SPACECRAFT SHIELDING LAYOUT AND OPTIMISATION USING ESABASE2/DEBRIS

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ABSTRACT

ESABASE2/Debris is the PC version of ESA's well-known ESABASE/Debris tool for the risk assessment and damage prediction of orbiting spacecraft.
The paper briefly addresses the capabilities of the ESABASE2/Debris software, which are explained by means of its application to a selected analysis case.
In particular manned spacecraft such as the modules of the international space station ISS, but also indispensable and expensive unmanned space assets require a proper layout of their shielding against impacts of space debris and meteoroid particles in the size range from tens of microns up to centimetres. It is shown how ESABASE2/Debris facilitates the optimisation of such shields.
An outlook on further upgrades and extensions of ESABASE2/Debris is given, addressing also the implementation of further space environment related analysis capabilities, such as analysis of the effects of atmospheric and ionospheric constituents, or outgassing and vent analysis.

1. INTRODUCTION

The analysis of the risk posed by space debris and meteoroids more and more becomes an integral part of the spacecraft design engineering process.
Due to the high complexity of the risk and damage analyses on a three-dimensional spacecraft geometrical model, considering shadowing effects as well as impacts of so called secondary ejecta, and allowing the application of various environment models and particle/wall interaction models, it is obvious that only sophisticated software tools can meet the requirements of such analyses.
Since the 1980ies ESA supports the development of the ESABASE software. ESABASE2 is the successor of ESABASE, coming with a modern look and feel, and running on Windows PC platforms. The first of the ESABASE various applications (e.g. “Atomic Oxygen”, “Sunlight”, “Mass”, “Field of View”, etc.), which was implemented in ESABASE2, was the “Debris” application.

The objective of the risk analysis is the confirmation of the survivability of a spacecraft or its components in the relevant particulate environment over the whole mission duration, where the survivability is expressed by the probability of no penetration (PNP), which has to meet a pre-defined value, e.g. 0.9999 for hazardous ISS external payloads [1]. The goal of the shielding layout process is to meet the PNP requirement while minimising the mass of the shielding. Hence, the shielding design is an iterative process, which mostly requires design adaptation or optimisation by means of the selection of appropriate wall configurations.

The shielding design requires some basic input, which is to a certain extent specified in standards or guidelines, or which is given by the basic configuration and the intended mission of the respective spacecraft:

- orbit and mission duration,
- required PNP,
- space debris and meteoroid environment models to be used,
- maximum particle diameter to be considered,
- spacecraft wall and interior layout and material properties,
- spacecraft pointing and kinematics,
- damage equations suitable for the respective wall configurations.

Often the first step is the determination of the critical particle diameter, which depends on the wall configuration and the selected damage law. All particles larger than the critical particle will have to be considered in the following PNP evaluation. The actual risk analysis for a three-dimensional geometrical model of the spacecraft yields the PNP. If the required PNP cannot be reached with the basic configuration, several iterations might have to be performed to optimise the shielding layout with respect to mass and PNP.

2. CAPABILITIES OF ESABASE2/DEBRIS

ESABASE2 is designed to be used as a stand-alone desktop application on Windows PC platforms. It comes with a freely customisable graphical user interface, which is based on the well known open source Eclipse software (s. Figure 1) [10].

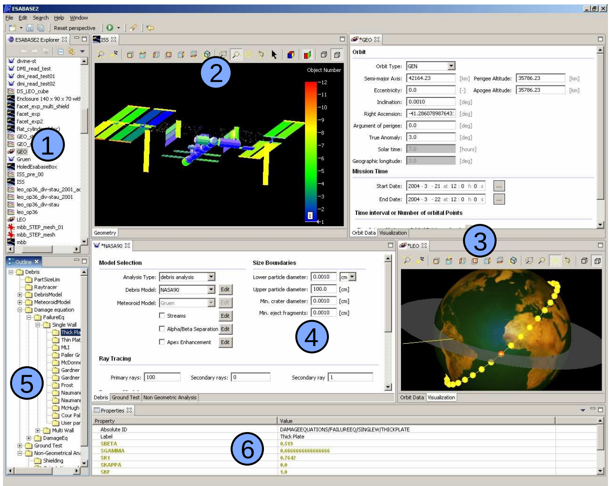

Figure 1. ESABASE2 GUI layout

The following elements of the graphical user interface (GUI) can be distinguished:

1. **Project explorer**: Provides access to all ESABASE2 projects in the user's workspace and the related input and output files.
2. **Geometry editor**: Provides geometry creation, viewing and editing capabilities.
3. **Mission editor and visualisation**: Enables the specification of the orbit and mission and its visualisation.
4. **Debris editor**: Allows the specification of all debris and meteoroid analysis related input such as selection of the environment models and their parameters, failure and damage equations, ray-tracing parameters and particle size range to be considered.
5. **Outline**: Displays the content of an editor or the underlying file, respectively.
6. **Properties editor**: Displays the content of an outline item and allows editing of its parameters (if possible).

In principle, the user of ESABASE2/Debris has to generate three input files for the meteoroid and orbital debris (M/OD) analysis:

1. The geometry file, which contains the spacecraft geometrical model and its hierarchy. For each object, the size, meshing, position and attitude, kinematics and pointing, as well as the debris protection properties have to be specified. 3D modelling is performed through so called "shape wizards". Currently, 15 pre-defined shapes are available.
2. The mission file, which specifies the orbit, the mission start and end date, as well as the number of orbital points to be evaluated. Pre-defined orbits such as GEO or Sun-synchronous orbit can be used.
3. The debris file, which defines all M/OD analysis related input such as the models to be used, their specific parameters, the particle size range to be considered, the ray-tracing parameters and the failure and damage equations to be applied.

The Debris application of ESABASE2 provides three analysis scenarios:

1. The "ground test" to verify the correctness of the failure and damage equations.
2. The non-geometrical analysis to perform a first assessment of the flux level. The analysis is performed on an oriented or a randomly tumbling plate.
3. The geometrical analysis to perform full 3D risk assessment and PNP calculation.

The analysis result viewing capabilities cover freely customisable 2D charts, the superimposition of relevant quantities on the 3D spacecraft geometry as well as tabled output. The ESABASE result listing files are of course still available in ESABASE2.

Additional features of ESABASE2 comprise an interface to commercial CAD tools via STEP import capabilities. ESABASE2 also allows the re-use of "old" ESABASE input system [*.BAS], mission [*.INPDEB], and debris [*.DMI] files.
The project oriented approach of ESABASE2 allows an easy exchange of models and results.

3. APPLICATION CASE

The following sections describe the debris and meteoroid shielding layout process by means of a simple example. They also contain further details about ESABASE2/Debris.

3.1. Requirements

The PNP assessment is part of a hazard report, which becomes part of the safety data package. In most cases, overall guidelines for the hazard evaluation exist, which include requirements for the M/OD risk assessment.
In case of the ISS, these guidelines are provided in [1] and [7].
According to [4] and [9], the PNP requirements are as follows:

PNP = 0.9885 over ten years for Columbus

PNP = 0.9999 or PNP = $(0.99999)^{AY}$, whichever is less, for hazardous external payloads, where A is the payload total hazardous impact surface area in square meters, and Y is the exposure time in years.

With an overall surface area of 6.6015 m^2 and a mission duration of 3 years, the PNP would have to be larger than 0.9998 in case of the Columbus external payload ACES (Atomic Clock Ensemble in Space). However, it is assumed that not the entire surface area of ACES has to be regarded as hazardous impact surface area, but only the ram, starboard and port facing sides of the box, which yield a surface area of 3.65 m^2. Thus, the requirement of PNP = 0.9999 is valid.

3.2. Geometric Model

The first step in an ESABASE2/Debris analysis is the establishment of an appropriate geometrical model of the spacecraft to be analysed. Of particular interest in this respect is the required level of detail, which depends on the complexity of the structure. In case of large structures such as the ISS, all shadowing parts (with respect to the debris and meteoroid flux directionality) will have to be included in the model.
Figure 2 shows a rather simple model of the European Columbus module including the most important shadowing parts of the Space Station as well as the external EuTEF (European Technology Exposure Facility) and ACES payloads.

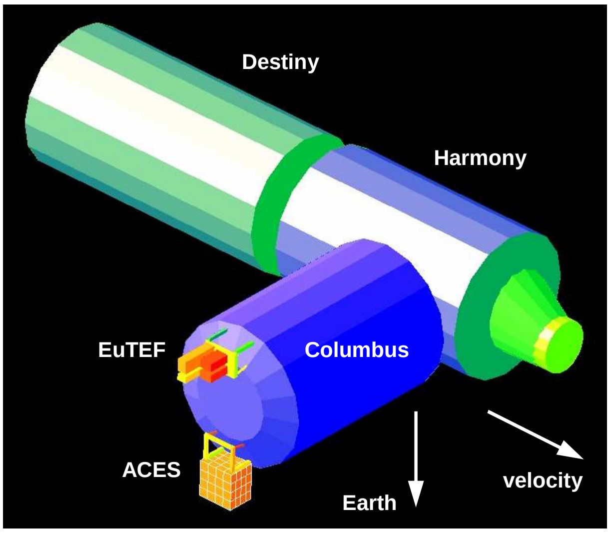

Figure 2. Geometrical model of Columbus and its external experiment platforms

Since on the ISS orbit the debris and meteoroid particles are mostly approaching from ± 90 deg measured from the velocity direction in the horizontal plane (cp. Figure 3), shadowing is sufficiently considered through the inclusion of the node 2 “Harmony” and the US laboratory module “Destiny”. All other elements of the ISS are located in directions, where the particle flux is much less. Additional part time shadowing is provided by the solar arrays and by the space shuttle attached to the station, which is not considered here.
The reference attitude of the ISS used in this paper is depicted in Figure 2.

3.3. Basic Shielding Design Concept

With the establishment of the geometrical spacecraft model, a first layout of the basic shielding can be specified. In ESABASE2, it is possible to define for each shape of the model, whether it is a single wall, a multiple wall or whether a user defined shielding and related damage equations shall be used. For all shielding types the respective wall thicknesses, spacing between the walls and the material densities have to be specified.

The example described here will consider the Columbus laboratory and the external ACES payload. Table 1 specifies the basic shielding properties used in the example.

Object and shielding property	Value
Columbus cylindrical and conical parts (starboard and port sides)	
shield thickness	0.2 cm
shield material density	2.713 g/cm^3
back-up wall thickness	0.3 cm
back-up wall density	2.713 g/cm^3
spacing	12.0 cm
ACES box	
shield thickness	0.1 cm
shield material density	2.713 g/cm^3
back-up wall thickness	0.5 cm
back-up wall density	2.713 g/cm^3
spacing	25.0 cm

Table 1. Basic shielding properties (not the real shielding of these ISS modules)

Both Columbus and ACES receive a multiple wall shielding consisting of a shield and the so called back-up wall.
It must be noted that the shielding properties used in this example do not coincide with the real shielding of Columbus and ACES (cp. [4]).

3.4. Orbit and Mission

Table 2 shows the orbit and mission parameters for the ISS and Columbus or ACES, respectively.

Parameter	Value
Mission duration	10 years for Columbus 3 years for ACES
Orbital altitude	389.18 km circular orbit
Inclination	51.6°
Start year	2008 for Columbus 2010 for ACES

Table 2. Mission parameters [9]

3.5. Space Debris and Meteoroid Models

ESABASE2/Debris analyses are based on the results of space debris and meteoroid models, which are made available through the ESABASE2 software. Currently, the models listed in Table 3 are implemented:

Debris models	
NASA 90	analytical model, very good performance; applicable to ISS design analyses, but fairly outdated
ORDEM 2000 [11]	NASA's current engineering model; to be replaced by ORDEM 2008 in the near future
MASTER 2001 [3]	2001 version of ESA's deterministic MASTER model; Standard application implemented in ESABASE2
MASTER 2005 [13]	ESA's most recent model
Meteoroid models	
Gruen	analytical omni-directional model, very good performance
Divine-Staubach [6], [14]	based on NASA's Divine meteoroid model; the MASTER 2005 implementation is integrated in ESABASE2
MEM [12]	NASA's most recent meteoroid engineering model

Table 3. Implemented environment models

According to [7], NASA 90 still is the required model for ISS-related debris analyses, although it is known that several effects are not included in the model (e.g. debris on eccentric orbits) and the environment has drastically changed since its establishment.

In the analyses described in this paper, NASA 90 was used and some cross-check analyses were performed with ORDEM 2000. The parameters given in Table 3 were used for the analyses.

Parameter	**Value**
Solar flux, $F_{10.7}$ [10^{22} W/(m^{2}Hz)]	70
Debris Model	NASA90
▪ debris mass growth rate	0.05
▪ small debris growth rate	0.02
▪ constant debris material density	2.8 g/cm^3
Meteoroid Model	Gruen
▪ constant velocity	20 km/s
▪ constant meteoroid material density	2.0 g/cm^3
Impact direction cut-off angle	65°

Table 4. Space debris and meteoroid model parameters

No specific settings can be made for ORDEM 2000.
The particle size range considered in the analyses is 100 µm to 20 cm [1].

3.6. Failure and Damage Equations

The particle/wall interaction modelling can be subdivided in the so called failure calculation, where the critical particle diameter is calculated, and the so called damage assessment, which describes the percentage of the damaged surface area considering both craters and holes resulting from space debris and meteoroid impacts.
The selection of appropriate failure laws (BLE: ballistic limit equation) for the calculation of the probability of no penetration (PNP) is the most demanding part of the risk and damage assessment analysis preparation.
Since BLEs are relying on experimental data and such data are mostly derived for specific shielding configurations, it is often not possible to use one of the predefined BLEs. Generally, ESABASE2/Debris offers the following possibilities with respect to the specification of failure (and damage) equations:

Pre-defined equations	12 single wall equations and 8 multiple wall equations available with fixed parameters (which can be changed by the user)
User parameter set	use of the parametric BLE with user defined parameters
User subroutine	use of BLEs programmed by the user and linked to ESABASE2 as DLL

Equation (1) depicts the parametric form of the single wall BLEs:

$$d_{p,\lim} = \left[\frac{t_t}{K_f \cdot K_1 \cdot \rho_p^{\beta} \cdot v^{\gamma} \cdot (\cos\alpha)^{\xi} \cdot \rho_t^{\kappa}} \right]^{\frac{1}{\lambda}} \qquad (1)$$

where the meaning of the parameters is as follows:

$d_{p,\lim}$	minimum particle diameter, which is able to penetrate the given structure (critical diameter)
t_t	target wall thickness
K_f	failure factor describing the type of damage (e.g. $K_f \geq 3$: no spallation; $K_f < 1.85$: perforation)
K_1	target material factor
ρ_p	particle material density
ρ_t	target material density
v	impact velocity
α	impact angle, measured from the surface normal
$\beta, \gamma, \xi, \kappa; \lambda$	specific BLE parameters

A similar parametric form is available for the multiple wall BLE:

$$d_{p,\lim} = \left[\frac{t_B + K_2 \cdot t_s^{\mu} \cdot \rho_s^{\upsilon_2}}{K_1 \cdot \rho_p^{\beta} \cdot v^{\gamma} \cdot (\cos\alpha)^{\xi} \cdot \rho_B^{\kappa} \cdot S^{\delta} \cdot \rho_s^{\upsilon_1}} \right]^{\frac{1}{\lambda}} \quad (2)$$

where the additional parameters have the following meaning:

t_B	back-up wall thickness
t_s	shield thickness
S	spacing between shield and back-up wall
K_2	material factor
ρ_S	shield material density
ρ_B	back-up wall material density
ν_1, ν_2, δ, μ	specific BLE parameters

In addition, ESABASE2/Debris provides the possibility to estimate the cratered area by means of a number of pre-defined damage equations. However, these are not further described here, since they are not required for the PNP assessment.

As Table 1 shows, all objects to be analysed exhibit a multiple wall shielding requiring the application of one of the respective BLEs. For the example case the NASA ISS BLE was selected with the standard parameters given in Table 5.

	v ≤ 3 km/s	v ≥ 7 km/s		v ≤ 3 km/s	v ≥ 7 km/s
K_1	0.55352	0.15736	λ	1.056	1.5
K_2	0.92253	0	ν_1	0	0.1667
β	0.5	0.5	ν_2	0	0
γ	0.667	1	δ	0	-0.5
ξ	1.667	1	μ	1	0
κ	0	0			

Table 5. BLE parameters, NASA ISS equation [5]

4. RESULTS

Three different representations of the analysis results are available in ESABASE2/Debris:

1. Superimposition of the most important result parameters on the spacecraft model (cp. Figure 4).
2. Output of the environment models (flux vs. particle diameter, vs. impact azimuth angle and vs. impact elevation angle) by means of tabled data and 2D diagrams on orbital point and mission average levels (cp. Figure 3).
3. So called listing files, which contain the complete information about the analysis run. These listing files correspond to those established by the former ESABASE/Debris tool. The level of detail in the listing file output can be controlled by the user.

An example of the 2D charts generated from the output of the environment models is displayed in Figure 3. The ORDEM 2000 impact flux vs. impact azimuth angle is given, averaged over all analysed orbital points, for a particle size range from 100 µm to 20 cm.

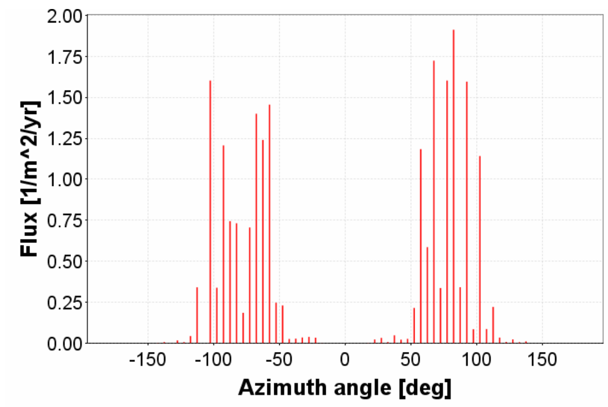

Figure 3. 2D results of the environment models (ORDEM 2000)

As outlined above, the space debris particles are approaching from two main directions: ± 50 deg to ± 100 deg counted from the velocity direction in the horizontal plane.

Figure 4 shows the results of the NASA 90 and Gruen M/OD flux analysis, which serves as the basis for the PNP determination. The colour scale on the right hand side depicts the total impact flux in 1/(m^2 yr).

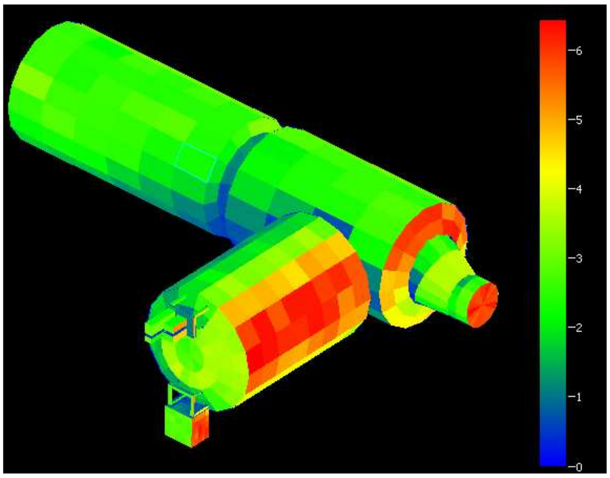

Figure 4. Impact flux displayed on the geometry; particles ≥ 100 µm considered (NASA 90)

As expected, the forward facing parts of the structure are those with the highest impact risk. Shadowing effects on the ISS modules “Harmony” and “Destiny” are clearly visible.

The results of the PNP assessment are summarised in Table 6. For the selected parts of the structure the PNP

is given, and it is stated, whether the requirement is met or not.
Please note that the real Columbus shielding of course meets the PNP requirements and that the results in Table 6 serve as an example only.

Object	PNP	Req. met?
Columbus	0.94459	no
ACES box	0.99989	no

Table 6. PNP assessment results (NASA 90 + Gruen) Note: The analysis was not performed with the real shield layout.

It can be seen that the Columbus module needs an enhancement of the shielding. Also the ACES box shielding has to be slightly enhanced.
Table 7 allows the comparison of the results obtained with the NASA 90 model with those obtained with the ORDEM 2000 model. Note that in both cases also meteoroids are considered.

Object	PNP
Columbus	0.98785
ACES box	0.99997

Table 7. PNP assessment results (ORDEM2000+Gruen)

The PNP results in Table 7 show that NASA 90 provides a relatively conservative PNP evaluation. The ORDEM 2000 analysis would require no changes in the basic shielding configuration of ACES, since the PNP requirement would be met. A marginal improvement of the Columbus shield would be required only.

5. OPTIMISATION OF THE SHIELDING DESIGN

In case the required PNP is not reached for all or some of the spacecraft components, a shielding enhancement is required. Due to the fact that the cost for additional shielding is highly depending on the shield mass, the optimisation of the protection measures has to take into account this factor. Currently, no automated shield optimisation can be performed with ESABASE2/Debris. Consequently, the engineering experience of the user is required to perform the shielding optimisation.
In many cases, in particular in later phases of a project, the shield design will be constrained by fixed design decisions. This would obviously limit the shield design options leading to potentially non-optimal shielding.

In the application example shielding enhancements are required. (In reality, the Columbus shielding is subdivided into a ram facing and a wake facing part with different shield thicknesses [4].)
In order to meet the required PNP, shielding enhancements are applied as follows:

- back-up wall thickness of Columbus increased to 0.48 cm and shield thickness increased to 0.25 cm,
- increase of the shield thickness of the ACES box to 0.25 cm.

With these changes the PNP calculation was rerun. The results are given in Table 8:

Object	PNP	Req. met?
Columbus	0.98852	yes
ACES box	0.99995	yes

Table 8. PNP assessment results with enhanced shields Note: The analysis was not performed with the real shield layout.

It can be seen that the PNP requirements are met with the improved wall configurations.

6. CURRENT AND FUTURE DEVELOPMENTS

The main objectives of the ongoing upgrade and improvement of ESABASE2 are

- to enable the accomplishment of various engineering tasks in the spacecraft design process within one software tool.
- to keep the tool up-to-date. This requires the timely implementation of new environment models, the update of its software components, continuous maintenance activities, acquisition of user feedback and implementation of user requirements.

An overview of the development status is given in the following.
The upgrade of the ESABASE2/Debris application is close to finalisation. Main objective was the implementation of new environment models such as MASTER 2005, the Divine-Staubach meteoroid model implementation of MASTER 2005 and NASA’s new meteoroid engineering model MEM. In addition, some geometry enhancements (BAS-file import; additional shapes) and further improvements were implemented.
Currently ongoing is the implementation of additional ESABASE applications. It is planned to make the former “Atomic Oxygen” application available, which will be split into an “Atmosphere” and an “Ionosphere” application. The “Sunlight” application will also be implemented in the framework of this activity. Additionally, ESA’s contamination, outgassing and vent analysis tool COMOVA will be integrated into ESABASE2.
Another important topic is the exchange of geometrical spacecraft models between software tools used in the different design domains, e.g. risk analyses, radiation analyses and thermal analyses. Currently, different model descriptions are used in the different domains. It is widely accepted that the tools cannot be harmonised,

but interfaces between the tools could be developed. A first attempt in this direction was undertaken in the thermal analysis field with the development of the STEP-TAS exchange format. A similar solution, called STEP-SPE, which is based on STEP-TAS, is available in the environmental engineering field. These protocols could facilitate the exchange of model data between different tools in the thermal and environment analysis domains.

Future upgrades of ESABASE2 could include the implementation of a generic optimisation module allowing for a highly automated optimisation of the shielding design within ESABASE2. The optimiser could also be used for other optimisation tasks within the tool, e.g. the optimisation of the placement of the inner components of a spacecraft in order to obtain optimum M/OD shielding properties for critical components.

7. ACKNOWLEDGEMENTS

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