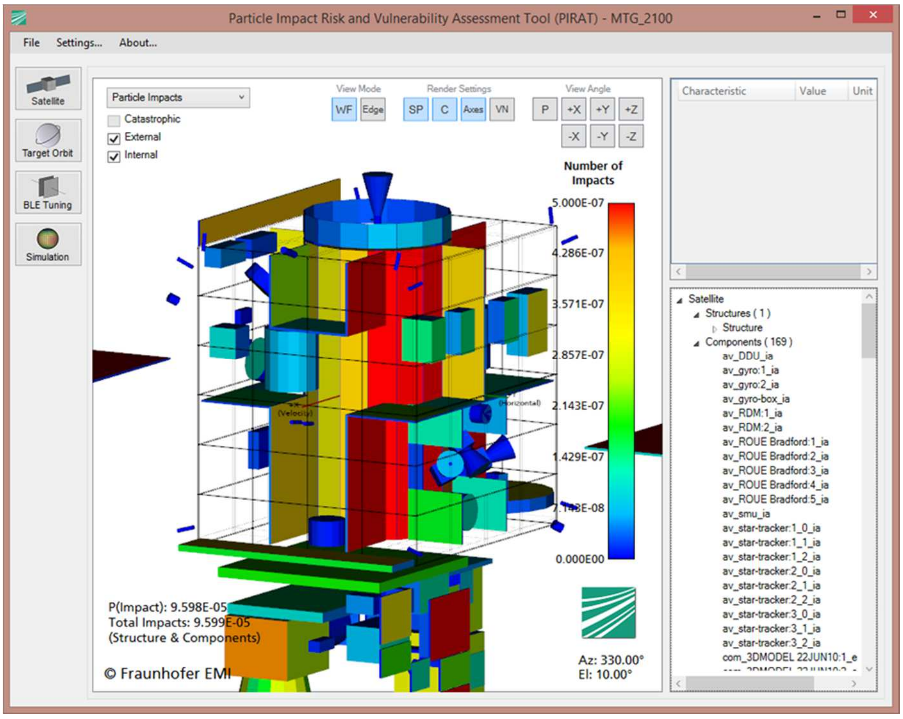
Simplified models for spacecraft vulnerability assessments in early design phase

ESA contract 4000108581/13/NL/MV

Executive Summary

Report I-57/14



Prepared by:
S. Kempf

Contributions:
F. Schäfer
M. Rudolph

Management:
F. Schäfer

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Freiburg, Germany

Fraunhofer Institute for High-Speed Dynamics
Ernst-Mach-Institut, EMI
Director: Prof. Dr. Klaus Thoma

EMI Freiburg,
Eckerstrasse 4, 79104 Freiburg, phone +49 761 2714-0
EMI Efringen-Kirchen,
Am Klingelberg 1, 79588 Efringen-Kirchen, phone +49 7628 9050-0
www.emi.fraunhofer.de

Simplified models for spacecraft vulnerability assessments in early design phase
ESA contract 4000108581/13/NL/MV – Executive Summary

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Prepared by:

S. Kempf
Research Fellow – Spacecraft Technology Group

Management:

Dr. F. Schäfer
Head of Spacecraft Technology Group

Dr. M. Wickert
Head of Impact Physics Department

Prof. Dr. rer. nat. K. Thoma
Director of Ernst-Mach-Institut

Table of contents

1 Scope of this document

The executive summary at hand summarizes the work performed in the study "Simplified models for spacecraft vulnerability assessments in early design phases" funded by the European Space Agency (ESA) under contract no. 4000108581/13/NL/MV. It covers a literature review on spacecraft vulnerability studies and the existing Particle Impact Risk and Vulnerability Assessment Tool (PIRAT), and a review of satellite collisional fragmentation by large impact masses; the requirements specification for the integration of PIRAT in the CDF facility as well as further expansion of the tool functionality in compliance with the requirements of the corresponding Statement of Work (SoW), the methodology for implementing those changes and the documentation of development and testing; and finally the establishment of a validation methodology in correspondence with the IADC, the evaluation of a test case provided by the ESA, and recommendations for future evolutionary models, S/C designs and studies.

2 Acronyms and abbreviations

BLE	Ballistic Limit Equation
CAD	Computer Aided Design
CDF	Concurrent Design Facility
CFRP	Carbon-Fiber-Reinforced Polymer
CPE	Cell-Passage Event
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
DST	Domain Specific Tool (OCDT)
EMI	Ernst-Mach-Institut (Fraunhofer)
EMR	Energy-to-Mass Ratio
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
HVI	HyperVelocity Impact
IADC	Inter-Agence space Debris coordination Committee
LAD	Large Area Detector (LOFT)
LEO	Low Earth Orbit
LOFT	Large Observatory for X-ray Timing
MMOD	Micro-Meteoroid and Orbital Debris (also MM/SD)
MM/SD	Micro-Meteoroid and Space Debris (also MMOD)
NAUO	Next Assembly Usage Occurrence (STEP)
OCDT	Open Concurrent Design Tool
PBEE	Panel Back-End Electronics (LOFT)
PIRAT	Particle Impact Risk and vulnerability Analysis Tool
PLM	Payload Module (LOFT)
PNF	Probability of No Failure
PNP	Probability of No Penetration
RDL	Reference Data Library (OCDT)
S/C	Spacecraft
SiMo	Simplified Models for spacecraft vulnerability assessments in early design phase
SoW	Statement of Work
SRL	Schäfer-Ryan-Lambert (BLE)
STEP	STandard for the Exchange of Product model data (ISO 10303)
SVM	Service Module (LOFT)
TAS-I	Thales Alenia Space - Italy
TUBS	Technical University of Brunswick (Technische Universität Braunschweig)
WFM	Wide-Field Monitor (LOFT)

3 References

[1] M. Rudolph, N. Welty, R. Putzar, F. Schäfer, D. Koebel, R. Janovsky, J. Apeldoorn and M. Lambert, "Extending the Applicable Range of the SRL Ballistic Limit Equation to Oblique Hypervelocity Impacts," *Proc. of the 12th European Conference on Spacecraft Structures, Materials & Environmental Testing*, 20-23 March 2012.

[2] „Constitution and Bylaws of the Hypervelocity Impact Society," Hypervelocity Impact Society, November 1989.

[3] F. Schäfer, S. Ryan, M. Lambert and R. Putzar, "Ballistic limit equation for equipment placed behind satellite structure walls," *Int. J. Impact Engng*, no. 35, pp. 1784 - 1791, 2008.

[4] N. Welty, M. Rudolph, F. Schäfer, J. Apeldoorn and R. Janovsky, "Computational methodology to predict satellite system-level effects from impacts of untrackable space debris," *Acta Astronautica*, http://dx.doi.org/10.1016/j.actaastro.2013.01.021

[5] D. M. McKnight, R. Maher and L. Nagl, "Refined algorithms for structural breakup due to hypervelocity impact," *Int. J. Impact Engng*, vol. 17, pp. 547 - 558, 1995.

[6] "Validation of Tools," Inter-Agency Space Debris Coordination Committee – Protection Manual, Version 4.0, IADC-04-03, pp. 2-21 – 2-26, April 12, 2011.

4 Introduction

The space debris environment poses an ever-increasing risk to spacecraft particularly in low Earth orbits (LEO). Due to limitations of existing vulnerability models, increasing the overall survivability of a spacecraft by enhancing the protection of sensitive parts was not possible in the past. The aim of this study was to adopt and develop methodologies that allow increasing the survivability of a spacecraft by varying individual parameters, e.g. the position of sensitive components or the thickness of component casings. This tool was designed for use in the ESA Concurrent Design Facility (CDF) to support a robust design against space debris in early design phases.

Risk assessments for spacecraft in the past were limited to the assessment of the so-called probability of no penetration (PNP) of the outer hull. This key figure represents the inverse of the probability that a micrometeoroid or space debris particle will penetrate through the spacecraft outer hull within the planned mission time. The assessment of the damaging effects of the particle fragments inside the spacecraft was left to judgment of the person in charge of the analysis. PNP in itself is not a sufficient criteria for component failure as it is a strongly approximated approach. Penetrating particles do not necessarily cause damage to components. On the other hand, particles without penetration capabilities can still damage components (e.g. optical components) positioned outside the spacecraft outer hull.

The Schäfer-Ryan-Lambert (SRL) equation is a three-wall ballistic limit equation that predicts the impact-induced damage to a component wall that is placed inside a spacecraft hull typically made up of honeycomb sandwich panels. Combining this equation with space debris population models allows for the calculation of failure probabilities for specific components.

The Particle Impact Risk and Vulnerability Analysis Tool (PIRAT), developed at Fraunhofer EMI, provides an automated way to calculate failure probabilities for individual components positioned inside a spacecraft. This allows identifying and reducing vulnerable parts of the spacecraft, thus contributing to more robust designs.

The same tool also allows estimations on the probability of catastrophic collision. Although not much is known on the effects the impact location has on a catastrophic satellite fragmentation, some parts of the satellite are identified to couple kinetic energy of the colliding particle more efficiently to the satellite structure than others. The projection of those components on the direction of large particles can give a first order estimation of the overall probability of fragmentation of the satellite during a specified analysis time window.

5 Literature review

The interference of satellite missions by micrometeoroid and space debris (MM/SD) occurs on various levels, roughly differentiated based on MM/SD impactor energy. Low energy impactors threaten the functionality of individual components. These included particularly exposed (external) components or, for energies at the higher end of this spectrum, insufficiently shielded internal components. For this reason, the development of risk and vulnerability analysis based on probability of no failure (PNF) are replacing the conventional risk analyses based on probability of no penetration (PNP). Higher energy impactors are capable of fragmenting a target satellite, not only disabling the mission but also producing a secondary cloud of debris particles and exacerbating the debris environment.

Satellite vulnerability assessments

Both impactor energy regimes lie partially or fully in the hypervelocity impact (HVI) domain [2]. The particular physical principles observed during a hypervelocity impact are the subject of a significant number of test campaigns and are a particular area of expertise for the Fraunhofer EMI. To this purpose, conventional two-wall HVI ballistic limit equations (BLEs), which predict the response of sandwich panels or Whipple shields, were expanded to an analysis of internal components under various failure modes to produce the three-wall Schäfer-Ryan-Lambert (SRL) BLE. Figure 5-1 demonstrates a general characteristic curve for a 2- or 3-wall BLE. Figure 5-2 shows the standard configuration for a SRL target set-up [3].

During a previous EU FP7 study, a semi-deterministic methodology was developed to apply the SRL, along with the outputs of debris environment models like MASTER-2009, to the assessment of the vulnerability of modelled satellites to MM/SD. This was implemented in the Particle Impact Risk and vulnerability Assessment Tool (PIRAT) [4]. Unlike previous tools, such as ESABASE or NASA BUMPER, PIRAT assesses vulnerability based on PNF by performing a geometrically analysis of external structure panels and internal components and applying the three-wall SRL BLE. In addition to the assessment of the vulnerability internal components to MM/SD, PIRAT is capable of determining catastrophic impact based on a catastrophic energy-to-mass ratio (EMR) threshold defined in [5].

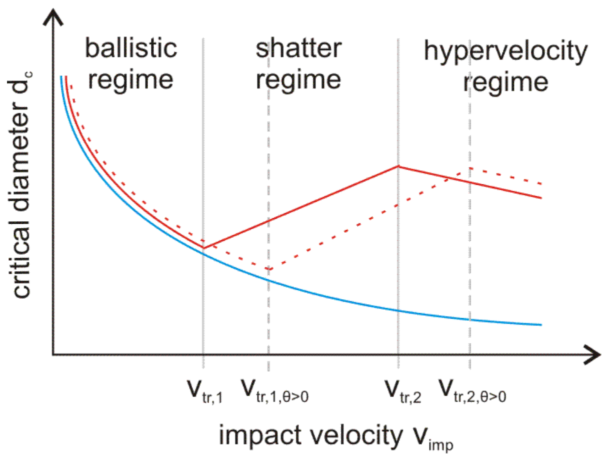


Figure 5-1: Schematic SRL ballistic limit curve. Single wall curve without spacing (blue), multi-wall curve with spacing (red), multi-wall curve with spacing and oblique impact (red, dashed) [1].

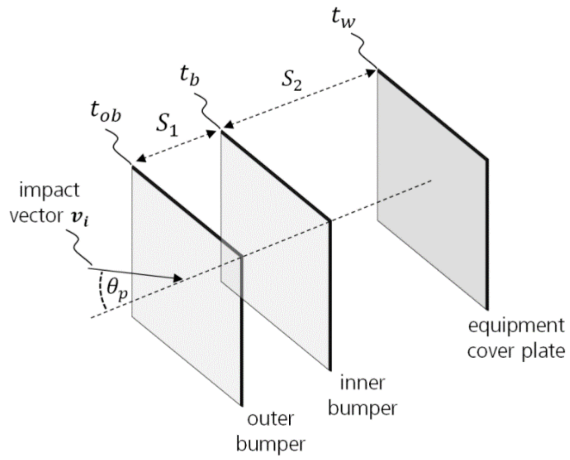


Figure 5-2: Typical SRL configuration [3].

During the performance of this study, a concern was raised that the ability of non-inline debris clouds and debris cloud cones to induce component failure was neglected with the existing methodology. Based on existing empirical evidence, it was demonstrated that this effect was negligible, and that the existing methodology constituted the most reasonable model of the hypervelocity impact process.

Satellite Fragmentation

Satellite collisional fragmentation also constitutes a major concern of the space community. While not common, fragmentation collisions exacerbate the debris environment by increasing the debris population. Several institutes are involved in developing or refining fragmentation models in order to better understand the break-up process.

The PIRAT fragmentation implementation focuses on determining when catastrophic impact occurs. The analysis is applicable if the energy-to-mass ratio (EMR) exceeds 40 J/g, a value that originates from a hypervelocity impact study mainly on satellite components [5]. The energy coupling coefficient is also introduced here, a concept which is believed to be valuable since it addresses non-central impacts.

The energy coupling coefficient P describes the share of impactor energy that couples to the structure. It can adopt values from 0 to 1 and is low for easily penetrable structures such as solar arrays ($P_{solar\ array}$ = 0.1) and close to 1 for the satellite main body. Figure 5-3 illustrates the concept.

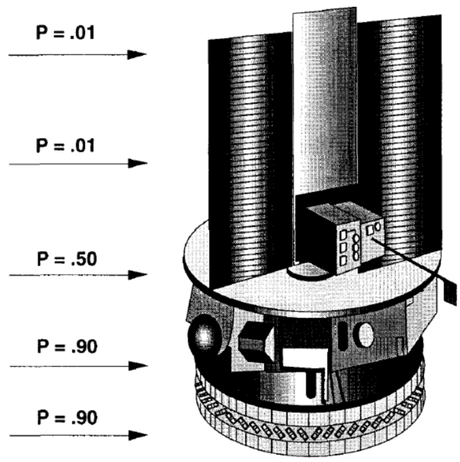


Figure 5-3: P-78 satellite with corresponding energy coupling coefficients for impacts at different locations [5].

6 Development of a vulnerability model

Requirements

Before expanding the functionality of PIRAT, a set of requirements was specified based on (a) the SoW requirements, (b) user requests from industry, and (c) requirements for integration in the CDF. In addition to formally requiring the implementation of PIRAT to cover SoW requirements, the following new major functionalities were specified:

- Implement STEP importer
- Implement OCDT importer
    - o Definition of OCDT – STEP interface specification
    - o Definition of OCDT – PIRAT interface specification
- Improve PIRAT model with regard to improved flexibility of CAD modelling (via STEP), improve:

    - Improve organizational flexibility of PIRAT physical model
    - Support for irregular polygons
    - Support for unspecified import shapes
- Improve navigation with regard to updated PIRAT model
- Update vulnerability assessment algorithm with regard to updated PIRAT model
    - Re-develop in C++
    - Analysis at surface-level
    - Improved analysis settings for run-time – accuracy trade-offs (in-session / out-of-session)
    - Improved testing functionality for assessing new algorithm
- Implement energy coupling factors for catastrophic impacts

CDF Trade-off

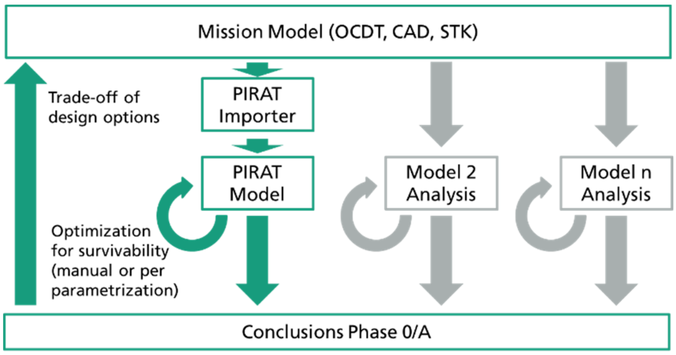


Figure 6-1: Role of PIRAT in the CDF.

Due to the unstable nature of early phases of the satellite model, the implementation of efficiency-accuracy trade-off measures will be utilized in favor of efficiency settings (simplified forms, either defined in the CAD model or via manual modelling of shapes in PIRAT, and course threat discretization). As the satellite model stabilizes in later phases, the trade-offs can be re-calibrated with considerations of more specific forms, finer threat directions, and smaller parameterization loops.

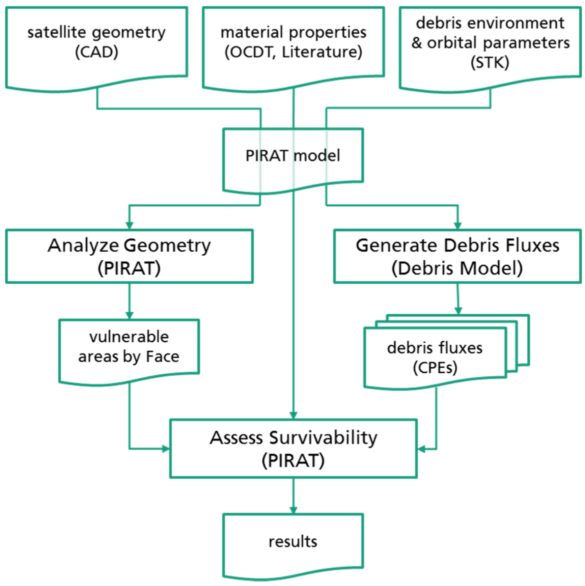
The application of PIRAT as a vulnerability assessment mode can be visualized in the basic trade-off study flow diagram in Figure 6-1.

Vulnerability Assessments

The vulnerability assessment methodology considers inputs from both MASTER (-2005 and -2009) and ORDEM2000 debris models and applies primarily the Schäfer-Ryan-Lambert (SRL) BLE [3], which is the preeminent triple-wall BLE.

The SRL provides fit parameters for configuring the BLE equation depending on the type of target or configuration and can be refined through additional impact tests. At the request of earlier project partners/customers, these fit parameters are configurable by the user in PIRAT.

The computational methodology is divided into three major steps, the debris flux generation, geometrical analysis and survivability assessment. In order to consider the additional import functionality, the top-level flow diagram has been re-created from Figure 6-2.



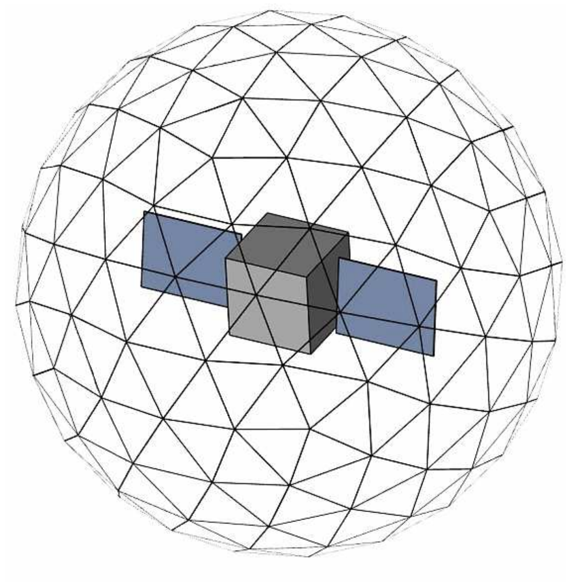


Figure 6-2: Main PIRAT computational methodology: interaction between jobs and I/O data.

Figure 6-3: Example threat direction allocation (10° discretization).

The performance of geometrical analysis involves creating threat directions by defining a geodesic sphere around the satellite. For each threat direction, the vulnerable areas of each external component and structure panel are calculated. For each structure panel and threat direction, the vulnerable areas of each internal component through the "window" of the structure panel were calculated. In each case, the vulnerable areas considered both the projection based on the threat direction angle, as well as the shadowing effect of any closer components or structure panels. "Vulnerable area" refers to the visible (non-shadowed) projected area of a component or structure panel with respect to the threat direction.

Due to the increased flexibility mentioned above, the shadowing, as well as the Z-ordering and S2 algorithms had to be re-imagined. For the most part, geometrical analysis is now performed exclusively at the face-level, as in Figure 6-4.

Upon assessment of individual impacting particles, the particles are "binned" to a particular pre-analyzed threat direction based on impact direction. In order to associate the individual fluxes with the threat directions, every possible impact angle is assigned to the nearest threat direction based on its location within the geodesic sphere (see Figure 6-3).

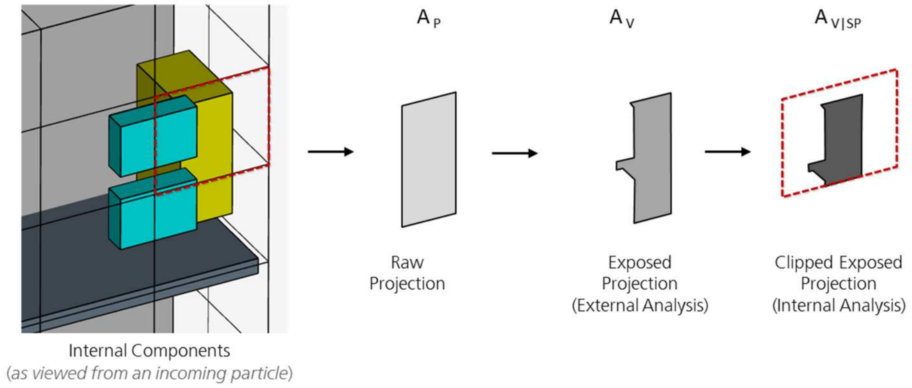


Figure 6-4: Evaluation of exposed area of components through structure panels.

Improved efficiency – accuracy trade-off shall be accomplished via manual modelling (user dependent), the existing threat direction discretization functionality and additional computational switches, including:

- Enabling / disabling threat direction distribution
- Enabling / disabling external impact assessment
- Enabling / disabling internal impact assessment
- Enabling / disabling internal impact assessment on face level
- Enabling / disabling internal structure panel impact assessment

Catastrophic Assessment

The assessment of catastrophic impact is performed by initially assessing an incoming particle based on its specific kinetic energy. The kinetic energy of an incoming particle is calculated using the following equations (all units SI):

$$E_{kin} = 0.5 \cdot m_p \cdot v_p^2 \tag{1}$$

Following the initial impact assessment however, an impact particle exceeding the catastrophic impact threshold is initially only flagged as catastrophic. Catastrophic flagged particles are then additionally assessed for all primary (external) impacts on the additional basis of the energy coupling factor for that component or structure panel (if enabled) for determination of actual catastrophic impacts. A catastrophic flagged impact particle can now be considered catastrophic for certain structures / components (e.g. main body, payload) and non-catastrophic (then further assessed for penetration / cratering) for others (e.g. solar panel, gravitational boom). Equation (2) demonstrates this:

$$\mathrm{E_{kin,transferred}} = \mathrm{P} \cdot E_{kin} \tag{2}$$

where P is the energy coupling coefficient from [5] (see also Figure 5-3).

CDF Import

The most time intensive aspect of the original modelling procedure is the calculation and input of the structure and component geometrical characteristics. The STEP-Importer enables a much faster and more flexible geometrical modelling process.

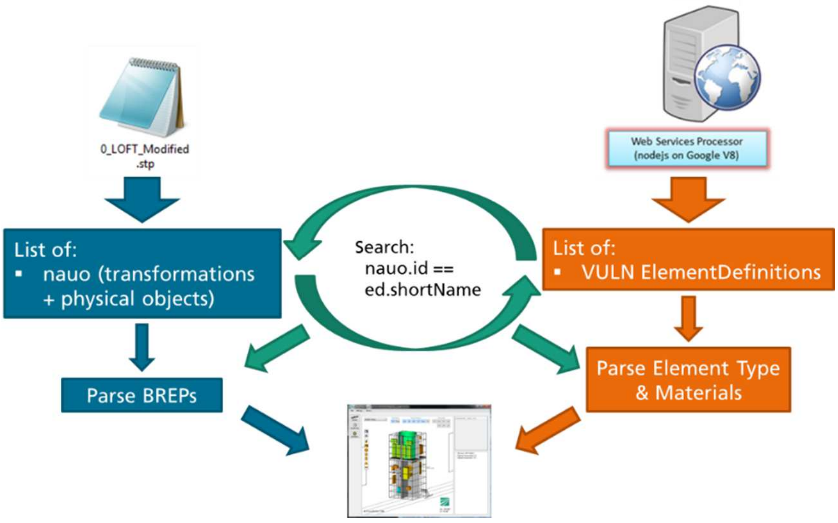


Figure 6-5: CDF-Import association process.

In order to perform a PIRAT analysis, it is necessary to assess each object as an individual physical object. Based not only on the material properties and the geometry, but also the location and orientation of an object, the results differ. For this reason, it was necessary to determine at which points in the import sources a 1-to-1 association between the source models and the PIRAT model could be made. In this case, next assembly usage occurences (NAUOs) from the STEP file provide both the basic product data and the transformation specifications for individual physical objects. Although the equivalent OCDT ElementUsages would appear to fulfill the same function, limitations on modification of their parameters require the application of repeated ElementDefinitions for analysis tools.

Note: The OCDT design foresees the application of a third type of entity, the Nested Element. This will provide access to the real component created by an ElementUsage of an ElementDefinition, similar to the NAUO or a PIRAT object. When implemented, this should provide the necessary interface which is required for analysis tools such as PIRAT.

Note: The OCDT interface development required the development of additional parameter types, measurement scales and units, element categories and category rules in the form of a new reference data library (RDL), as well as new users, domains of expertise, etc. For a more detailed discussion of these modifications, see the corresponding Final Report for this project.

For non-OCDT applications, a standalone STEP importer was also developed, whereby the individual import elements (again from NAUOs) are configured via characteristics dialogs, similar to those already provided for the modelling interface. This also provides the possibility to enter literature based default parameters.

7 Model evaluation and validation

Model Validation

The validation of a model such as that developed and implemented in PIRAT is extremely difficult due to the nature of probability predictions and the availability of statistical data. While individual parts of the model can be validated (validation of BLEs is outside the scope of this project), the approach within SiMo with respect to validation is as follows:

- the McKnight catastrophic impact threshold (40 kJ/kg) [5] and energy coupling factors are compared with available historical collisions provided by TUBS and
- an expansion of the conventional IADC calibration cases is proposed, which accounts for the expansion of vulnerability/risk models to internal components.

In a separate analysis of available impact data for historical S/C on S/C impacts, all collisions resulted in catastrophic failure except the Cerise – Ariane Debris collision. The McKnight procedure, however, recommends the assessment of certain external appendages separately of the whole satellite. In this case, a catastrophic break-up of the gravitational boom did occur, however not that of the satellite. In all other cases, the catastrophic EMR plus coupling factors exceeded the 40 J/g specified. While the collection of 7 cases provided do not constitute a statistically significant population, and all represented break-up cases, the data available agrees with the model as proposed and implemented.

For non-catastrophic impacts, validation has conventionally been performed in the form of calibration or benchmark cases due to the complex nature of the analyses. The existing cases for risk analysis tools involve determining PNP for specific debris environments for three basic satellite shapes.

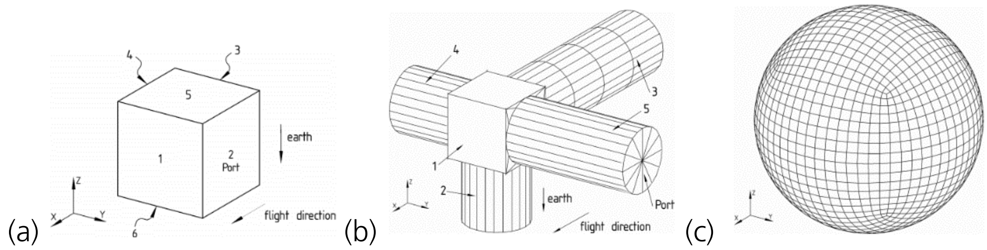


Figure 7-1: Geometry of (a) the Box, (b) simple Space-Station Model and (c) Sphere (1m2 cross-sectional area, 1.1284m diameter) [6].

PIRAT's extended application regime requires an expansion of the test cases. Because it is based on the same principle, specifically the application of NASA and ESA debris models and empirically defined BLEs to structure and mission models, a set of new calibration cases for internal component failure analysis has been specified and recommended to the IADC for inclusion in the Protection Manual v7.0. The following pre-requisites for the new cases were defined:

- Validation procedure shall be based on IADC protection manual risk analysis tool calibration method

- All approaches shall be based on inputs from established debris models (e.g. MASTER-2009, ORDEM2000)
- Validation shall be based on scientifically published experimental HVI vulnerability data (as far as possible)

Test Case and CDF-Demonstration

The test case that was eventually chose for the SiMo project was the ESA mission Large Observatory for X-ray Timing (LOFT). LOFT represents a good test case for PIRAT because of its mission and orbit. In LEO, the density of MMOD is at its greatest, which provides a good opportunity to assess realistic threats due to MMOD. Additionally, scientific payloads represent a large number of applications in this orbit. The ability to assess not only historically known components and subsystems, but to determine how to model and assess new types of sensors is important for demonstrating how to apply PIRAT to the assessment of satellite vulnerability.

For the model, generalizations were made regarding the types of component cover plates and structure panels applied. In most cases, simple aluminum cover plates (1mm 2024-T3), with some titanium components (tanks, thrusters). The LAD panels were assessed as single panel structure panels and the body (structural tower, SVM and PLM) as double panel aluminum. Figure 7-2 displays the model post STEP-import in PIRAT.

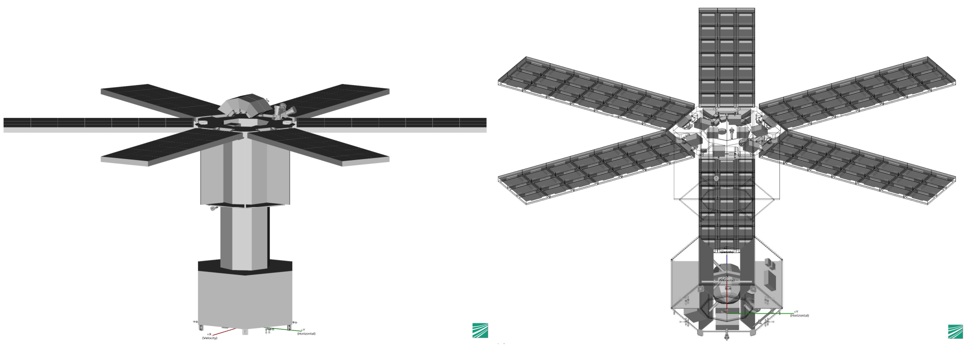


Figure 7-2: Imported satellite model in PIRAT – external view (l.) and internal view (SP as wireframe) (r.).

The test case was used as a jumping off point for the performance of the CDF demonstration. The following pre-session conclusions were reach regarding the test case:

- the catastrophic impact risk and internal failure rate lie in acceptable ranges,
- a selection of external components (star-trackers, sun sensors) require attention regarding their high potential failure rates (primarily, these components have to be modelled better and the input verified), and
- protection measures have been suggested in the form of added structure panels in the horizontal for the LAD PBEEs.

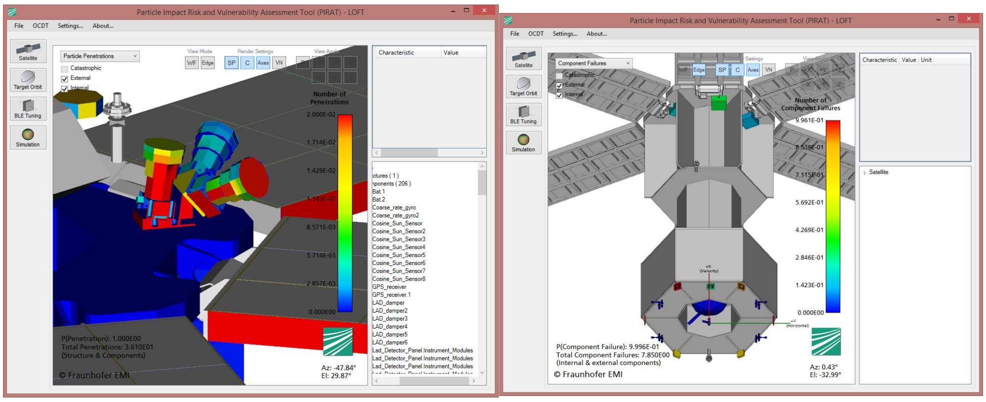


Figure 7-3: External view of star-trackers in particle penetration view mode (l.) and sun sensors and PBEEs in component failure view mode (r.).

The performance of the CDF-demonstration session included the execution of five analysis iterations. The PIRAT execution in each cases lasted between 20 and 27 minutes. The iterations tested the following functionality:

- Modification of external panel characteristics (thickness) in OCDT and its impact on penetration and corresponding internal component failures,
- The addition of new components in OCDT and CAD,
- The re-location of components in CAD and its influence on component failure rates,
- The modification (standoff) / addition of new structure panels in OCDT and CAD and their respective influences on internal and external component failure rates, and
- The modification of the mission orbit and its effect on catastrophic impact rates.

In each case, the results delivered were traceable based on the EMI's understanding of the hypervelocity impact process. This served to showcase the functionality of PIRAT and demonstrated the feasibility of application of vulnerability analyses using PIRAT in real phase 0/A CDF studies.

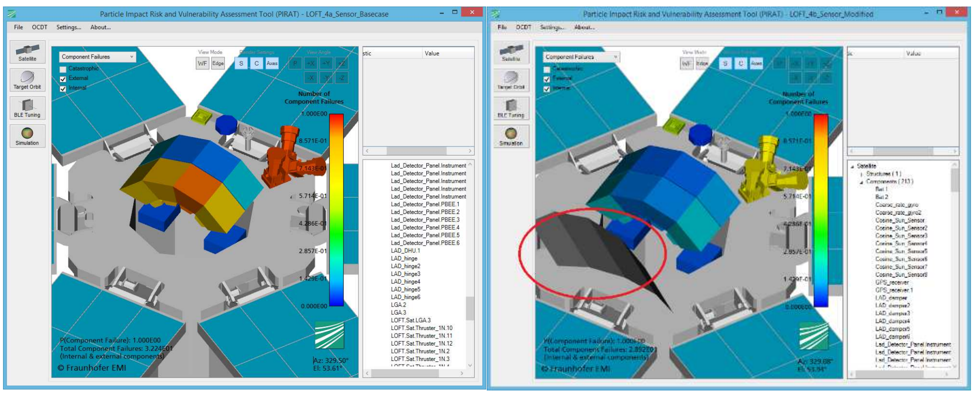


Figure 7-4: Example before (l.) and after (r.) results for external component failures based on the implementation of a sun shield (highlighted). Visible are the WFM modules and the star-trackers.

Figure 7-5: CDF-demonstration of PIRAT at ESTEC on Nov. 5, 2014.

Recommendations

At the conclusion of the SiMo study, several aspects were observed where significant improvements to the vulnerability analysis process could be applied. These improvements would be best implemented via future studies. The general areas for improvement include:

- Improved understanding of the fragmentation / catastrophic process,
- Improved procedure for interfacing OCDT, CAD and simplified vulnerability models (PIRAT),
- Increased functionality of PIRAT based on user feature requests,
- Improved understanding of the HVI physical process in the form of increase BLE application regime and statistical relevance, and
- The application of the vulnerability process in real test cases, in order to further evaluation and refine the results of this study.

8 Summary

As it has been established that the amount of MMOD present in common earth orbits presents a growing threat to S/C missions, it is becoming necessary to consider these threats during design phases. That alterations to satellite design can most efficiently undertaken during early design phases, it was decided to apply vulnerability assessment models during the ESA CDF 0/A design phases. These phases constitute the feasibility studies for satellites. Here basic physical models are first available and material characteristics, mostly based on previous missions and literature values, are applied.

In the framework of the ESA project "Simplified models for spacecraft vulnerability assessments in early design phase" (SiMo), the existing Particle Impact Risk and vulnerability Assessment Tool (PIRAT) was integrated into the CDF for use during early phase CDF-sessions. While initially planned for integration based on interfaces to existing models, including STEP and IDM, the development of the new Open Concurrent Design Tool (OCDT) prompted the development of an OCDT interface and PIRAT has become one of the first OCDT domain specific tools (DST) applied in the CDF.

While certain functionalities of OCDT (Nested Elements) and standards for associating OCDT and STEP models still need to be developed, an initial association and organization scheme for vulnerability assessments was developed, that the tool was successfully installed and demonstrated during a day-long CDF-demonstration session.

While the assessed test case did not contain the real information for developing accurate conclusions concerning the mission, it sufficed to showcase both the functionalities of the tool and CDF interface, as well as to highlight the next necessary steps for completing the conversion in CDF to OCDT and for integrating OCDT with other models, such as STEP.

A list of recommendations, for evolutionary models, HVI testing, BLE development, further PIRAT software development and the performance of future vulnerability assessments was generated based on the results of the project and can be used to define the roadmap ahead for vulnerability assessment as a process in satellite design.

9 List of distribution

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