The ESA MASTER'99 Space Debris and Meteoroid Reference Model

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1. Abstract

The second release of the European Meteoroid and Space Debris Terrestrial Reference Model MASTER issued by ESA is labelled as the MASTER`99 model[1]. Compared to its predecessors, the MASTER`99 release offers a number of significant improvements with respect to the model's scope of application, its user friendliness and its documentation.

MASTER '99 describes the man-made and natural particulate environment of the Earth and its incident flux on user-defined target orbits down to an impactor diameter of 1 micron. All relevant man-made and debris source terms are considered by the MASTER'99 model. Dedicated computer models are used to simulate the generation of objects due to all known debris sources and their orbit evolutions with time.

This paper provides a brief survey of the MASTER model history before it provides a brief introduction to the model philosophy and the model background. The application modules of MASTER'99 namely its Graphical User Interface, the MASTER Standard Application (SA), and the MASTER Analyst Application (AA) are introduced. A brief survey of output features using exemplary results for results provided by the model is given before the outlook to already ongoing model enhancements is given.

2. Introduction

The purpose of MASTER is the characterisation of the natural and the man-made particulate environment of the Earth, and the fast and simple evaluation of the resulting effects on space missions. The model is based on a semi-deterministic analysis of a reference population derived from the simulation of all major space debris source terms. Meteoroids, as the natural component of the Earth particulate environment, are modelled according to state-of-the-art approaches for both, the sporadic background component and the meteoroid streams.

For each simulated source, a corresponding debris generation model in terms of mass/diameter distribution, additional velocities, and directional spreading has been developed. A comprehensive perturbation model was used to propagate all objects to the reference epoch of August 1st, 1999.

Currently, apart from spent payloads and upper stages (TLE background), fragmentation from on-orbit collisions and explosions, dust and slag from Solid Rocket Motor (SRM) firings, sodium-potassium (NaK) coolant droplets from RORSAT satellites, surface degradation particles (paint flakes), and ejecta are considered.

In order do describe the steady state natural meteoroid environment the Divine-Staubach meteoroid model /5/ was implemented into MASTER. This model considers core and asteroidal meteoroids and is available as high-resolution flux model via the MASTER Analyst Application. Time correlated, seasonal meteoroid stream events are also included based on the optional Cour-Palais or Jenniskens/McBride model /7/, /8/, /9/.

The MASTER model offers a full three dimensional description of the terrestrial debris distribution reaching from LEO (r > 6564 [km]) up to the GEO region (r < 45164 [km]). Flux results relative to an orbiting target or to an inertial volume can be resolved into source terms, impactor characteristics and orbit, as well as impact velocity and direction. Also 3D flux analysis with respect to any two of these parameters simultaneously is possible.

The current release of the MASTER model comes along with a TCL/Tk based graphical user interface (GUI), which allows for a more ergonomic and intuitive installation and handling of the tool. Results are displayed automatically and can be interpreted or re-formatted for documentation purposes directly from the program environment. The software splits into a 'Standard' application (SA) for quick assessment purposes and a more sophisticated 'Analyst' application (AA) and is delivered on a CD-ROM supporting the most common computer platforms (Windows 9x/NT, Linux, UNIX (Solaris, AIX, HP-UX) and Mac-OS).

One of the key features of the MASTER model is the detailed prediction of flux and impactor characteristics including directional distributions not only on a sphere as for the previous model releases, but also on up to 10 user

[1] The MASTER '99 model was developed between 1997 and 1999 under an ESA/ESOC.

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

defined surfaces. This makes it a valuable tool for the development of a spacecraft design uncritical to space debris influences.

3. Model History

The history of the MASTER model shows a continuos record of model improvements.

- 1995 (Beta Release)

The first release of a MASTER Beta version was issued in 1995. It was offered to a restricted circle of users for evaluation. This version (see /11/) considered objects larger than 100 micron stemming from 121 on-orbit fragmentations and the trackable population. Meteoroids were considered by the Grün meteoroid model, which was included in the so called Engineering Application. The model allowed to compute flux to a target, idealised as a unit sphere. The modelling approach already considered any type of debris orbit (incl. highly elliptical) and allowed any kind of target orbit. As today, the software supported all important computer platforms and was delivered on CD-ROM.

- 1997 (Release 1)

The first 'official' release of the MASTER model was issued by ESA/ESOC in 1997. It reflected the comments received during the evaluation period and provided an update of the reference population. The number and kind of source terms considered by the model, however, remained unchanged. Compared to the 1995 version, the main difference of this release was the replacement of the Grün sporadic meteoroid model by the Divine-Staubach model, which was now available in the Analyst Application.

- 1999 (Release 2)

The features implemented to the MASTER'99 release of the model represents the most significant evolution step of the model since its creation (see /2/, /3/, /4/) :

- Based on the same semi-deterministic modelling concept as its predecessors, the latest MASTER release incorporates a number of new source terms, namely SRM dust and slag particles, NaK droplets, paint flakes, and ejecta particles.

- Previous releases of MASTER suffered from the fact that a lower size threshold of 100 micron made it difficult to compare the model output to measurements from space returned hardware. In MASTER'99 the threshold has been lowered to 1 micron

- MASTER'99 is accompanied by a graphical user interface (GUI) for all platforms, enhancing the user friendliness and ergonomy of the model.

- For the first time, the model also considers meteoroid streams, Both, the Jenniskens-McBride (default) and the Cour-Palais stream models are included.

- The model is able to determine flux to surfaces of a user defined orientation.

- Spatial density results are provided.

- Outlook to the next release

The modelling philosophy of the MASTER model requires periodic updates of the underlying database. The next release of the model is already under development. This update will further increase the value of the model by providing some unprecedented features. Chapter 7 gives further details on the projected enhancements.

4. Model Background

The MASTER'99 debris reference population for the epoch Aug 1, 1999, consists of the following sources larger than 1micron in size:

- launches
- explosions and collisions
- slag and dust particles from SRM firings
- coolant release from nuclear reactors in space (NaK)
- surface degradation particles (paint flakes)
- ejecta generated by impacts of small man-made objects and meteoroids

Figure 1 gives the size ranges covered by the various man-made debris sources represented by MASTER '99 and its predecessor. Only a small fraction of the population resulting from the above mentioned sources can be detected by ground based sensors.

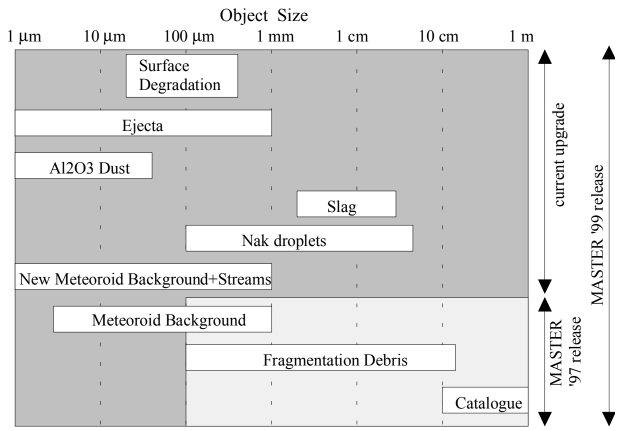

Figure 1 size range and source terms represented by MASTER '99 and its predecessor

The USSPACECOM catalogue as considered by MASTER '99 consists of 8,522 objects larger than about 10 cm in size. This accounts only for about 5% of the population larger than 1cm assumed to be in orbit. The catalogue has been implemented into the model, while the data for the by far larger amount of untrackable objects was supplied by simulations.

In addition to fragmentation debris models which were already considered by previous releases, new debris generation models were developed for the non fragmentation sources. The larger residues from solid rocket motor (SRM) burns (see /4/), i.e. the so called slag, as well as coolant droplets released from spent nuclear reactors in space now are considered in the larger size regime by new sub-models. These objects are in the size regime larger than some micron up to some centimetres in diameter. The fragmentation model for describing the historical explosion events as used in the 1997 MASTER release has been revised concerning the input data definition (classification of high or low intensity) on the basis of the IADC considerations, and by discussions with NASA/JSC (USA), DERA (UK), and CNUCE (Italy). Table 1 summarizes characteristics of all source terms represented by the MASTER '99 model.

Source	lower size threshold	upper size threshold	number of objects	comments
TLE Catalog	16 cm	> 10 m	4.698	Fragment TLEs are part of the fragment population
Fragmentation Debris	100 µm	10 m	0.6E+11	160 fragmentation events
NaK Droplets	3 mm	5 cm	286.550	RORSAT core dump in the 80's
Solid Rocket Motor Slag	100 µm	3 cm	0.25E+12	> 1000 SRM firings
Al_2O_3 Dust	1 µm	80 µm	0.11E+18	> 1000 SRM firings
Ejecta	1 µm	6 mm	0.65E+08	
Paint Flakes	20 µm	200 µm	0.38E+13	
Meteoroid Background	< 1 µm	5 mm	-	Meteoroid Model acc. to N. Divine
Meteoroid Streams	< 1 µm	5 mm	-	Jenniskens/ McBride or Cours-Palais

Table 1 source term characteristics of MASTER '99

Fragmentation events, firings of solid rocket motors and NaK release events are modelled individually. Objects representing the smaller size regimes, as e.g. the smaller exhaust products (so called dust) from SRM burns, particles generated by surface degradation (often referred to as paint flakes), as well as ejecta due to small impacting primary objects are considered. Again, all creation events are simulated individually: deterministically in case of the SRM dust (number of events see above), and statistically for paint flakes and ejecta, since no single events can be identified in the latter cases.

The extension of the MASTER'99 model to a lower size threshold of 1 micron requires to model the meteoroid environment of the Earth. The damage potential of these mostly small particles results from their high relative velocities (up to 72 km/s) and the resulting kinetic energy. In contrast to the highly dynamic space debris environment, the yearly averaged meteoroid environment can be supposed to be static. The activity during the course of the year, however, can periodically vary with annually recurring seasonal stream events.

The MASTER meteoroid background flux model is based on Divine's theory of five distinct populations with specific signatures in terms of mass spectrum, eccentricity, inclination and perihelion distance in an ecliptic reference system /5/. The Divine model was modified by Peter Staubach in 1996 /6/ under ESOC contract. The updated model is implemented in the MASTER model and takes into account also data from dust detectors flown aboard the Ulysses and Galileo spacecraft. Staubach re-organized the minor populations. Three of the five distinct populations were redefined and new distribution parameters were derived from additional data of the Ulysses and the Galileo missions. Instead of the inclined, eccentric and halo population, smaller particles are now represented by the A, B and C population.

Figure 2 depicts the cumulative size/flux relation of the Divine/Staubach model. Gravitational focussing or shielding effects are part of the model implemented in MASTER, but are not considered here. The vertical lines mark the size thresholds as applied for the generation of the meteoroid CPE database.

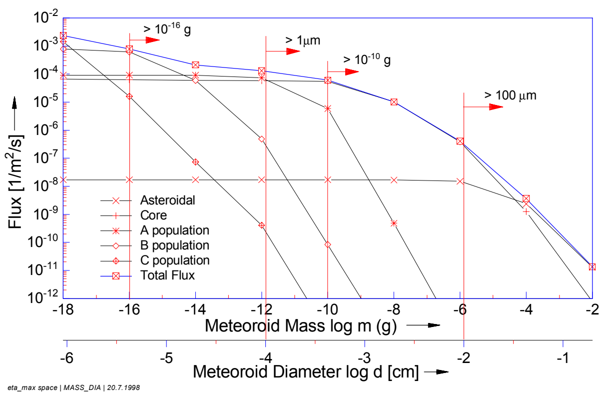

Figure 2 Size/Flux relation of the Divine/Staubach model

To derive spatial density contributions and absolute velocities, an Earth-centred spherical control volume is deployed, with segmentations in right ascension and declination defined in an ecliptic system. The reference control volume is discretized into seven concentric shells of variable height, four zonal partitions, and eight tesseral partitions. Symmetry is assumed for complementary hemispheres. For meteoroid flux computations a terrestrial target orbit is firstly translated into the rotating ecliptic, sun-oriented co-ordinate system. In this system cell passage events are determined for the target object, and flux contributions are cumulated along the orbit in a similar way as for the debris model. Earth shielding and gravitational focusing effects are taken into account as defined by Divine and Staubach.

The consideration of seasonal streams caused by the intersection of orbits of existing or disintegrated comets with the Earth's orbit is a new feature of the MASTER model. Their implementation requires the consideration of effects such as time dependency and meteoroid flux directionality, which were of secondary importance for former releases of MASTER. While the background flux is known to remain fairly constant over the year, the individual stream activity is characterised by a seasonal dependent appearance.

The Cour-Palais (see /7/) and the Jenniskens-McBride (see /8/ and /9/ models have been implemented in the MASTER model. The default meteoroid stream model inside MASTER is based on data compiled by P. Jenniskens and a count rate/flux conversion proposed by N. McBride. The data stem from naked eye and photographic observations made by amateur astronomers in the northern and southern hemisphere.

5. Application

MASTER consists of the Standard Application (SA) for a quick assessment of debris flux characteristics, and the Analyst Application (AA) with high resolution flux results and additional analytical capabilities, as for example flux on oriented surfaces, future constellation traffic simulation, or meteoroid flux determination. All applications are shipped together with an easy-to-use Graphical User Interface (GUI) and online documentation on a CD-ROM.

The model can be installed and executed on a broad variety of platforms (Sun Solaris, IBM AIX, HP-UX, Linux, Windows 9x/NT and Apple Mac-OS).

5.1. Graphical User Interface

MASTER is operated via its TCL/TK based graphical user interface (GUI). The GUI is a major extension to prior releases of the MASTER model and allows an intuitive and efficient interaction with the software. Due to its design concept it is platform independent and can be used without any licensing constraints. The main aims of the GUI are

- the manipulation of the input settings like
  - the specification of the population sources,
  - the size range to be considered,
  - the analysis time interval,
  - the target orbit parameters,
  - the 2D and 3D output settings,
- the display of the results like 2D and 3D spatial density and flux spectra. This is accomplished by an integration of the GNUPLOT plotting package into the GUI.
- the provision of the possibility to save and load complete program runs including all input and output files as ‘projects’.
- Access to model documentation

The MASTER Standard Application and the MASTER Analyst Application are operated via a common GUI. Figure 3 shows the main widget of the MASTER GUI.

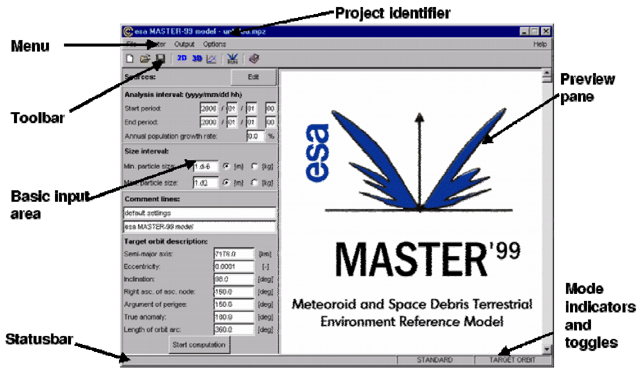

Figure 3 Main widget of the MASTER GUI

The GUI allows a number of graphics operations including thumbnail preview, scrolling, change of graphics options by editing of the GNUPLOT driver file. On Windows platforms, graphics produced by the MASTER’99 model can directly be imported to Office tools via the clipboard. On all platforms, the GUI allows the creation of hardcopies via postscript output files. Via the and some more. Figure 4 shows details on the presentation of graphical output and the options for editing.

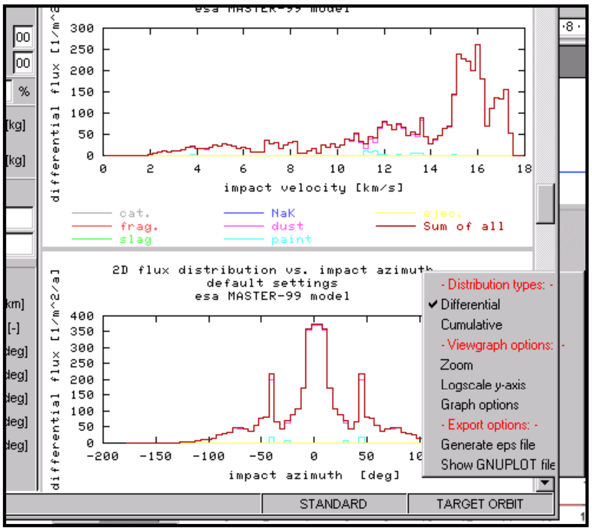

Figure 4 Graphics provided by the MASTER GUI

5.2. MASTER Standard Application (SA)

In former versions of the MASTER model the so called Engineering Application was intended to derive low resolution flux calculation results. These results were obtained by interpolating between a data-grid of Analyst Application results. The restriction to circular target orbits, the high CPU-time consumption and the low resolution of the results of the Engineering Application lead to the decision to follow a completely new approach in the development of the application. In order to make this change visible to the community of the MASTER users, the new application is named MASTER Standard Application.

The approach of the Standard Application is based on the mathematical theory used by N. Divine /5/ to calculate meteoroid fluxes to space probes in interplanetary space. This theory had been adapted to the Earth's debris environment using the MASTER '99 Reference Population instead of the meteoroid population described by Divine.

The central tasks of the MASTER Standard Application are

- Determination of flux to any target orbit determined by its semi-major axis, eccentricity, inclination and the length of orbit arc.

- Determination of spatial density

A detailed description of the modelling approach realised by the SA is given in /10/.

Both, flux and spatial density contributions can be traced back to their originating debris populations included by MASTER. Flux is resolved with respect to

- impactor size
- impactor orbit (semi major axis, eccentricity, inclination)
- true anomaly of the impact location
- impact velocity vector (abs. velocity, azimuth angle, elevation angle)
- geocentric coordinates of the impact location

and any 3D combination of these.

The strengths of the MASTER Standard application are its low CPU time requirements (<5s for circular targets in LEO), its low storage need (input data < 450 KByte, total < 1.5 MByte), its low RAM requirements (< 20 Mbyte) in connection with an acceptable resolution of the data output. One of the future extensions of this tool will concentrate on an improved consideration of cross-couplings in the orbital elements of the underlying population data.

5.3. MASTER Analyst Application (AA)

Analyst is an advanced flux analysis tool for man made debris and meteoroids. It provides detailed results and uses a large data base consisting of semi-deterministic flux contributions of individual debris and meteoroid objects. The main features of Analyst are:

- high resolution flux determination
- consideration of non-symmetric spatial distributions
- identification of individual flux contributions (CPE dump for further analysis)
- flux on spheres, randomly tumbling plates, and oriented surfaces
- consideration of meteoroid background flux and seasonal streams
- consideration of future constellations in addition to a TLE catalogue population

As for the Standard application, flux is resolved with respect to all important parameters (see list above). Analyst uses a pre-processed and compressed data base consisting of individual contributions of debris objects (projectiles), passing through a number of volume cells (also called bins). These contributions, called cell passage events (CPE), contain the following information:

- object identifier ID
- cell identifier IC
- cell passage velocity magnitude v (in an inertial frame)

- velocity azimuth angle A with respect to North in the local horizontal plane
- velocity elevation angle h with respect to the local horizontal plane
- spatial density contribution D generated by the object passage

The control volume surrounding the Earth is subdivided into a LEO, a GEO, and an intermediate MEO region as listed in Table 2.

	h_{min}	h_{max}	Δh	α_{min}	α_{max}	$\Delta\alpha$	δ_{min}	δ_{max}	$\Delta\delta$	
	km	km	km	°	°	°	°	°	°	
LEO	186	2.286	10	-180	180	10	-90	90	2	TLE, NaK
			20			20			5	Frgm., Slag
			100			10			4	Micro Src.
MEO	2.286	34.786	500	-180	180	180	-90	90	5	Macro Src.
			500			10			4	Micro Src.
GEO	34.786	36.786	20	-180	180	10	-90	90	2	Macro Src.
			100						4	Micro Src.

Table 2 Analyst application control volume segmentation

6. Results

The following figures provide a small survey of the results that can be generated by means of the MASTER model. Figure 5 shows flux vs. size resulting from different sources for an ISS like orbit (i=50,5°, h=400 km) in a log-log scale.

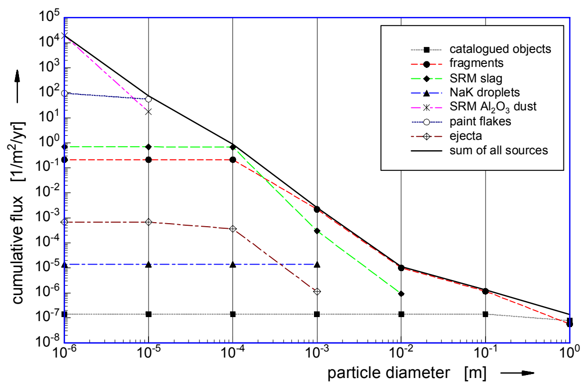

Figure 5 Flux vs. size resulting from different sources for an ISS like orbit (i=50,5°, h=400 km) (SA)

Figure 6 shows flux resulting from objects larger than 1mm vs. (circular) target orbit altitude. The results are averaged over all inclinations.

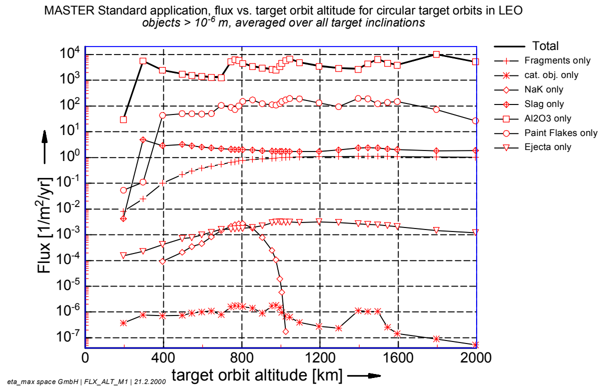

Figure 6 Flux resulting from objects larger than 1micron vs. (circular) target orbit altitude. (averaged over all inclinations) (SA)

The following figures show results of a flux calculation made by the Standard application for a geostationary target with the following orbital elements:

semi-major axis: 42164.0 km
eccentricity: 0.001
inclination: 0.01°

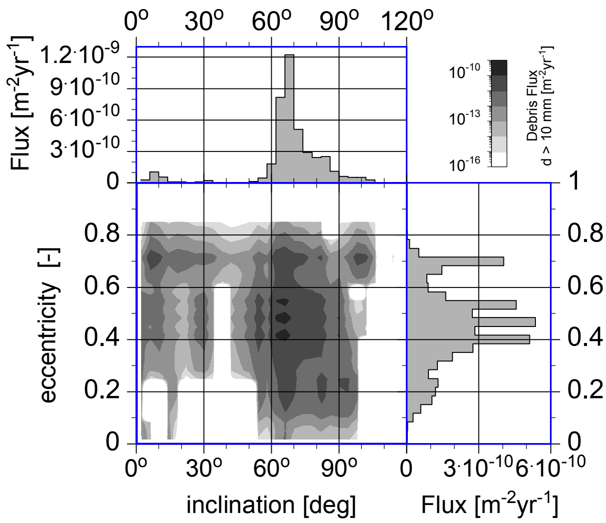

Fig. 7: Debris flux (fragments only) for d > 1cm on a GEO target as a function of particle eccentricity and particle inclination (SA)

Fig. 7 shows that the majority of the particle orbits has high inclinations of 65° to 85°, but also particles with orbital inclinations of 10° to 30° are contributing to the flux on a geostationary target. A wide range of eccentricities is covered reaching from 0.1 to 0.9. It is remarkable, that the low eccentric particle orbits may be subdivided to two inclination-classes (low inclined and high inclined orbits), while the near-GTO eccentricity band (about 0.7) contains particle orbits with all inclinations between 0° and 105°.

The discussed distributions of the particle orbits inclination and eccentricity leads to the impact velocity, impact azimuth angle, and impact elevation angle distributions as given in Fig. 8 and Fig. 9.

Fig. 8 depicts that the main flux contribution ranges from 2.8 to 4.0 km/s in the velocity distribution, and from ±(30 ... 60)° in the azimuth distribution. Additional minor contribution occurs in the ±15° azimuth range due to low inclined particle orbits. Impacts from quasi co-orbiting objects are resulting in low impact velocities, and impact azimuth and elevation angles covering the whole range from ±180° and ±90°, respectively (s. Fig. 8 and Fig. 9).

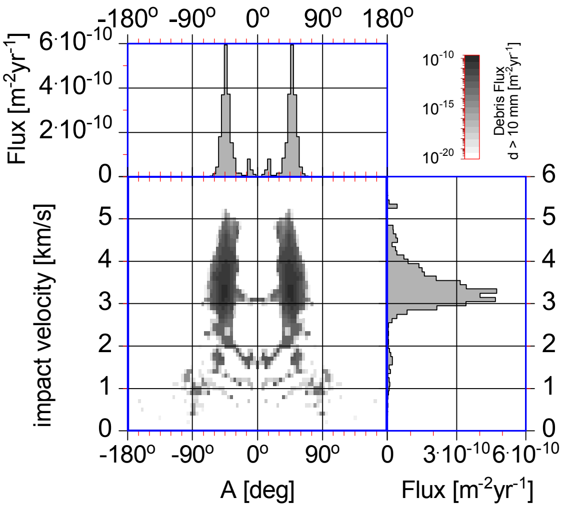

Fig. 8: Debris flux (fragments only) for d > 1cm on a GEO target as a function of impact azimuth angle A and impact velocity (SA)

From Fig. 9 can be seen, that the impact elevation angle spreading depends on the impact velocity: Due to the eccentricity and inclination distribution of the impacting particles, the elevation angle is restricted to a certain range, if the velocity exceeds a certain value. The main impact direction range with respect to the elevation is –30° ... +30°.

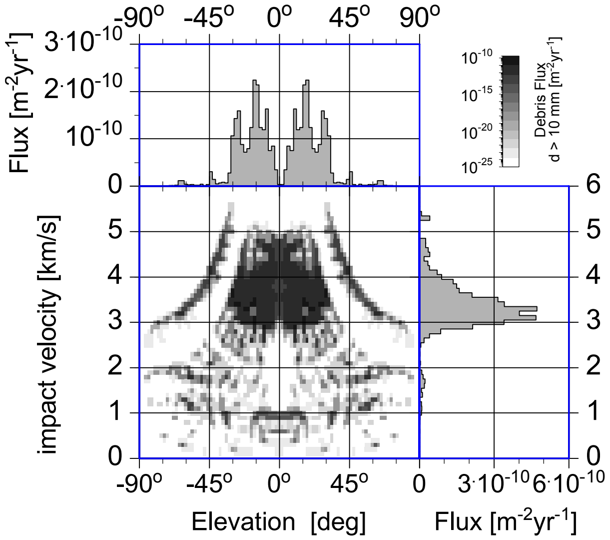

Fig. 9: Debris flux (fragments only) for d > 1cm on a GEO target as a function of impact elevation angle and impact velocity (SA)

The three dimensional output feature of both, Analyst and Standard, allows to resolve cross-couplings between impact parameters, as shown in Fig. 7 for the projectile eccentricity and inclination, or in Fig. 10 for the impact azimuth and impact velocity.

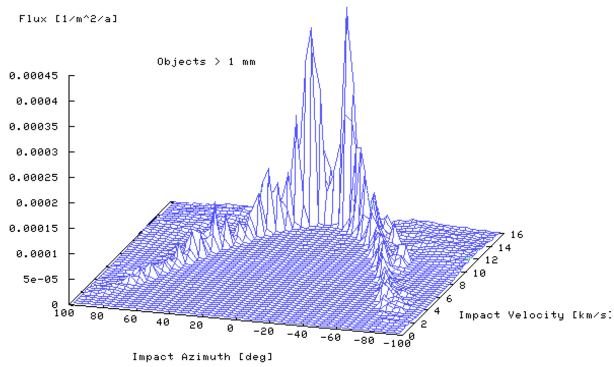

Fig. 10: Flux distribution vs. impact azimuth and impact velocity for a sun-synchronous ERS like target

An example for the Analyst application's capability to resolve flux to individual oriented surfaces is given in Fig. 11.

A simplified model of a sun-synchronous ERS like satellite was generated and the incident flux on the earth, space, west and ram directions was analysed with respect to the impact angle distribution, which is counted from the normal direction of the related surface. It becomes clear, that the total flux is clearly dominated by the flux on the surface in ram direction, which is mostly hit at comparatively low impact angles. Some further flux can be observed at high impact angles on the earth oriented surface and over a broad spectrum of impact angles on the back (west) side of the satellite. Impacts on the space surface again occur only at impact angles above 40°, but only on a very low level.

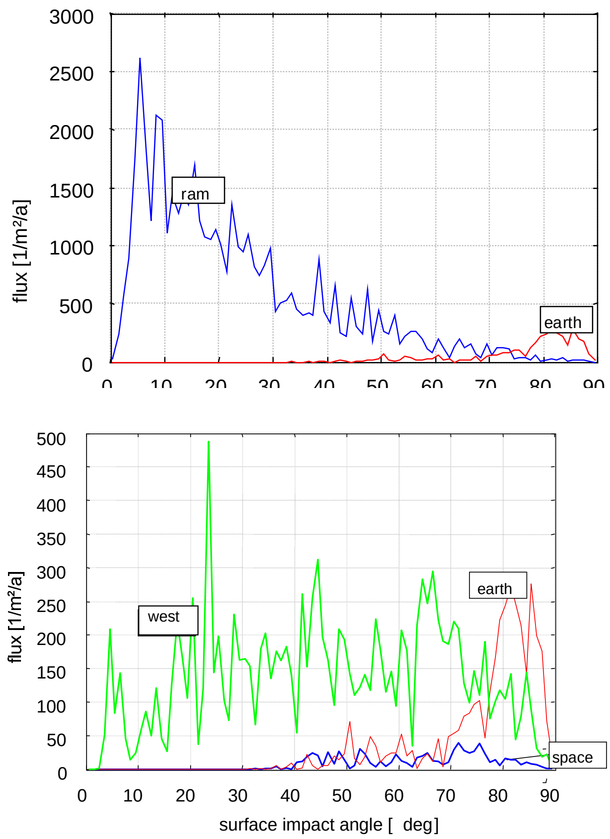

Fig. 11: Surface impact angle distribution of the debris flux > 1 µm on an ERS like satellite (earth oriented target)

7. Outlook

Within a currently ongoing model upgrade the capabilities of the MASTER'99 model will be further enhanced. A fundamental additional feature planned for the next MASTER release will certainly be its ability to provide flux and spatial density results not only around a given reference epoch (MASTER'99 : August 1999), but also for any point in time with a comparable reliability and information contents. In practice this means that the model will be able to base its flux predictions for historic and future missions on population data which the deterministic source term models in the background provided for this particular epoch. LDEF, for example can be investigated by applying the environment of the 1980's while an ISS simulation will be based on the environment of e.g. the year 2005.

This unique and useful feature will be made possible by making available highly condensed deterministic population 'snapshots' taken at regular intervals (e.g. each 3 months). For the historic environment these data are provided by the MASTER developer's branch, while the future environment will be described by parametric extrapolations into the future made by the DELTA (see /12/). These data will be pre-processed to provide highly condensed input data for the MASTER Standard Application.

Other activities projected for the next release are

- an update of source terms model with respect to new findings from observation
- a further extension of the MASTER Standard Application features by implementation of
  - the Divine Staubach meteoroid model (which is currently only available via the Analyst Application)
  - meteoroid stream model
  - ability to determine flux to oriented surfaces

8. Summary and Conclusion

The evolution of the MASTER model shows a continuos record of model improvements.

The current release of ESA's Reference model for Space Debris and Meteoroids (MASTER '99) model represents a significant evolution step of the model by providing a variety of new features, capabilities, and applications :

- new source terms are implemented
- the lower size threshold has decreased to 1 micron
- a graphical user interface (GUI) enhancing the user friendliness and ergonomy of the model is provided
- meteoroid streams are considered
- the model is able to determine flux to surfaces of a user defined orientation.
- spatial density results are provided.

These new features provided by MASTER'99 further strengthen the capabilities of the model. Within a currently ongoing model upgrade the capabilities of the MASTER'99 model will be further enhanced.

9. References

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