system leading to none-zero performances, and consequently a decrease of the performance of the function as time goes by.

Moreover, when untrackable debris threats affect the state of a physical component of the system, it causes a potential decrease in the availability of the produced resource (for instance: impacts of untrackable space debris on solar panels may destroy photovoltaic cells, leading to a decrease in availability of electrical power).

3.4 Trackable debris effects on the performance

To consequently update the probability of success of the mission, one should compute the probability of success of the system to initiate an avoidance manoeuvre. It is based on MASTER-2009 debris flux modelling coupled with a simplification of a collision avoidance procedure for LEO satellites where collision risk is evaluated by a multi stages approach before deciding of a manoeuvre [10]. In this study and according to the working assumptions, the probability of success of the AOCS mission is weighted by the probability to not initiate an avoidance manoeuvre at a given instant.

Note that for an entire satellite, only few functions are inhibited by an avoidance manoeuvre. In order to exclude performance dependencies between the functions, the probability to not initiate a manoeuvre would be considered as a fictive resource. It is hence assumed that if this probability is lower than a given threshold, defined by the need of the functions, then the probability of success of the mission will be zero. This update rule which constraints the mission realisation is very conservative and will be subject to improvements in future work.

The propellant cost of the probabilistic avoidance manoeuvres over time is managed internally and the evolution of the propellant mass expectancy for the satellite according to the different types of manoeuvres and the dry mass is evaluated. When the propellant mass expectancy moves below the de-orbiting mass then the system cannot fulfil its mission anymore and the global performance drops down to zero.

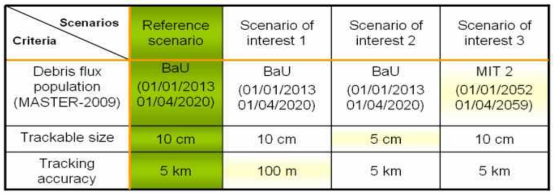
3.5 Description of the scenarios

In all the following, a scenario consists in a statistical repartition model of space debris combined with a SSA system model. The mission remains unchanged as well as the physical architecture.

The general idea of the method is that, under two different given scenarii, the various elementary functions will not be executed exactly in the same way, which will entail a performance gap at the mission level. The performance gap between a scenario of interest and a scenario of reference represents the gravity term in the risk formulation.

The scenario of reference in this study consists in considering the current debris flux population with the present SSA system. The Business-as-Usual (MASTER-2009) debris flux prediction is chosen, and two criteria reflecting the performances of the SSA systems, namely the trackable size and the tracking accuracy, are set to respectively 10 cm and 5 km.

Table 1. :Description of the different scenarios



Scenarios / Criteria	Reference scenario	Scenario of interest 1	Scenario of interest 2	Scenario of interest 3
Debris flux population (MASTER-2009)	BaU (01/01/2013 01/04/2020)	BaU (01/01/2013 01/04/2020)	BaU (01/01/2013 01/04/2020)	MIT 2 (01/01/2052 01/04/2059)
Trackable size	10 cm	10 cm	5 cm	10 cm
Tracking accuracy	5 km	100 m	5 km	5 km

On Tab. 1 is depicted all the scenarios. Only one parameter per scenario of interest is modify with regard to the reference parameters in order to evaluate the effects of each one on the mission's vulnerability. The two first scenarii of interest have the same debris flux scenario model but show gains in term of SSA performances. In the third scenario of interest the debris flux model is switched from BaU to MIT2 (full mitigation).

Finally, from these scenarios the goal is to assess the efficiencies of the mitigation related to SSA system "improvements" and the mitigation measures impacting the debris population.

4 VULNERABILITY ASSESSMENT AND MITIGATION EFFICIENCY

4.1 Vulnerability index definition

Vulnerability is defined as a risk of degradation in mission performance between two scenarios. This vulnerability index has been evaluated for the proposed scenarios of interest with regard to the reference scenario. Here below is called back the vulnerability index formula for the period of study:

$$V^{\mathrm{int/}ref}=\int_{to}^{tf} p^{\mathrm{int/}ref}(\tau+\Delta(\tau))\times\beta(\tau)\times\left[\sigma^{\mathrm{int}}(\tau,\tau+\Delta(\tau))-\sigma^{ref}(\tau,\tau+\Delta(\tau))\right]d\tau \qquad (1)$$

Where:

- $\beta(\tau) \in [0,1]$ represents the likeliness that the user requires the service from the AOCS at instant τ. For numerical evaluation, it is assumed that a user's request is permanent over the period of study, that is $\beta = 1$ (worst case).
- $\Delta(\tau)$ is the maximum delay in which an answer to this order at instant τ is acceptable for the user. As the behaviour of the AOCS was modelled to react instantaneously when required, a maximum response delay of the system allowed by the user is fixed to $\Delta = 0$ second.
- $p^{\mathrm{int/ref}}$ $(\tau+\Delta(\tau))$ is the probability of realisation of the scenario of interest rather than the reference one, and here is set to 1 in order to compare the scenarii without referring to their respective likeliness.
- $\left[\sigma^{\mathrm{int}}(\tau,\tau+\Delta(\tau))-\sigma^{ref}(\tau,\tau+\Delta(\tau))\right]$ represents the difference of cumulated performances of the mission between time τ and $\tau+\Delta(\tau)$. Note that $\sigma(s,t)= \sum_{s\le d\le t}\pi^{F}(s,d)$.

The SAVESPACE tool supports of course more realistic time evolutions of the variables $\beta(\tau)$, $\Delta(\tau)$, and $p^{\mathrm{int/ref}}$ $(\tau+\Delta(\tau))$.

4.2 Vulnerability index evaluation

The vulnerability assessment is presented in two steps. On the one hand the vulnerability of the AOCS mission is evaluated considering only the untrackable debris effects (left part of Tab. 2). On the other hand the vulnerability is evaluated considering both, untrackable and trackable debris effects (Right part of Tab. 2). Explanations are given to justify the trends of the results.

Each SAVESPACE's run takes about 3 hours to evaluate the performance of the AOCS mission over 7.25 years (so 6 hours to evaluate a vulnerability index). Numerical results presented in Tab. 2 are expressed by two derived forms of the vulnerability index as described below:

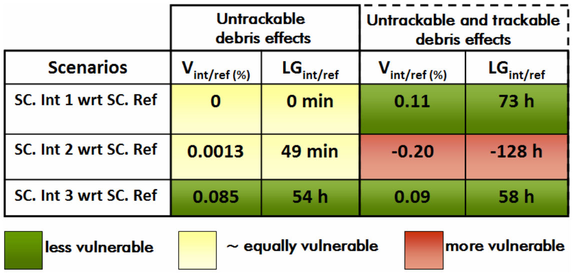
$$V\%^{\mathrm{int/}\,ref}=\frac{V^{\mathrm{int/}\,ref}}{\int_{to}^{tf}\beta(\tau)\times\sigma^{ref}(\tau,\tau+\Delta\tau)\,d\tau}\times 100 \qquad (2)$$

$$LG^{\mathrm{int/}\,ref}=\frac{V^{\mathrm{int/}\,ref}}{\overline{P^{ref}}} \qquad (3)$$

- $V\%^{\mathrm{int/ref}}$ is the percentage of the maximal vulnerability index.
- $LG^{\mathrm{int/ref}}$ is the mission lifetime gap between the two scenarios for equal mean performances.

Each "vulnerability" value in Tab. 2 reveals by row a risk level of a scenario of interest i (SC. Int i) with regard to the scenario of reference (SC. Ref).

Table 2.:Vulnerability indexes for all scenarii



	Untrackable debris effects		Untrackable and trackable debris effects	
Scenarios	$V_{\mathrm{int/ref}\,(\%)}$	$LG_{\mathrm{int/ref}}$	$V_{\mathrm{int/ref}\,(\%)}$	$LG_{\mathrm{int/ref}}$
SC. Int 1 wrt SC. Ref	🟨 0	🟨 0 min	🟩 0.11	🟩 73 h
SC. Int 2 wrt SC. Ref	🟨 0.0013	🟨 49 min	🟥 -0.20	🟥 -128 h
SC. Int 3 wrt SC. Ref	🟩 0.085	🟩 54 h	🟩 0.09	🟩 58 h

🟩 less vulnerable 🟨 ~ equally vulnerable 🟥 more vulnerable

The greater $V\%^{\mathrm{int/ref}}$ is, the lower vulnerable to the threat the mission is. This reasoning is identical for $LG^{\mathrm{int/ref}}$.

4.3 Risk mitigation efficiency by reducing the tracking accuracy (SC Int 1 wrt SC Ref)

Performances are equal between the scenario of interest 1 and the reference one because the sensitivity parameter is the propagated track accuracy and concerns only the trackable debris. Indeed, the failure probabilities of the AOCS components are equal for both scenarios and hence the vulnerability indexes are equal to zero.

A propagated track accuracy of 100 m (instead of 5 km initially) allows a better space situational awareness. Predictions of collision risks are improved and the probability to realize anti-collision manoeuvres is thus lower.

The mission is less vulnerable {$V\%^{int/ref}=0.11$; $LG^{int/ref} = 73$ hours} in the scenario of interest 1 with respect to the reference scenario thanks to the risk mitigation on trackable debris.

4.4 Risk mitigation efficiency by reducing the tracking debris size (SC Int 2 wrt SC Ref)

Scenario of interest 2 is slightly less vulnerable to the untrackable threat than the reference scenario because the upper limit of the untrackable debris size is gone down to 5 cm (instead of initially 10 cm). There is thus a lower untrackable debris flux in scenario of interest 2 with respect to the reference scenario, that's why the vulnerability indexes are positive.

A flux study on MASTER-2009 highlights that the proportion for object diameters ranging from 5cm to 10 cm is approximately the same that object diameters ranging from 10 cm to 10 m (the upper diameter limit in this study), consequently the trackable flux is doubled in the scenario of interest 2. For a given propagated track accuracy of 5 km, the rate of alerts would be much greater for a minimum size of catalogued objects of 5 cm than 10 cm [11]. Finally the negative trackable debris effects overcome the "gain" of untrackable debris effects. The value of the vulnerability indexes are consequently negative.

The mission is finally more vulnerable {$V\%^{int/ref}=-0.2$; $LG^{int/ref} = -128$ hours} in the scenario of interest 2 with respect to the reference scenario. Two recommendations can be made from this case:

- The tracking debris size as to be consistent with the tracking accuracy. Uncoupled evolution of these parameters could worsen the SSA.
- The vulnerability of a mission has to deal with both, untrackable and trackable effects especially when conflicting effects appears.

4.5 Risk mitigation efficiency by reducing the debris population (SC Int 3 wrt SC Ref)

Since on scenario of interest 3 (Full mitigation) the overall debris population is slightly lower (very optimistic mitigation measures coupled with a "favourable" solar activity), then for the same SSA system as the reference scenario, the beneficial trackable debris effects are added to the untrackable ones, decreasing the global vulnerability of the mission.

The mission is less vulnerable {$V\%^{int/ref}=0.09$; $LG^{int/ref} = 58$ hours} in the scenario of interest 3 with respect to the reference scenario thanks to the risk mitigation on trackable and untrackable debris.

5 CONCLUSION

The numerical results provided in this paper illustrate the application of the method on a simplified example. These results represent a first step in the use of the global SAVESPACE tool developed under the P²-ROTECT project. The global trends are correct and the tool shows its ability to catch fine sensitivities. Mitigation efficiencies must be evaluated at short, mid and long term in order to figure out its sustainability over time. The tool allows this evolution aspect by running the scenarii of interest for different timeframes. The vulnerability index gives a relative value to a reference that has to be used for comparison of mitigation efficiencies and not for quantification. Nevertheless the mission lifetime gap index is evaluating an average of the gain or the lost of a mission lifetime and thus offers a cost index that can be put in regard with the cost needed for the implementation of a mitigation measure. The notion of return on investment is hence reachable.

More representative case studies will be addressed in the P²- ROTECT project since one objective consists in assessing vulnerability to space debris of three missions of interest for EU: Sentinel-1 at LEO, the GALILEO constellation at MEO, and the MTG weather observation constellation at GEO.

More accurate models about the physical architecture and its ability to fulfil the mission will be developed to apply this methodology to more representative case studies.

Finally, the SAVESPACE tool evaluates the vulnerability of space missions due to orbital debris and its approach is unique since

- This tool works at mission level (i.e. the services offered to Users) instead of S/C level only. Then, it allows analyzing very innovative protection solutions like S/C redundancy, S/C factorization ….
- It also allows the analysis of global trade-offs to increase safety in space (e.g. Space Surveillance Tracking vs protection, SST vs Active Debris Removal, ADR vs mitigation).
- At space segment level, it takes into account threats coming both from trackable debris (i.e. inducing avoidance maneuvers) and from untrackable debris (i.e. inducing collisions with the S/C from catastrophic to minor levels).
- At space segment level and for the untrackable part of debris, the underlying method is able to deal with

both external and internal components, in one run.

- This tool is able to show effects (or sensitivities) of multi-scale protection solutions (i.e. at mission level, at space segment level, at component level) as well as combined external solutions (i.e. coming from Space Surveillance and Tracking, mitigation measures or Active Debris Removal measures).

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