Micrometeoroid Impact Risk Assessment for Interplanetary Missions

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ABSTRACT

For Earth-orbiting manned and unmanned space systems the analysis of the risk due to hyper-velocity impacts by space debris and/or micrometeoroids is an integral part of the spacecraft design. As more challenging missions beyond low-Earth orbit and into the interplanetary space are devised, planned, and designed, meteoroid impact risk assessment become a necessity for ensuring subsystem, mission or crew safety using the least amount of micrometeoroid/orbital debris (MMOD) shielding possible to save mass. This paper will provide an overview of the ongoing software development activities towards extending ESABASE2/Debris, ESA's standard tool for analysing the effects of space debris and meteoroid impacts on spacecraft, for interplanetary missions.

1 INTRODUCTION

Meteoroids are solid particles of interplanetary or interstellar origin. Hypervelocity impacts of micrometeoroids (with typical velocities of tens of km/s) pose a significant environmental hazard to spacecraft and/or astronauts conducting EVAs. The damage caused by impacts of meteoroids depends on the size, density, porosity, speed, and direction of the impacting particles on the outer surface element of a spacecraft. Repeated impacts of micron-sized to sub-mm particles or lead to the gradual degradation of spacecraft surfaces and materials by erosion/cratering, affecting for example mirrors, lenses and sensors. Larger particles can perforate insulation layers and optical baffles. A micrometeoroid with sufficient kinetic energy can puncture pressurized vessels (manned habitats, propulsion tanks), batteries, coolant lines or spacesuits, as well as sever cables, tethers and springs. Millimetre-sized grains are able to cause structural damage by penetration or spallation, leading to the potential failure of components or subsystems up to the complete destruction of the spacecraft or loss of crew in the worst case.

Statistical environmental models have been developed that describe the expected flux (i.e. the number of particles per unit area and unit time), speed, and sometimes also directionality of meteoroids. The so-called meteoroid models have to make strong assumptions on the particle properties, often fixing the bulk density. The expected damage on a spacecraft surface as a result of meteoroid impacts can be assessed through empirically derived design equations providing crater depths, crater diameters, or penetration probabilities as function of the particle properties (e.g. impact velocity, impact angle) and specifics of the target (e.g. thickness of outer shielding wall).

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, sophisticated software tools are needed to perform these kind of analyse. ESABASE2/Debris is the standard software for MMOD impact risks assessments and is used by ESA, various European satellites manufacturers, as well as in academia.

In light of upcoming interplanetary missions, and extension of the ESABASE2's Debris analysis capabilities is required to be able to assess the risk of meteoroid impacts during the entire mission. The capabilities of the ESABASE2/Debris software tool need to be enhanced to implement existing interplanetary meteoroid models, like IMEM, IMEM2, and MEMR2. Furthermore the software shall be able to ingest and process trajectory files in various common formats, e.g. SPICE or CCSDS/OEM, and allow user-defined spacecraft attitudes.

In Chapter 2 of this paper we provide a brief overview of the existing ESABASE2/Debris tool, explain the GUI layout and the general workflow for going from spacecraft model to impact fluxes and risk figures. Chapter 3 introduces the meteoroid models IMEM, IMEM2, and MEMR2 that are being implemented. Chapter 4 summarises the main software development activities, with emphasis on new features and functionalities. Also in this chapter, the approach for software validation and testing will be outlined and test cases listed. The paper concludes with an outlook on possible future extensions and enhancements of the ESABASE2/Debris interplanetary tool.

2 ESABASE2/DEBRIS

ESABASE2/Debris, developed by etamax space, is ESA's standard software application to analyse the effects of space debris and meteoroid impacts on spacecraft in the near-Earth environment, i.e. on Earth and lunar orbits, on transfer orbits to the Moon, and around the Sun-Earth Lagrangian points L1 and L2. ESABASE2/Debris allows reading in or building 3D spacecraft models, setting damage and failure equations/laws, and incorporates the latest models of the Near-Earth space debris and meteoroid environments. The software computes impact fluxes, distributions for mass, size and velocities of the impactors as functions of time and spacecraft surface area, as well as risk assessments (e.g. probability-of-no-penetration values) over the complete mission. A detailed description of the capabilities of ESABASE2/Debris can be found in [1].

ESABASE2 is stand-alone desktop application for Windows and Linux. It comes with a freely customisable graphical user interface (GUI) and is based on the well-known open-source Eclipse software. The GUI consists of the following main window elements (see Fig. 1):

- **Project Explorer (1)**:
  Provides access to all ESABASE2 projects in the user's workspace and the related input and output files.
- **Geometry Editor (2):**
  Provides geometry creation, viewing and editing capabilities.
- **Mission Editor and visualisation (3)**:
  Enables the specification of the orbit and mission and its visualisation.
- **Debris Editor (4)**:
  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.
- **Outline (5)**:
  Displays the content of an editor or the underlying file, respectively.
- **Properties Editor (6)**:
  Displays the content of an outline item and allows editing of its parameters

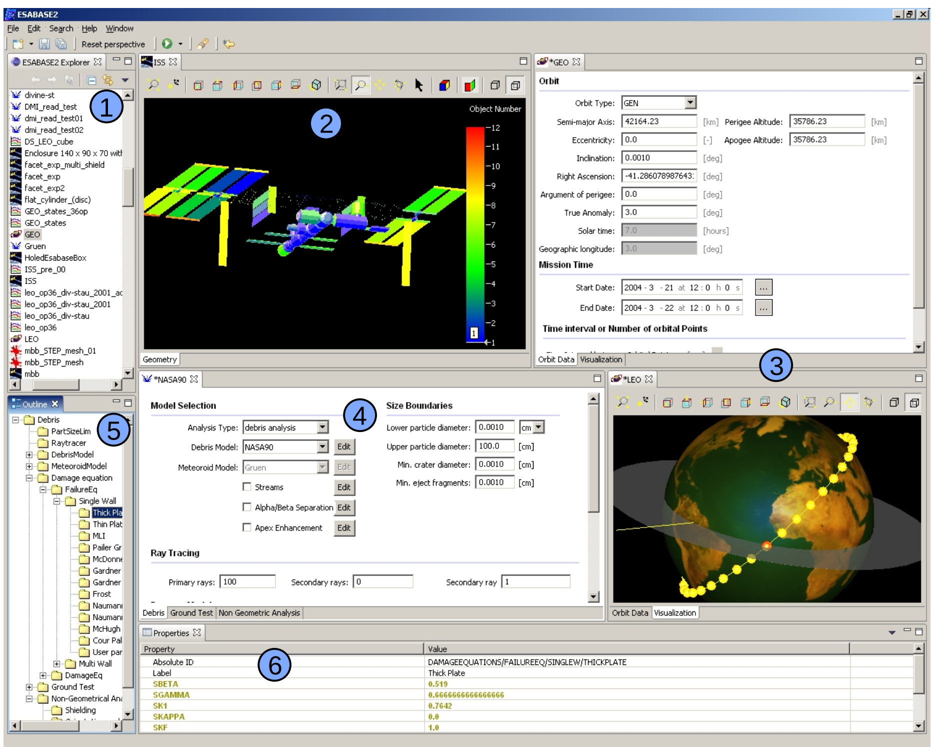

Fig. 1. Layout of the ESABASE2/Debris graphical user interface showing the main window elements for project setup, orbit and model input, visualization, and user information.

3 INTERPLANETARY METEOROID MODELS

The meteoroid environment encountered by a spacecraft are specified by different statistical models. They describe the spatial distribution of meteoroids (interplanetary dust particles) and provide information of their number (flux), impact speed, and directionality.

Meteoroids originate from three distinct sources: cometary activity (ejection through outgassing, fragmentation of the nucleus); mutual collision of asteroid or rotational break-up; and particles entering from interstellar space. The main contribution to the dust cloud in the inner solar system stems from Jupiter-family comets (JFCs) with orbital period below 20 years and low to moderate inclinations against the ecliptic (i<30 deg). Meteoroids model have been built from various types of observations and measurements, e.g. lunar microcrater number distributions [2], meteor observations by ground-based radars (e.g. AMOR, CMOR), zodiacal light/infrared sky brightness measurements (e.g. by Helios, COBE), as well as in-situ dust particle detectors (e.g. on Pioneers, Cassini, New Horizons).

Reference [7] contains a good summary of the history of meteoroid models for the interplanetary space. Here we focus on those interplanetary meteoroid models that are being implemented into the ESABASE2/Debris tool as part of an ongoing ESA project, see also Table 1.

3.1 IMEM

ESA developed the Interplanetary Meteoroid Environment Model (IMEM), which models the orbits of particles from Jupiter-family comets and asteroids, and was fitted largely to in situ data and infrared brightness measurements [6]. An interstellar population is parametrized as mono-directional stream. Cometary and asteroidal populations are split into heavier (“collision dominated”) and lighter (“Poynting-Robertson dominated”) groups. This results in a discontinuity in the mass flux at around 10^{-5} g. Modelled meteor observations were not used because they were found to be inconsistent with modelled infrared data.

3.2 IMEM2

IMEM2 contains a dynamical engineering model of the dust component of the space environment using state-of-the-art knowledge of dust cloud constituents and their development under dynamical and physical effects [7]. The aim was to improve on the IMEM model and to remove its step-wise mass flux by fully integrating the dynamics of particles of radii 1 µm–1 cm. The model is built from knowledge of the orbital distributions of the dust parent bodies (cometary and asteroidal populations). The model is designed to match dust observations as closely as possible, including infrared data from the Cosmic Background Explorer (COBE), lunar microcrater counts, meteor orbit radar velocity, and orbital element distributions, as well as the flux of dust particles at the Earth.

Table 1. Comparison of different interplanetary meteoroids models. Models shown in boldface are being implemented into ESABASE2/Debris. The inclusion of the Divine-Staubach model is considered as an option.

Meteoroid model	**Model range (au)**	**Particle radius (µm) or mass range (g)**	**Particle density (g/cm³)**	**References**
Grün model	at 1 au	10^{-18}... 100 g	2.5	Grün et al. (1985) [2]
Divine-Staubach model	r = 0.1…20	10^{-18}... 1 g	5 populations	Divine (1993) [3] Staubach (1997) [4]
IMEM	r = 0.05…6	10^{-18}... 1 g	5 populations	Dikarev et al. (2005) [6]
IMEM2	x, y, z = –6…6	1, 5, 12.5, 25, 50, 125, 250, 500, 1250, 2500, 5000, 10000 µm	3 populations, 2 g/cm³ assumed for JFCs	Soja et al. (2019) [7]
MEMR2	r = 0.2…2	10^{-6}…10 g	1.0	Moorhead et al. (2015) [8]
MEM 3	r = 0.2…2	10^{-6}…10 g	Two populations centred on ~1 and ~4 g/cm³, respectively	Moorhead et al. (2019) [10]

3.3 MEMR2

NASA continues the development of the Meteoroid Engineering Model (MEM [5] and updated version MEMR2 [8]), which uses dynamical models of cometary and asteroid particle orbits fitted to meteor orbit radar and in-situ data.

3.4 Comparison of meteoroid models

Reference [9] described the meteoroid complex as “one of the least-understood space environments”. Our limited understanding is evident when comparing different meteoroid environment models with one another. For particle masses above 10^{-6} g the fluxes computed from several models differ by at least an order of magnitude (Fig. 2, left); away from 1 au the difference can be even more. Velocity distributions show significant differences among meteoroid model (Fig. 2, right).

This should worry every spacecraft design engineer or analyst, since these numbers are needed to perform a reliable impact risk assessment in order to establish and, if needed, remedy a significant impact risk to the spacecraft. It is noteworthy that none of the meteoroid models captures the temporal variability of the meteoroid flux and assume rotational symmetry about the ecliptic pole [9].

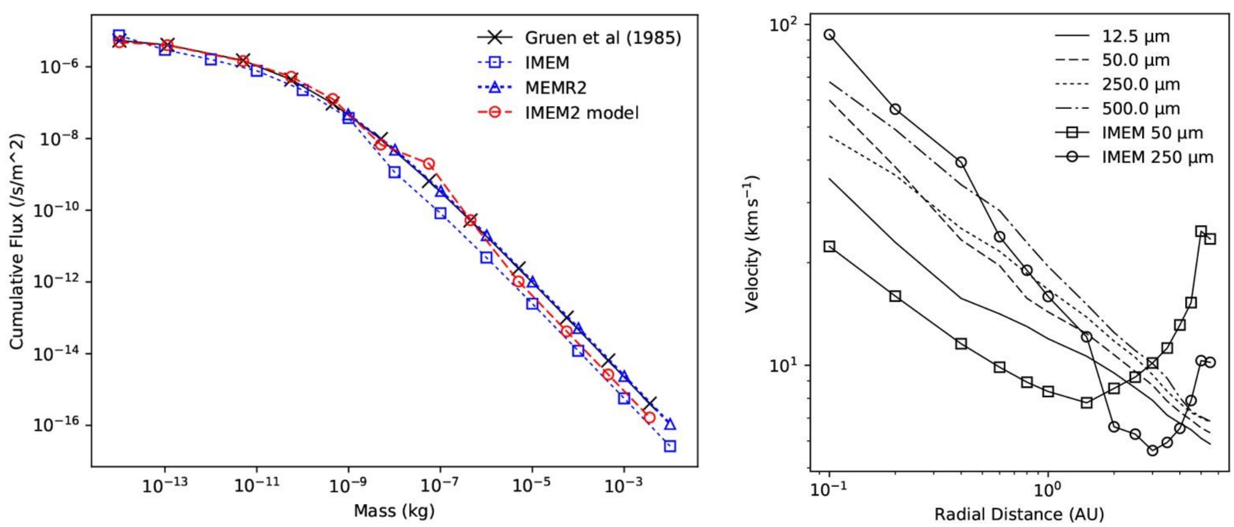

Fig. 2. Left: Comparison of cumulative flux on a flat plate for different meteoroid models [7]. Right: Differences in particle velocity as function of heliocentric distance for IMEM2 and IMEM, comparing various particle radii [7].

4 SOFTWARE DEVELOPMENT

The work presented in this paper is the result of an ongoing ESA-funded project to extend the ESABASE2/Debris software to enable interplanetary mission and to introduce several new features and functionalities to improve the tool’s handling and for the user. Below we list new the main software development activities:

- **Trajectory interface:** Read spacecraft trajectory files in the SPICE SPK kernel format (binary) or as a CCSDS OEM file (human-readable ASCII).
- **Loading SPICE meta-kernel:** Load SPICE meta-kernels (.tm) to included additional celestial bodies (DE ephemerides for the planets of the inner solar system are included by default) or update leap-second kernel.
- **Stepping algorithm:** Automatically propose a suitable number of orbital points for the impact analysis depending on changes in the spatial dust density
- **Visualisation:** Show spacecraft trajectory before computation, including orbital arcs of planets during mission time, see Fig. 3.

- **Quick-view of dust density:** Provide a visual feedback of the dust spatial density along the spacecraft trajectory, using precomputed look-up tables (density grids)
- **Post-processing:** Show “risk” (i.e. number of failures) as a function of time and location; display 3-d plots of fluxes as function of azimuth and elevation; display 3-d plots of fluxes as function of impactor mass and relative velocity
- **Highlighting of weak spots:** For each spacecraft element, provide a better statistical description of impact parameter distributions (impact angle, velocity) via five-figure summaries using the FAME algorithm [10].
- **Validation and tests:** The correct implementation of the meteoroid models will be validate by comparing the model results produced by ESABASE2/Debris for each particular model against its stand-alone version. Multiple test cases have been defined for various ESA mission interplanetary (BepiColombo, Solar Orbiter, ExoMars, and JUICE). Additional tests are meant to check possible model range violations at the inner and outer boundaries, or out of the ecliptic (Parker Space Probe, New Horizons, and Ulysses, respectively).

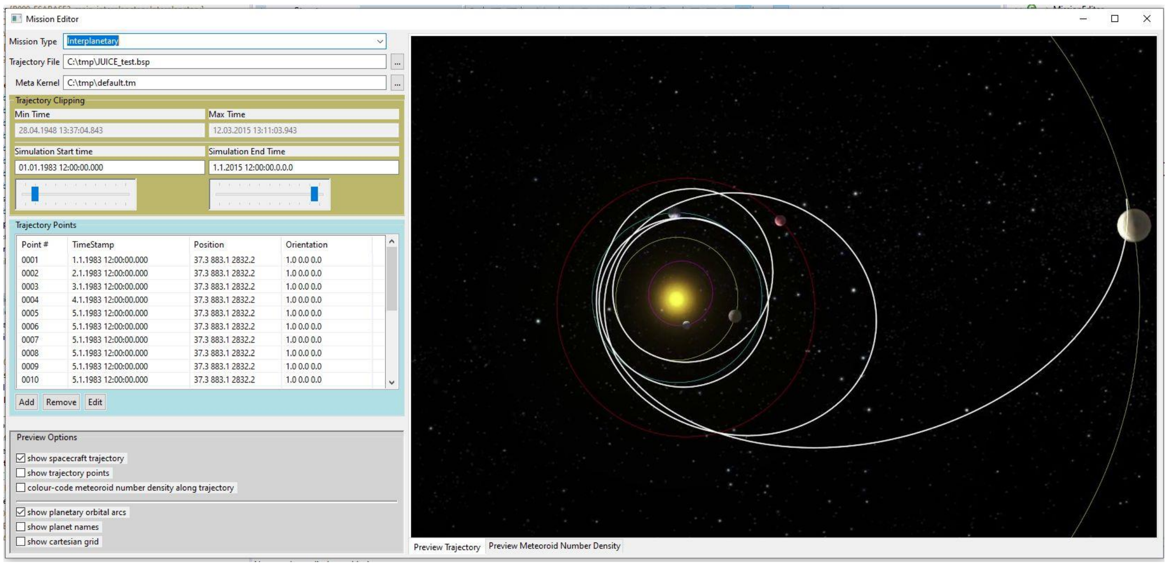

Fig. 3. Preliminary design of the Mission Editor GUI.

5 OUTLOOK FOR FUTURE DEVELOPMENTS

etamax space is currently extending and enhancing ESABASE2/Debris, ESA’s standard software tool for MMOD impact risks assessments, to enable the analysis of interplanetary missions. Several interplanetary meteoroid models are being integrated (IMEM, IMEM2, MEMR2, and optionally Divine-Staubach), which will greatly facilitate cross-validation of models by direct comparison of the corresponding outputs. In addition, the capabilities of the software during pre-analysis as well as the post-processing of analysis results are significantly improved. The software development described in this paper will be completed in the second quarter of 2020.

MMOD environments models are evolving and being updated, albeit slowly. The development of improved meteoroid models is the subject of ongoing research and development activities at NASA and ESA, some more science-oriented, others more engineering-driven. As these new models become available, they are good candidates for future major upgrades of ESABASE2’s Debris application. A case in point is the latest release of NASA Meteoroid Engineering Model MEM 3 [11]. Another possible future development could deal with the inherent uncertainties of meteoroid impact risk assessments, which are a combination of uncertainties related to the environment model itself and to the penetration equations applied (e.g. ballistic limit equation) [12].

ESABASE2 is distributed under an ESA Software License. Details about licensing conditions can be found at http://esabase2.net. Interested parties are invited to contact esabase2@etamax.de for further information and/or support.

6 ACKNOWLEDGEMENT

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7 REFERENCES

1. Bunte, K.D. et al. Spacecraft Shielding Layout and Optimisation Using ESABASE2/Debris, 5th European Conference on Space Debris, 2009.
2. Grün, E. et al. Collisional Balance of the Meteoritic Complex, ICARUS, Vol. 62, pp. 244-272, 1985.
3. Divine, N. Five populations of interplanetary meteoroids, J. Geophys. Res., 98, 17029, 1993.
4. Staubach, P. et al. The meteoroid environment near earth, Adv. Space Res., 19, 301, 1997.
5. McNamara, H et al. Meteoroid Engineering Model (MEM): A Meteoroid Model for the Inner Solar System, Earth Moon Planets, 95, 123, 2004.
6. Dikarev V., et al. The new ESA meteoroid model, Adv. Space Res., 35, 1282, 2005.
7. Soja, R. H. et al. IMEM2: a meteoroid environment model for the inner solar system, A&A 628, A109, 2019.
8. Moorhead, A. V. et al. NASA Meteoroid Engineering Model Release 2.0, NASA/TM-2015-218214, 2015.
9. Grün, E. et al. Comparitive Analysis of the ESA and NASA Interplanetary Meteoroid Environment Models, 6th European Conference on Space Debris, 2013.
10. Feldman, D. and Shavitt, Y. An Optimal Median Calculation Algorithm for Estimating Internet Link Delays from Active Measurements, Fifth IEEE/IFIP Workshop on End-to-End Monitoring Techniques and Services, 2007.
11. Moorhead, A. V. et al. Meteoroid Environment Model (MEM) 3, 2019.
12. Evans, S. W. Natural Environment near the Sun/Earth-Moon L2 Libration Point. Prepared for the Next Generation Space Telescope Program.