IMPACT RISK ASSESSMENT FOR LUNAR MISSIONS

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ABSTRACT

ESABASE2/Debris is ESA's tool to analyse the effects of the space debris and meteoroid environment on spacecraft in Earth orbit. It allows establishing 3D models and incorporates – amongst others – the latest models of the space debris and meteoroid environment.

In view of some upcoming missions to the Moon, an extension of the analysis capabilities of ESABASE2's Debris application was performed to be able to assess the risk posed by meteoroid impacts during the entire mission.

The main developments comprised the extension of the orbit propagation capabilities to lunar orbits including the consideration of several perturbations and the implementation of NASA's LunarMEM meteoroid model as well as the extension of the existing Grün meteoroid model to lunar orbits.

The validation of the software was performed by means of a comparison of the impact flux and damage assessment results with NASA's Bumper software.

1 INTRODUCTION

The 'Debris' application of ESA's space debris and meteoroid risk assessment software ESABASE2 enables the impact flux and damage analysis on a 3-dimensional spacecraft model. It incorporates different space debris environment models such as ESA's MASTER model (versions 2001, 2005 and 2009), NASA's NASA90 and ORDEM2000 models, as well as the Grün, the Divine-Staubach and the MEM meteoroid models. Impact fluxes are calculated on all surface elements of the geometrical model by means of a ray-tracing algorithm under consideration of shadowing by other spacecraft components [1] [2] [3] [4].

The software comes with an easy-to-use graphical user interface, which provides input editors for the specification of the mission to be analysed, for the definition of the debris and meteoroid models and analysis parameters. The geometrical model can either be established within ESABASE2, where the user can select basic object shapes from a comprehensive shape palette, or by an external CAD tool. In the latter case the model can be imported into ESABASE2 using the STEP interface.

The results of an ESABASE2/Debris analysis (impact flux, number of impacts, failure flux, number of failures, etc.) are provided superimposed on the 3D geometrical model, 2D diagrams and in tabled listings. In addition, the environment model characteristics are provided by means of 2D charts. All figures and charts can be exported.

The latest release of ESABASE2/Debris is applicable to Earth orbits only. Consequently, the tool could not be applied to lunar orbits or interplanetary trajectories.

The objective of the activity described in this paper is the extension of the analysis capabilities to any mission to the Moon. Two main tasks needed to be accomplished:

- Implementation of lunar orbit propagation capabilities including relevant perturbations.
- Implementation of lunar meteoroid environment models.

Following the software design and implementation phases, a comprehensive verification and validation of the new capabilities was performed.

2 ORBIT PROPAGATION

The orbit generator used within ESABASE2 is the numerical propagator SAPRE [3].

The equation of motion is integrated with 4th order Runge-Kutta with fixed step size. Osculating elements describe the motion of the spacecraft. SAPRE is a general purpose orbit propagator, thus it is not limited to a specific orbit type.

The perturbations due to the first few harmonics (except sectoral) of the Earth's gravity field and the perturbations due to Sun's and Moon's gravity fields can be considered. Also the air drag and the solar radiation pressure consideration are possible.

The orbit generator is extended to allow the usage of different constants for the centre of motion. In this way propagation of unperturbed lunar orbits can be performed.

The consideration of lunar spherical harmonics is based on the equations 8-25 and 8-27 of [8], with the maximum of 8 for degree and order. The used coefficients are taken from the Goddard Lunar Gravity Model-3.

The consideration of the 3rd body perturbation is extended to allow the application to lunar orbits. The selenocentric positions of the celestial bodies (Sun and Earth) to be considered and the corresponding gravity constants are required as input for the generic part of the perturbation calculation. The rotation of the position vectors to the selenocentric frame is done according to [10].

3 METEOROID MODELS

3.1 Grün

The Grün meteoroid model is an omni-directional, interplanetary flux model of the sporadic meteoroid environment. It represents the total meteoroid flux at 1 AU distance from the Sun in the ecliptic plane in absence of the Earth [1].

The Grün meteooid model is used as is, however the focusing and shielding formulae were extended.

The focusing effect calculation is expressed in Eq. 1. The calculation of the shielding effect is represented in Eqs. 2 and 3. The Earth equator radius is augmented by 100 km atmosphere height. Further information can be found in [1].

$$G_{\mathrm{e}}(h) = 1 + \frac{R_e + H_{Atmo}}{R_e + h} \qquad (1)$$

H_{Atmo} = 100 km (Earth)

H_{Atmo} = 0 km (Moon)

with the focussing factor G_e, the central body radius R_e, the object altitude above the surface h and the radius augmentation due to the Atmosphere H_{Atmo}.

The equations for the shielding factor η are given in the following:

$$\eta = \frac{1 + \cos\Theta}{2} \qquad (2)$$

$$\cos\Theta = \frac{R_e + H_{Atmo}}{R_e + h} \qquad (3)$$

The body radius R_e and the radius augmentation H_{Atmo}, are extended to be arguments to the computation routines instead of fix Earth's constants.

The Taylor HRMP velocity distribution [11] is also extended to be used on lunar orbits. It describes the meteoroid velocity distribution at 1 AU from the Sun in absence of the Earth's mass. For the consideration of the influence due to the Earth, the distribution is re-binned based on the body's radius and gravity constant, as given in [1]. The re-binning is modified in a way that allows varying the used constants of the celestial body. Thus the re-binning can be done based on the lunar constants if the distribution is applied to orbits around the Moon.

3.2 MEM and LunarMEM

NASA's Meteoroid Engineering Model (MEM) applies a physic-based approach for the modelling of the sporadic meteoroid environment. It is validated against radar observations. MEM provides the flux and velocity distribution of the meteoroids within the inner solar system (from 0.2 to 2.0 AU). The flux is computed for the mass range 10^{-6} g to 10 g and the gravitational focusing and shielding effects are considered. Further information can be found in [5].

LunarMEM is a MEM version, which is tailored to the vicinity of the Moon. It is applicable to Moon orbiting missions up to a distance of ca. 66000 km from the Moon's centre [6]. Further characteristics such as the particle density of 1 g/cm³ and the mass range are coherent to MEM.

The implementation approach of LunarMEM is oriented on the approach used for the already implemented MEM version that is tailored to the Earth. Fig. 1 depicts the flow chart of the approach of the LunarMEM model implementation into ESABASE2/Debris.

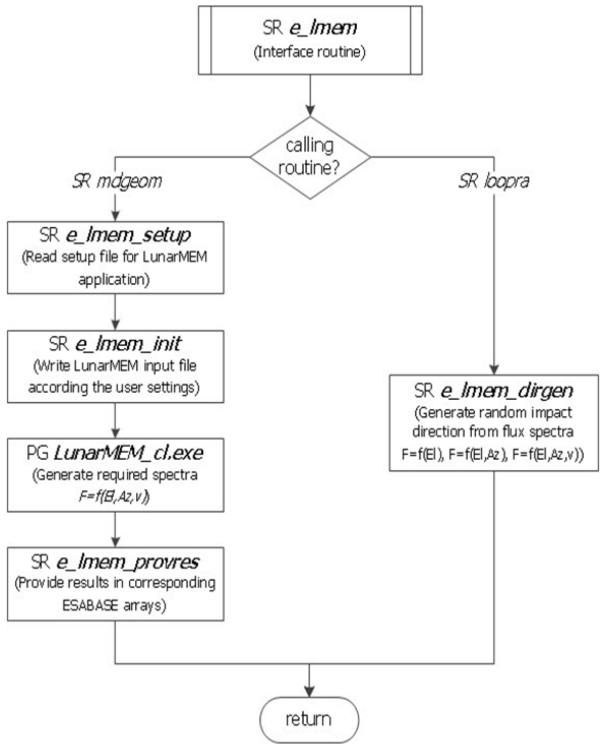

Figure 1. Flow chart of the LunarMEM implementation

The LunarMEM application is invoked through a single point interface '*e_lmem*'.

Before the geometrical analysis is performed, the left branch (‘*SR mdgeom*’) is passed. In this brunch the setup and input files for the LunarMEM application are written and the executable, provided by [6], is started to generate the flux distribution. The LunarMEM result files, which provide the 4-dimensional distributions (azimuth, elevation, velocity, flux), are parsed and stored into the appropriate ESABASE2 arrays. In this way the information is provided for the flux and damage analysis.

During the analysis phase the right branch (‘*SR loopra*’) is called. In this branch a random impact direction is generated based on the flux spectra stored in the ESABASE2 arrays in the earlier phase.

The used output resolution of the meteoroid flux direction and velocity of the LunarMEM application is 5 deg x 5 deg x 5 km/s (azimuth, elevation, velocity).

4 VALIDATION

4.1 General

The development and extension activities of the ESABASE2 software are following the test-driven development approach. Automated test cases are established for each function of the software before the actual development. The function development is considered as finalised if the test cases are running successfully. This allows effective automated regression testing of all software components. More than 1000 automated test cases exist for the complete ESABASE2 software. The regression tests are performed on a daily basis in a continuous integration process.

In addition to the automated tests, a separate manual validation test cases for all implemented functionality is performed (e.g. orbit propagation, pointing vector computation and LunarMEM execution).

In the following sections a variety of validation cases are presented.

4.2 Sun’s and Earth’s position vectors

The implementation of the 3rd body perturbation calculation is mostly generic. Thus the individual inputs, the position vectors of the considered celestial bodies, have to be validated. These position vectors calculations are also used for the pointing facility, which allows to align the axes of a spacecraft or even of certain components of it towards pre-defined or user-defined directions.

To validate the calculated position vectors in the selenocentric coordinate system special events were used. These events are listed in the following:

- A solar eclipse near the equatorial plane (14th December 2001,
- 5 full moon phases within the duration of one year, in the years 2013 and 2014, near equinoxes and solstices,
- 4 moon phases during a month (full moon, last quarter, new moon, first quarter) and the following full moon phase.

During the solar eclipse the Moon is between Sun and Earth. For this constellation the x- and y-components of the unit position vectors of Sun and Earth are expected to have nearly the same absolute value (one positive, one negative). This was the case for the test. A further expectation is that the differences of the components of the unit position vectors of Sun (s) and Earth (e) shall cross zero (exactly the same absolute values) at the same epoch. This epoch shall be roughly the greatest eclipse, which was at 18975.869406 Modified Julian Day 1950. The fulfilment of this expectation can be seen in Fig. 2.

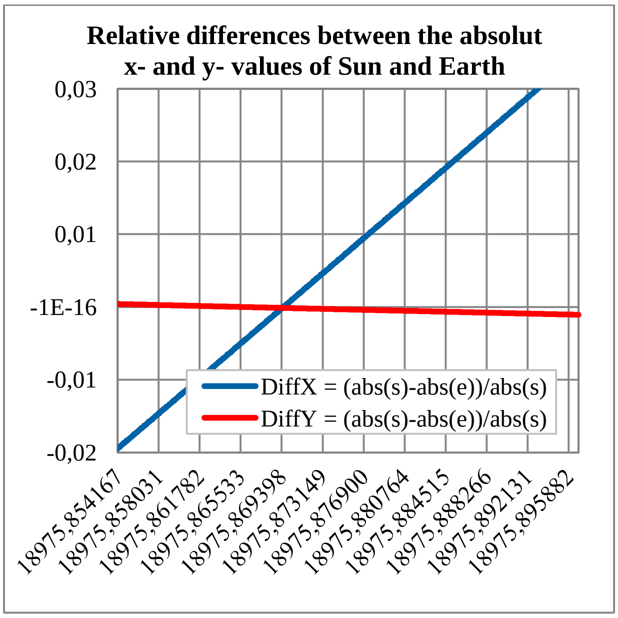

Figure 2. Solar eclipse near equator (greatest eclipse at Modified Julian Day 1950 of 18975.869406

During a full moon phase the Earth is between Sun and Moon. For such constellations the x- and y- components of the unit position vectors of Sun and Earth are expected to be almost the same in the selenocentric frame. The expected correlation of the values is depicted in Fig. 3.

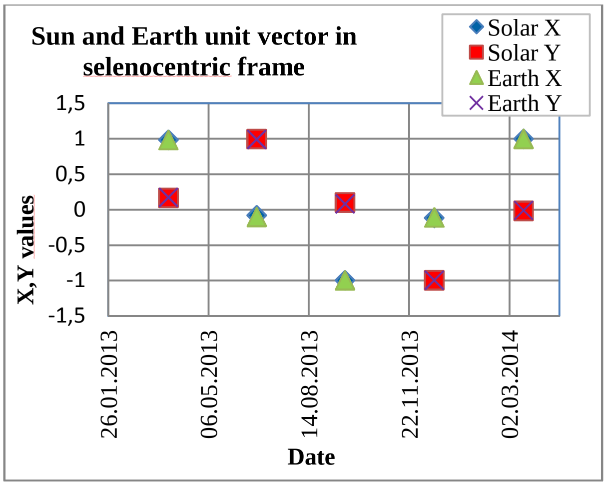

Figure 3. Sun and Earth unit vectors in selenocentric frame for the full moon phases: 2013-03-27, 2013-06-23, 2013-09-19, 2013-12-17, 2014-03-16

Also the Moon phases during one month showed the expected behaviour. Due to the fact that the Earth is orbiting the Sun, deviations compared to expected values for a stationary Earth have to be expected. These deviations could be nearly eliminated considering the angle between the Sun positions for the different epochs (simplified approach).

4.3 LunarMEM

To validate the implementation of LunarMEM, a cube with an edge length of 1 m on two lunar orbits was analysed. The flux distributions provided by the LunarMEM stand-alone application and the ESABSE2/Debris software using the implemented model for these two constellations were compared. The tests were also performed with different number of rays (100, 500, 1000, 5000, 10000) for the ESABASE2 analysis.

The analysed lunar orbits are:

- Circular, polar, altitude = 100 km;
- Circular, incl. = 30 deg, altitude = 300 km.

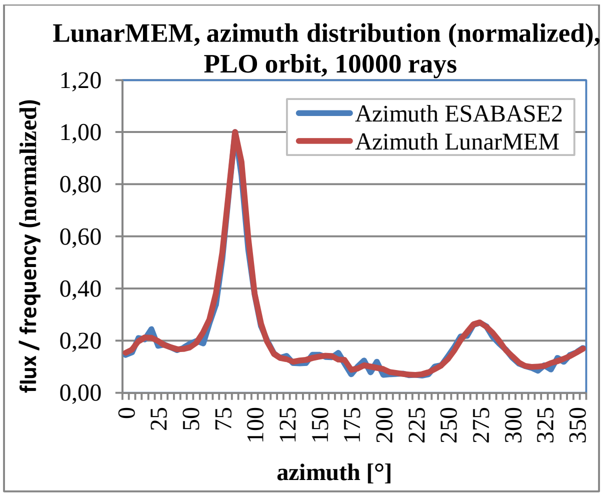

Figure 4. Normalised azimuth distribution of the LunarMEM stand-alone and ESABASE2 applications

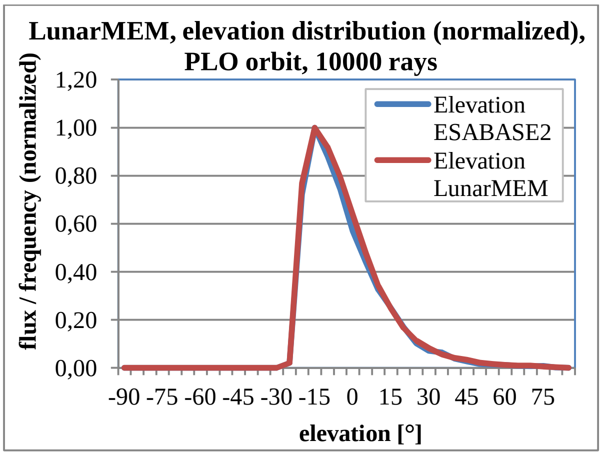

Figure 5. Normalised elevation distribution of the LunarMEM stand-alone and ESABASE2 applications

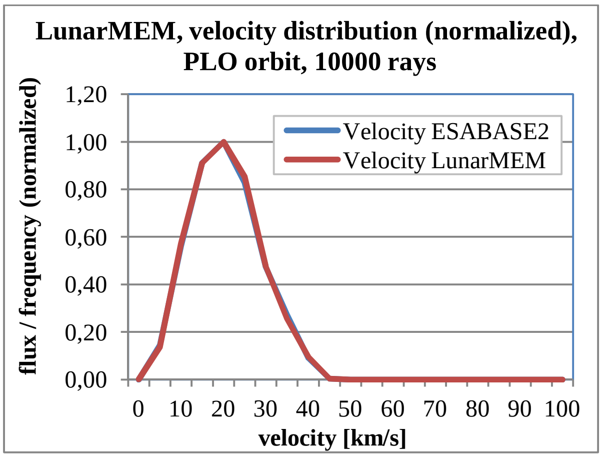

Figure 6. Normalised elevation distribution of the LunarMEM stand-alone and ESABASE2 applications

Fig. 4 illustrates the very good compliance of the azimuth distributions provided by LunarMEM stand-alone and ESABASE2 analysis with 10000 rays for the lunar polar orbit. As expected the curve of the distribution achieved from the ESABASE2 analysis with 10000 rays shows the smoothest progress due to the minimised statistical effects. In Fig. 5 the elevation distribution for the same analysis of the lunar polar orbit is shown. The Fig. 6 depicts the very good compliance of the velocity distributions for the analysis.

4.4 IADC test cases

4.4.1 General

The validation of the flux and the failure results achieved with the MEM models for an abstracted lunar mission is based on the tests defined in the IADC Protection Manual [9].

The ESABASE2 results are compared with the results provided by the Bumper software [7]. Bumper is a tool for the flux and damage assessment used by NASA. For the Bumper analyses, the low Earth and low lunar orbits were represented by state vectors with ten minutes intervals, which were analysed. The highly elliptical orbit was described by state vectors with 60 seconds intervals for one year. For the latter orbit 4000 randomly selected points were used for the analysis.

The implementation of both applications (ESABASE2 and Bumper) was performed completely independent. Thus it is very likely that they are using different flux and damage assessment algorithms. On the other hand both tools can be used with the same meteoroid models, MEM and LunarMEM, although the implementation of the use is different.

4.4.2 Test definition and execution

The definition of the tests for an abstracted lunar mission is based on the specification in [9] and agreed with NASA [7].

The following two geometries are tested:

- Cube, edge length of 1 m;
- Sphere, 1 m² cross-section (1.1284 m diameter)

The following three orbits are used to abstract the lunar mission:

- Earth orbit (ISS like orbit), as defined in [9]:
  - Circular
  - Altitude = 400 km
  - Inclination = 51.6 deg
  - Other angles = 0.0 deg
- Transfer orbit, according to [7]:
  - Highly elliptical orbit
  - Perigee = 400 km
  - Apogee = 400000 km
  - Inclination = 28.5 deg
  - Other angles = 0.0 deg
- Lunar Orbit, according to [7]:
  - Circular
  - Altitude = 100 km
  - Inclination = 90 deg (polar)
  - Other angles = 0.0 deg

The used meteoroid density is adjusted to 1 g/cm³ for all particles.

The used wall material is Al 6061-T6 with the following properties, as described in [9]:

- Brinell hardness = 95
- Density = 2.713 g/cm³
- Speed of sound = 5.1 km/s

The ballistic limit equations are used as parameterised formulations in the ESABASE2/Debris application. The parameterised single wall equation is given in Eq. 4. Tab. 1 lists the shield configuration dependant parameters of the equations as well as those parameters, which vary during the analysis, e.g. impact velocity or impact angle.

Table 1. Shield configuration dependant and varying parameters of the damage equations

Symbol	**Unit**	**Description**
$d_{p,lim}$	[cm]	Critical diameter for penetration
t_t	[cm]	Thickness of target
K	[-]	Characteristic factor
ρ_t, ρ_p	[g/cm³]	Density of target, particle
v	[km/s]	Impact velocity
α	[-]	Impact angle

$$d_{p,lim} = \left[\frac{t_t}{K_f \cdot K_1 \cdot \rho_p^{\beta} \cdot v^{\gamma} \cdot (\cos\alpha)^{\xi} \cdot \rho_t^{\kappa}}\right]^{\frac{1}{\lambda}} \quad (4)$$

Table 2. Single wall equation parameters

K_f	**K_1**	**λ**	**β**	**γ**	**ξ**	**κ**
1.8, 2.2	0.5665	1.056	0.5	0.6667	0.6667	-0.5

The parameters of the single wall equation as applied for the tests are listed in Tab. 2. $K_f = 1.8$ was used for the perforation case and $K_f = 2.2$ for the test case considering a minimum crater depth.

The test cases defined in the following list are performed:

- Number of impacts of particles with $d \geq 0.1$ mm
- Number of impacts of particles with $d \geq 1.0$ cm
- Number of impacts resulting in craters with a crater depth $p \geq 1.0$ mm
- Number of penetrations of a single wall structure: 'Single', 1 mm wall thickness

The MEM model considers a seasonal dependency of the meteoroid flux. To average out this seasonal dependency (as done for the Bumper runs) 12 ESABASE2 runs at different epoch of the year were performed for each test with MEM or LunarMEM. The average of these 12 individual results is compared with the Bumper results.

The Earth and lunar orbits are described by 4 orbital points. The highly elliptical orbit with 4 orbital points showed higher differences from the Bumper results than the other orbits, thus the tests were repeated with 16 points describing the orbit.

The minimum particle mass considered by MEM is 10^{-6} g. Considering a material density of 1 g/cm³, this corresponds to a minimum particle diameter of 0.12407 mm instead of the 0.1 mm as defined for the first test. To achieve the desired flux for this test case MEM and LunarMEM results have to be scaled. With the information provided by NASA [7], a correction factor of $f_{correct} = 1.74866$ could be calculated for the flux with a lower particle diameter of 0.1 mm. The equations for the calculation of the factor are expressed in Eqs. 5 and 6.

$$f_{correct} = 10^{2.994350 \cdot 10^{-3}} \cdot 10^{-2.662014 \cdot x} \cdot 10^{-1.059993 \cdot x^2} \cdot 10^{+0.397943 \cdot x^3} \cdot 10^{-0.057949 \cdot x^4} \quad (5)$$

where,

$$x = \log_{10}\left(\frac{d}{0.012407\ cm}\right) \quad (6)$$

with $d < 3$ cm.

4.4.3 Results

The results of ESABASE2/Debris analyses are compared with the Bumper results in Tab. 3.

The result differences for the cube geometry on a low Earth and on a low lunar orbit, which are described by 4 orbital points, are less than 6 %. Using 4 orbital points for the highly elliptical orbit, too, showed result differences less than 10 %, but higher than the differences for Earth and lunar orbits. Thus the tests were repeated with 16 orbital points for the highly elliptical orbit. The results are presented in Tab. 3. Obviously a much better compliance with the Bumper results could be achieved, if the orbits are described by 16 orbital points.

Similar results are obtained for the tests with the sphere geometry.

Table 3. Cube results of Bumper [7] and ESABASE2 for Low Earth (4 points), Low Lunar (4 points) and highly elliptical (16 points) orbits

	Test cases	BUMPER	ESABASE2	diff [%]
MEM ISS orbit	d > 0.1 mm	1.929E+01	1.93E+01	-0.16
	d > 1.0 cm	1.289E-06	1.26E-06	-2.09
	p > 1.0 mm	1.378E-01	1.34E-01	-2.47
	single	8.807E-01	8.53E-01	-3.18
MEM LLO	d > 0.1 mm	9.555E+00	9.71E+00	1.59
	d > 1.0 cm	6.387E-07	6.36E-07	-0.42
	p > 1.0 mm	6.892E-02	7.29E-02	5.73
	single	4.388E-01	4.60E-01	4.88
MEM HEO	d > 0.1 mm	1.408E+01	1.438E+01	2.13
	d > 1.0 cm	9.413E-07	9.423E-07	0.11
	p > 1.0 mm	1.045E-01	1.046E-01	0.10
	single	6.651E-01	6.618E-01	-0.50

Fig. 7 provides the comparison of the number of impacts on the 6 sides of a cube calculated with ESABASE2 and Bumper. The number of impacts is computed for the test with $d > 0.1$ mm.

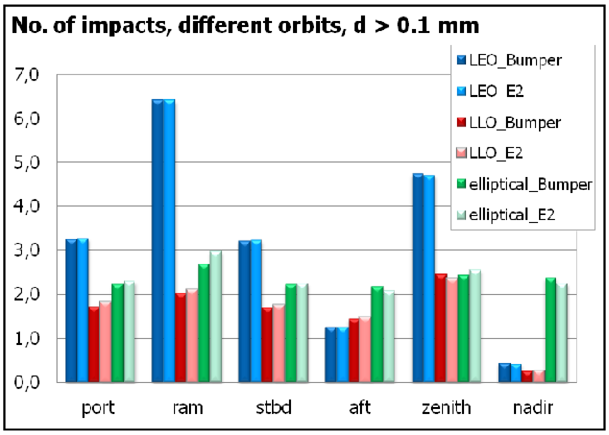

Figure 7. Comparison of ESABASE2 (E2) and Bumper results on the sides of a cube

An excellent correspondence can be seen for low Earth (LEO) and low lunar orbits (LLO) in the chart. The distribution results of the highly elliptical orbits (HEO) also show a very good correspondence. It is assumed that for this special orbit more orbital points and possibly more considered epochs of the year are required to get an even better correspondence of the results for the individual sides of the cube.

5 SUMMARY AND CONCLUSIONS

ESABASE2/Debris now offers the capability to perform a space debris and meteoroid impact risk assessment for lunar missions. Such mission can be represented either by any number of different orbits (e.g. ISS like LEO, highly elliptical and lunar orbit), or by up to 100 state vectors provided via an external trajectory file. Main development steps were

- the extension of the orbit propagator to lunar orbits accompanied with the implementation of the respective reference frames and pointing capabilities, and
- the implementation of NASA's LunarMEM meteoroid model as well as the extension of the applicability of the Grün meteoroid model.

Besides the verification of all new features by means of unit and integration test cases, a comprehensive validation was performed via a comparison of the results of ESABASE2 and NASA's Bumper software. This comparison revealed an excellent correlation of the impact/failure analysis results for all three analysed orbits, two different target shapes and also for the six faces of an Earth/Moon oriented orbiting cube.

The upcoming release 6.0 of ESABASE2/Debris will provide the full lunar mission analysis capability as well as all features already available in the previous releases.

6 ACKNOLEDGEMENTS

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