

SATELLITE VULNERABILITY TO SPACE DEBRIS – AN IMPROVED 3D RISK ASSESSMENT METHODOLOGY

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ABSTRACT

The work described in the present paper, performed as a part of the P²-ROTECT project, presents an enhanced method to evaluate satellite vulnerability to micrometeoroids and orbital debris (MMOD), using the ESABASE2/Debris tool (developed under ESA contract). Starting from the estimation of induced failures on spacecraft (S/C) components and from the computation of lethal impacts (with an energy leading to the loss of the satellite), and considering the equipment redundancies and interactions between components, the debris-induced S/C functional impairment is assessed.

The developed methodology, illustrated through its application to a case study satellite, includes the capability to estimate the number of failures on internal components, overcoming the limitations of current tools which do not allow propagating the debris cloud inside the S/C. The ballistic limit of internal equipment behind a sandwich panel structure is evaluated through the implementation of the Schäfer Ryan Lambert (SRL) Ballistic Limit Equation (BLE).

1 INTRODUCTION

With the continuous growth of the space debris population occurred in the last decade, the need for an improvement over the traditional way of computing the risk induced by micrometeoroids and orbital debris (MMOD) to orbiting spacecrafts, from the early design phases to mission operations, strongly emerged.

The traditional approach to space mission vulnerability with respect to MMOD impacts, typically evaluates the probability of structural penetration. This approach, developed to deal with manned mission, is not well suited to evaluate satellite vulnerability: penetration of a

satellite structural panel does not necessarily lead to the loss of the satellite or the loss of a component.

The 30-month project P²-ROTECT (Prediction, Protection & Reduction of Orbital Exposure to Collision Threats), funded by the European Commission via the Framework Programme 7 under contract number 262820, was initiated in February 2011 to develop improved methodologies and tools to evaluate the vulnerability of space missions, for both trackable and untrackable space debris. A more precise and realistic estimation of the risk induced by on-orbit impacts (i.e. a vulnerability index) allows the comparison of different future scenarios and the evaluation of the effectiveness of protection, mitigation and remediation actions to reduce the space debris threat.

This paper is focused on the risk induced by untrackable debris and micrometeoroids to space missions and it presents an enhanced methodology to evaluate satellite vulnerability with respect to the traditional approach.

2 METHODOLOGY

In Figure 1 is illustrated the enhanced methodology developed to evaluate the spacecraft (S/C) vulnerability using the ESABASE2/Debris tool. Inputs and outputs are shown in blue, computational tools are shown in green. This methodology avoids overestimating the S/C vulnerability through the adoption of the Schäfer Ryan Lambert (SRL) Ballistic Limit Equation (BLE) to evaluate failures on internal components and the inclusion of a functional analysis of the S/C accounting for the redundancies and the interactions between components.

The first inputs come from the analysis of the S/C system (orbital and mission parameters, physical

architecture, and functional analysis): starting from these inputs internal and external ESABASE2/Debris models are derived.

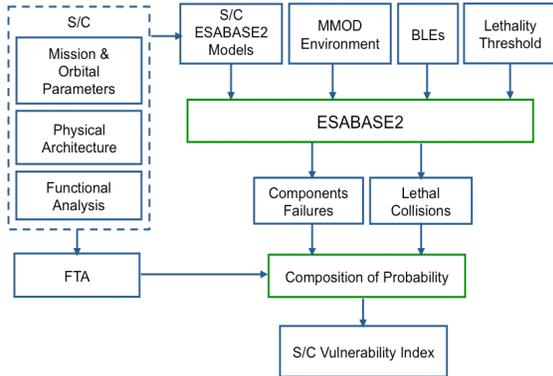


Figure 1: Vulnerability methodology flow

Other inputs required by the computational tool ESABASE2 are the Micrometeoroids and Debris (MMOD) environment models and the Ballistic Limit Equations (BLEs).

Finally, a lethal threshold that allows discriminating between impacts that lead to component failure and impacts that impair the whole S/C causing the loss of the mission, is defined.

All these elements are used as inputs for the ESABASE2 simulations to evaluate the number of failures caused by MMOD impacts on internal and external components, as well as the number of lethal impacts. Component failures and lethal impact probabilities are determined based on failure and impact rates by using the Poisson distribution equation (Eq. (1)) derived from the discrete probability function:

$$P(\lambda > 0) = 1 - e^{-\lambda} \quad (1)$$

where P is the probability that at least one event will occur and λ is the expected number of events.

The last input coming from the satellite analysis is the S/C Fault Tree, used in the vulnerability evaluation: for each Satellite Sub System (S/S) a Fault Tree has been developed, modeling the redundancies and interactions between the components. The various S/S Fault Trees are combined with the probability of losing the system by lethal impact to obtain the satellite vulnerability index, according to a standard Fault Tree Analysis (FTA) approach.

Inputs and outputs of the above described methodology are discussed in more detail in the following sections.

2.1 Case Study

In order to develop and benchmark the 3D risk assessment methodology, detailed analyses have been performed by Thales Alenia Space and OHB System on three reference case studies: the satellites Sentinel-1 (S-1), Galileo and Meteosat Third Generation (MTG), respectively for the three orbital regimes LEO (Low Earth Orbit), MEO (Medium Earth Orbit) and GEO (Geostationary Orbit). The evaluations performed for the MTG and Galileo spacecrafts are not presented in this paper, whereas the Sentinel-1 analyses and results are discussed.

Sentinel-1 is an Earth Observation Satellite for Synthetic Aperture Radar (SAR) operational applications, placed on a Sun-Synchronous, dawn-to-dusk, polar orbit at an average altitude of about 693 km. The Sentinel-1 mission duration is of 7.25 years.

The external structure of the satellite is composed by aluminum and CFRP honeycomb sandwich panels, with skins of variable thickness.

2.2 MMOD Environment

The MMOD environment models characterize the natural and man-made particulate environment of the Earth orbital regions in terms of spatial density and fluxes. The most recent meteoroids and debris environment model, MASTER-2009, developed under ESA contract, has been used in the present work.

In more detail, in this analysis the following models have been used:

- Debris: MASTER-2009; future scenario, business as usual (BAU); epoch 2015; debris density equal to 2.8 g/cm^3 . All debris sources have been considered, except for the multi layer insulation (MLI) sources, as the MASTER2009 data relative to MLI are incompatible with ESABASE2 3.0 version used.
- Meteoroids: Divine-Staubach Model; meteoroid density equal to 2.5 g/cm^3 . Individual meteoroids streams averaged over yearly flux.

The debris and micrometeoroids size interval, adopted in this work, ranges from $100 \mu\text{m}$ to 10 cm (debris trackable threshold in LEO). Figure 2 to Figure 4 show the debris flux in the Sentinel-1 orbit (MASTER2009 outputs) as a function of azimuth and elevation angle, and velocity.

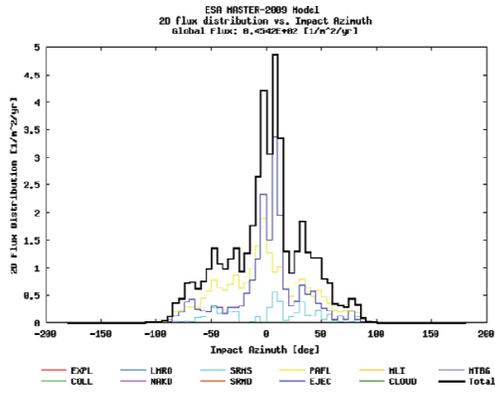


Figure 2: Debris flux [1/m²/yr] distribution over azimuth [deg] – Sentinel-1 orbit

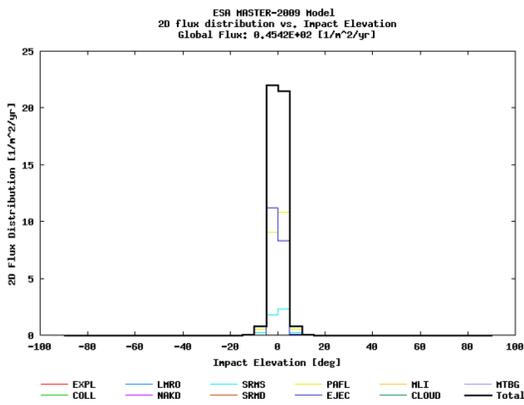


Figure 3: Debris flux [1/m²/yr] distribution over elevation [deg] – Sentinel-1 orbit

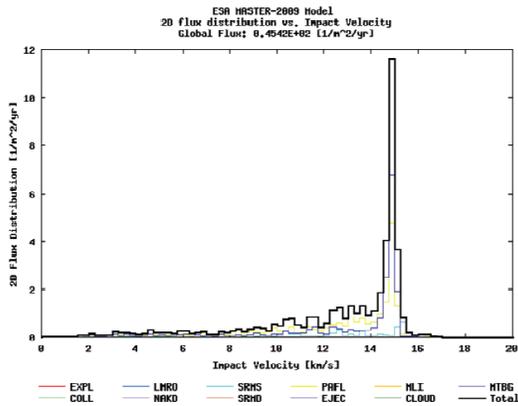


Figure 4: Debris flux [1/m²/yr] distribution over velocity [km/s] – Sentinel-1 orbit

2.3 Lethality Threshold

The effects of an MMOD impact on a S/C can range from a negligible scratch on the external surfaces to the complete fragmentation of the satellite, depending on

the impact energy and the part of the satellite that is hit.

Therefore, in order to better estimate the overall satellite vulnerability, it is required to discriminate between impacts that can lead to component failure and impacts that impair the whole S/C causing the loss of the mission, through the definition of a lethality threshold.

The lethality threshold is defined as the particle diameter threshold above which a collision with the S/C BUS, and possibly other main S/C items (taking into account structural considerations), causes the loss of the mission. Therefore:

- Non-lethal collisions: can cause component failure; the potential damage is assessed through BLEs.
- Lethal collisions: any impact with the S/C main structure and SAR antenna is lethal to the overall system functionality.

In order to define a lethal particle diameter, taking into account that in ESABASE is not possible to implement an energy threshold but only diameter boundaries, we started from the assumption that, in the Sentinel-1 orbit, a 1 cm debris hitting the BUS or the SAR antenna will cause the loss of the mission. Then, considering:

- the debris average velocity in the Sentinel-1 orbit (11.9 km/s - evaluated using MASTER 2009, year 2015, debris diameter from 1 to 10 cm);
- the debris density, equal to 2.8 g/cm³;
- a S/C mass of 2055 kg (S-1 dry mass without solar array wings);

a threshold value of 0.05 J/g as Kinetic Energy / Unit mass of the satellite was derived. This value has been used as a reference to derive the meteoroid lethal diameter for Sentinel-1, equal to 0.85 cm. The same procedure was used to derive the MMOD lethal diameters for the vulnerability analyses conducted by OHB on the MEO and GEO satellites.

2.4 Ballistic Limit Equations (BLE)

The Ballistic Limit Equations define the critical diameter that leads to a failure as a function of the velocity and the impact angle as well as the characteristics (materials, thicknesses and configuration) of the impacted item. In this study two different BLEs have been adopted respectively for external and internal items.

External items have been considered as protected by aluminum cases made of thin plates. A perforation of the case can be considered as critical failure. The single plate Cour-Palais formula has been selected to predict the perforation of a thin wall. This formula, recommended by NASA [2], is based on a large number of experiments performed in the past and gives reliable predictions for hypervelocity impacts on thin aluminum plates.

The Schäfer Ryan Lambert (SRL) triple wall BLE has been adopted to compute the number of failures on internal components. The SRL BLE allows computing the ballistic limit of internal equipment behind a sandwich panel structure. The SRL calculates the critical diameter necessary to produce a component failure (via penetration or detached spall from the inner side of the component cover plate) based on the material characteristics and spacing of the structure panel and cover plate, as well as the characteristics of the impacting particle. The SRL BLE has been developed during an ESA study [1] and later calibrated and validated via a series of test campaigns [3][4][5].

2.5 Satellite model

In order to evaluate damages on both internal and external components, and because ESABASE2/Debris does not propagate the debris cloud inside the satellites, two different S/C models have been created: an “External Model” including all the external components and appendages (SAR antenna and Solar Array) and the main BUS structure (see Figure 5); and an “Internal Model” (see Figure 6) including all the internal components, without the external panel and including all the appendages.

The External Model has been created to evaluate failures of the external components and perforations of the BUS panels. Furthermore, it is used to have an estimation of the number of lethal collisions on the BUS panels and the SAR antenna.

The Internal Model has been created to assess failures of the internal components, whereas external components and appendages have been modeled only for shadowing reasons.

All the major components (external and internal) have been modeled (harness and piping excluded). Simplifications have been made to reduce component complexity: internal components have been modeled as aluminum cases 2.0 mm thick, external components have been modeled as aluminum cases 3.5 mm thick.

This modeling approach allows an estimation of the internal component failures by modeling the S/C internal components and computing the ballistic limit of the internal equipment behind a sandwich panel structure through the implementation the Schäfer Ryan Lambert BLE. The internal items are modeled as boxes, constituted by six separated faces, or cylinders to enable the identification of most vulnerable side.

For each face of each component, SRL equations have been implemented with specific values to characterize the structural sandwich panel (Honeycomb (HC) height, thickness of the skins) and the stand-off from the structural panel. Those values depend on the S/C side taken as reference for each face of the components. The

appropriate choice is defined on a case-by-case basis, depending on the following factors:

- Prevailing debris flux direction.
- Position of the component with respect to the Honeycomb (HC) panels.
- Position of the component with respect to other internal components and shadowing effects by other internal components, external items and structure elements.

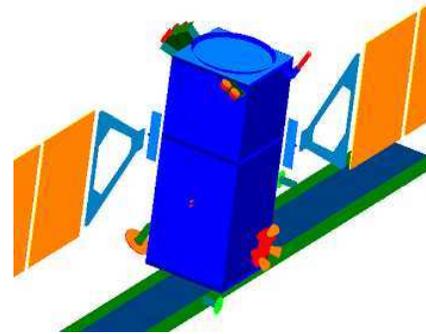


Figure 5: Sentinel-1 ESABASE2/Debris External Model

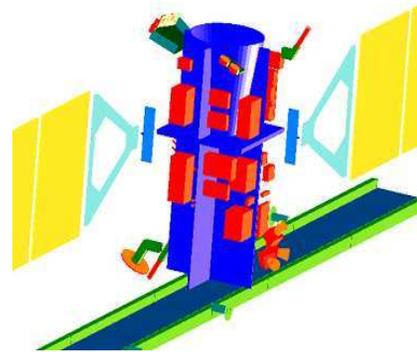


Figure 6: Sentinel-1 ESABASE2/Debris Internal Model

2.6 Fault Tree Analysis (FTA)

Starting from the functional analysis of the satellite mission, the overall system has been broken down into its subsystems, every subsystem has been subdivided into its components and redundancies and interactions between components have been modeled.

For each Sub System a Fault Tree has been developed, considering only space debris induced failures. Failure probability at component level and probability of lethal impacts, provided by the ESABASE2/Debris simulations, are composed according to a standard FTA approach (Boolean logic) obtaining an estimation of the Sentinel-1 space system vulnerability with respect to

MMOD impacts. The FTA developed in this study considers the nominal mission only.

3 RESULTS - VULNERABILITY INDEX

The outputs of ESABASE2/Debris simulations on Sentinel-1, performed with the described methodology, are given in terms of number failures and impacts at components level. Figure 9 reports a screenshot of the output of an ESABASE2/Debris simulation (Internal Model): the color scale shows the impacts flux.

Figure 7 and Figure 8 show a comparison between the percentage of impacts, failures and surfaces on internal and external components, respectively. The results are influenced by the position of the components with respect to the flight direction (affecting the number of impacts) as well as by the impact angle and the average velocity of the impacting particles. Components positioned in the direction of flight (+x side) experience the greatest number of failures. On the contrary, components placed on the S/C side opposite to the flight

direction (-x side) are subject to a very small number of impacts and failures if compared to the other S/C items. Furthermore, shielding effects provided by other components and appendages (e.g. solar array wings) can play a significant role.

Table 1 lists the overall number of failures on external and internal items (without considering redundancies). For comparison, the number of penetrations on the BUS panels (plus an inner plate) evaluated using the SRL BLE (as in a more traditional approach) is also reported. The number of failures on internal components is about one third of the estimated penetration on the BUS panels, thus showing that a modeling of the inside of the satellite is needed in order not to overestimate the risk on the internal components

Table 2 reports the total number of lethal collisions. It can be seen that they are not negligible with respect to the total number of components failures, showing the need to discriminate between lethal and non lethal impacts.

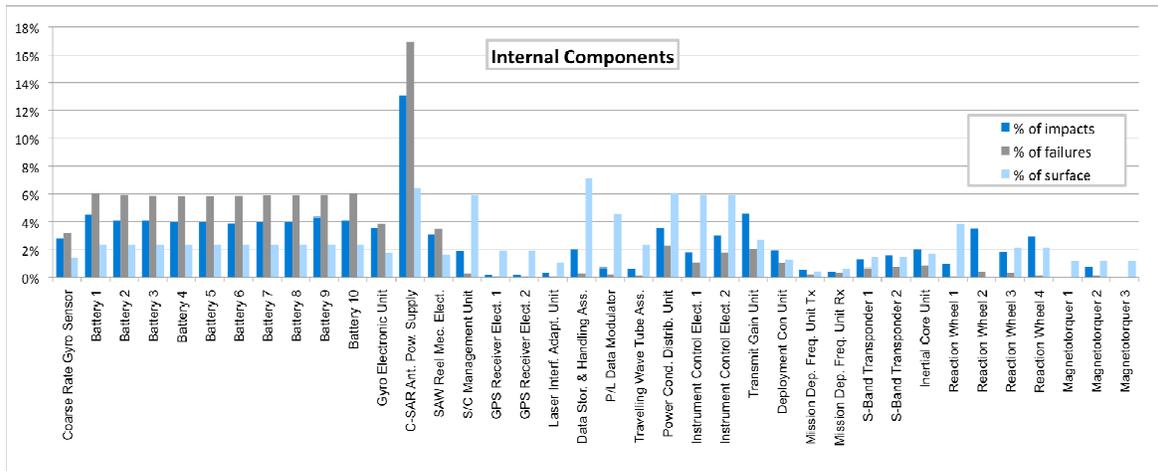


Figure 7: Internal components – Relative percentages of impacts, failures and surfaces

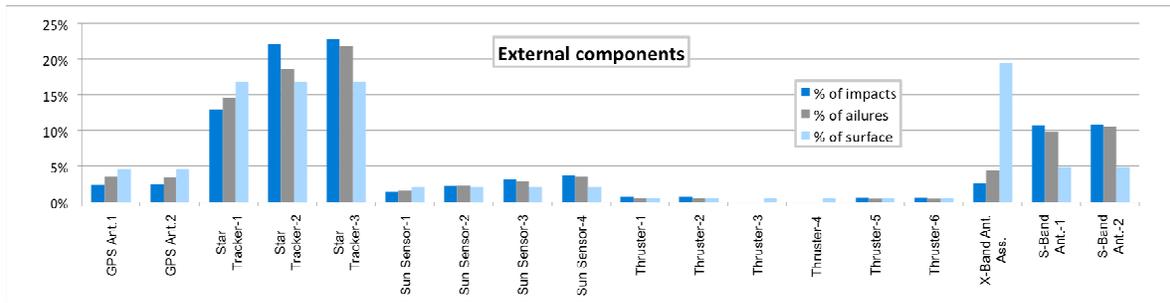


Figure 8: External components – Relative percentages of impacts, failures and surfaces

- Moving vulnerable components toward the S/C centre, thus increasing the stand-off between internal items and external walls, leads to a reduction of failures on the modified items of about the 60%
- Relocating vulnerable components to the anti-velocity (-x) side causes a reduction of the failures on the modified items of about the 98%

The composition of the results at vulnerability index level shows that the simple modifications introduced significantly increase the mission reliability with respect to MMOD impacts: with the decrease of the Sentinel-1 S/C vulnerability from 4.51E-02 to 3.67E-02 (see Figure 10). However, a detailed design improvement exercise is an iterative process taking into account all the system design aspects (e.g., thermal, structural, etc.). These aspects have been considered only at a preliminary level in the present work, that is focused on the definition of the vulnerability evaluation methodology.

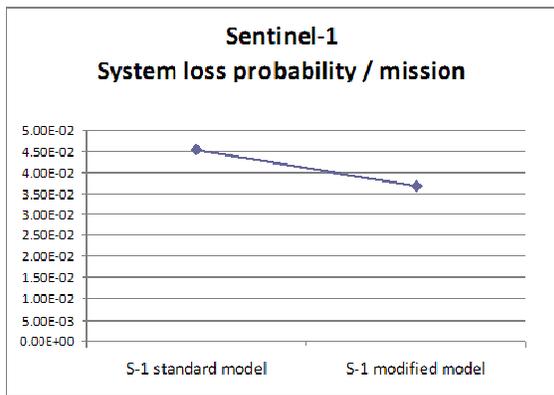


Figure 10: Probability of loosing the S/C – Standard vs Improved Sentinel-1 model

5 HVI TESTS

In order to better select protection strategies and improved design, HVI tests on the analyzed configuration are always recommended. In the contest of this study, ten HVI tests have been performed at the EMI Fraunhofer Institute with a two-stage light gas gun on a Sentinel-1-like configuration.

The tested configuration (see Figure 11) consisted in a Honeycomb panel, an aluminum plate (2 mm thickness) posed at 100 mm representing a satellite equipment cover plate, and a witness plate posed at 50 mm from the cover plate. The selected HC panels correspond to the Sentinel-1 external panels. The purpose of this test campaign was to have good reference testing results to calibrate the SRL with respect to a Sentinel-1-like configuration, and to compare symmetric vs. asymmetric HC performances. Two angles of impact (0° and 45°) have been tested, with projectile diameters ranging from 4 to 6 mm, and impact velocities ranging

between 6.3 and 7.2 km/s. Figure 12 shows an High Speed Shadowgraph picture of a test with impact angle 0°; velocity 6.4 km/s; projectile diameter 4.5 mm.

A detailed description and analysis of the HVI tests is beyond the purpose of the present paper. However, it can be said that the results showed that SRL ballistic limit equations are conservative for a Sentinel-1-like configuration, in particular for impacts at 45°. A detailed analysis of the results could bring to a less conservative dependency on the angle of impacts for a Sentinel-1-like configuration. Moreover, channeling effects has been observed in two out of five normal impacts.

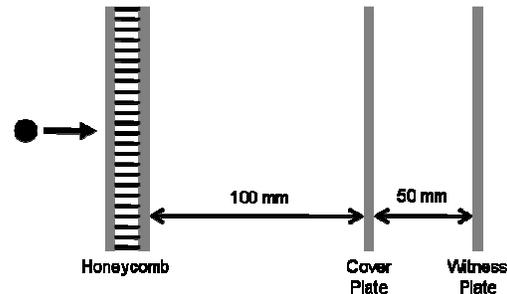


Figure 11: HVI tests configurations



Figure 12: HVI test on Sentinel-1-like configuration

6 CONCLUSIONS

An enhanced methodology to evaluate S/C vulnerability to untrackable debris and micrometeoroids has been developed. This methodology includes the capability to estimate failures on internal components and takes into account redundancies and interactions between components, thus allowing a more realistic estimation of the risk posed by MMOD impacts on satellite missions with respect to a traditional approach to vulnerability. A key aspect of the methodology is the capability to discriminate between impacts that can lead to component failures and impacts whose energy can impair the whole S/C leading to loss of the mission.

This methodology has been applied to three satellite case studies. The workflow and the results of the

analyses conducted on one of the case studies (LEO satellite Sentinel-1) showed the S/C vulnerability index to be in the range of about 4 % over the complete mission, with a significant reduction with respect to the results typically obtained with the traditional analysis, i.e., considering as a failure a structural penetration of the satellite BUS. Furthermore, the use of the methodology to select design strategies in order to improve S/C protection with respect to MMOD impacts has been demonstrated. A simple design improvement exercise to investigate few modification measures showed a significant efficiency in reducing the overall vulnerability index (of about the 18% with a very limited mass increase of about 2 kg).

7 ACKNOWLEDGEMENTS

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