THE MASTER-2009 SPACE DEBRIS ENVIRONEMENT MODEL

S. Flegel[1], J. Gelhaus[1], C. Wiedemann[1], P. Vörsmann[1], M. Oswald[2], S. Stabroth[2], H. Klinkrad[3], and H. Krag[3]

[1]*Institute of Aerospace Systems, Technische Universität Braunschweig, Hermann-Blenk Str. 23, 38108 Braunschweig, Germany*
[2]*Astrium GmbH - Satellites, 88039 Friedrichshafen, Germany*
[3]*Space Debris Office, ESA/ESOC, Robert-Bosch Str. 5, 64293 Darmstadt, Germany*

ABSTRACT

This paper provides an overview of the improvements which are currently being made to ESA's *MASTER* model in preparation for the release of the new version, *MASTER*-2009, in spring 2010. Within the current maintenance contract, improvements are being made to the population source models to account for new findings. Multi-Layered Insulation will be added as a new source for space debris based on a previously published model. The current paper highlights the background for the implementation of the model and changes which are being made to original model. On the user side of the tool, improvements will be made to allow a detailed investigation of individual fragmentation events. In the event of major fragmentation events which may pose a threat to operational satellites population files will be made available for download over the *MASTER* website. In addition, the current graphical user interface architecture will be revised. This will allow the current JAVA based user interface to be used for the online version of *MASTER*, replacing the current MARWIN interface.

NEW FEATURES

Within the frame of debris source modeling, the NASA breakup model and the model for sodium-potassium droplets are revised based on new findings [11],[12],[20]. In addition, a new debris source is included which addresses the results of several observations throughout recent years. This debris is characterized by a mean motion similar to that of GEO objects, high brightness fluctuations and quickly changing orbital elements. A possible source for this debris is the release of Multi-Layered Insulation (MLI) foil from satellites due to ageing related delamination or during fragmentation events. These two mechanisms will be simulated independently and will be included into the *MASTER Flux Browser* as a combined source. The lower diameter limit of the future debris environment will be brought into accordance with that of the historic population. Previously, the lower diameter for future epochs had been 1 mm while that of historic epochs was 1 micrometer. In the *MASTER*-2009 release, the lower limit for future epochs will be decreased from 1 millimeter to 1 micrometer. A major new feature within the *Flux Browser* will be the possibility to analyze the effects of individual fragmentation events. Debris from fresh clouds remains in a narrow ring for some time before distribution over the right ascension of the ascending node sets in. Fragmentation population files for contemporary events will be supplied over the *MASTER* website for download to keep the user up to date with the newest developments of the fragmentation debris environment. An online version of the Java-based graphical user interface on the *MASTER* website will replace the current MARWIN application.

Proc. '5th European Conference on Space Debris', Darmstadt, Germany
30 March – 2 April 2009, (ESA SP-672, July 2009)

FRAGMENTATION MODELING

The fragmentation model used in the developer's branch of *MASTER* is based on the Evolve 4.0 standard breakup model - the “NASA Breakup Model”. This model was established based on observational data from on orbit breakup events as well as a ground based test series, the SOCIT tests (Satellite Orbital Debris Characterization Impact Test). In these tests hypervelocity impact tests were made on flight ready U.S. Transit navigation satellites. The Transit navigation system was the predecessor to the GPS Navstar constellation and provided navigation services from 1964 to 1996. In the fourth test labeled SOCIT-4, fragments were analyzed down to approximately 1 millimeter. It is this data which was used to describe the small fragment area-to-mass ratio and Δv in the 1998 NASA Breakup Model [9].

The original model was initially not intended to be used for submillimeter fragment simulation. For the area-to-mass distribution of these sizes, a continuation of the distribution of the millimeter size range was therefore initially used. During the implementation of the NASA Breakup Model into *MASTER*-2005, it was discovered, that this continuation lead to an unrealistic increase in material density for these fragments. A mean material density of $2.7\,g/cm^3$, which corresponds to that of aluminum, was therefore applied in *MASTER*.

In the course of the upgrade of their ORDEM2008 tool [21], NASA initiated a reinvestigation of the SOCIT-4 data [11, 12]. In the recent studies, Krisko et al. introduced three material density ranges according to Table 1 to analyze in greater detail the fragment properties. The density ranges correspond roughly to the predominant materials used in the test satellite: aluminum, steel and phenolic/plastic. The studies reveal that in the SOCIT-4 test, the composition of material densities and fragment shapes changed with the fragment size. In particular, the share of low density plastic objects increases towards smaller characteristic lengths L_c. For L_c of 1 mm these low density fragments have a share of approximately 75 % of all fragments, followed by medium density fragments with a share of about 20 %, the rest being made up of high density fragments. This stands in contrast to the current modeling of these small fragments which assumes medium density objects to dominate this size regime. The light weight phenolic/plastic materials in the SOCIT-4 data originate from the electronic components and the outer skin of the satellite. If one assumes that rocket bodies do not use electronic components to the extent that satellites do. a look may be taken at the distribution between the medium and high density fragments. Here, a constant ratio between aluminum and steel of approximately 9:1 is found. For the *MASTER*-2009 model, independent area-to-mass distributions will be used for satellites and a rocket bodies.

Table 1. Fragment density ranges [12]

Low density (Plastic)	Medium density (Aluminum)	High density (Steel)
$< 2\,\mathrm{g/cm^3}$	2 - $6\,\mathrm{g/cm^3}$	$> 6\,\mathrm{g/cm^3}$

Printed circuit boards can be made of a variety of materials such as Polyimide with a density in the order of $1.4\,\mathrm{g/cm^3}$ or PTFE with a density of $2.2\,\mathrm{g/cm^3}$ [3]. According to an evaluation report published in 1999 by Hughes Space & Communications [8], the most common printed circuit board prepreg material which makes up the largest part of the printed circuit board mass, was polyimide glass laminate. This type of material has a density of around $1.9\,\mathrm{g/cm^3}$ [13]. Aluminum in contrast has a density of $2.7\,\mathrm{g/cm^3}$. Applying the density to the equation for area-to-mass ratio (1) shifts the lower boundary towards higher characteristic lengths.

$$(A/m)_{\mathrm{debris}} = \frac{3}{4\rho_{\mathrm{debris}} r} \qquad (1)$$

ρ_{debris} is the debris material density and r the sphere radius.

Figure 1 shows the envisaged solution using a mean density of $1.9\,\mathrm{g/cm^3}$ while retaining the original standard deviation along with the mean area-to-mass ratio for Polyimide.

This new mean density would lead to an increase in area-to-mass ratio by a factor 1.5 approximately compared with the aluminum implementation. Atmospheric drag on satellite fragmentation debris with diameters below approximately 1.6 mm will thus lead to shorter orbital lifetimes.

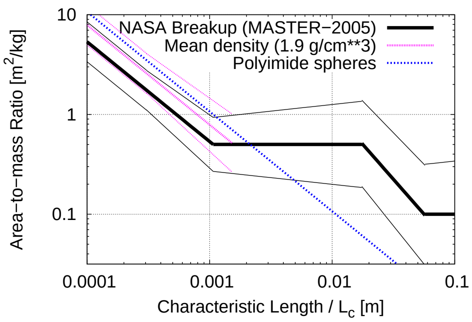

Figure 1. Area-to-mass ratio assignment for small particle regime for payloads. Comparison of current lower limit for aluminum spheres to modified lower limit for polyimide glass laminate with standard deviations and the mean value for polyimide.

Following the reasonable assumption, that rocket bodies use fewer low density materials than satellites, the mean values for the area-to-mass ratio over diameter are shifted to that of aluminum. The small size distribution for rocket bodies will thus retain the current parameter set for sizes below one millimeter. The diameter range between 0.001 m and 0.178 m in the area-to-mass distribution of the current NASA Breakup Model implementation is a horizontal distribution (see Figure 1). In the SOCIT-4 data, this size regime was dominated by phenolic/plastic fragments. The parameters in this range will be adjusted to that of the medium density aluminum. Figure 2 compares the current small size approach to a fit to the pure area-to-mass distribution of aluminum from the SOCIT-4 data [12]. The mean area-to-mass ratio of aluminum can be seen to approach the theoretical limit of a sphere for fragments below 1 mm. For larger characteristic lengths, the shape diverges from that of a sphere, creating more oblong and plate like fragments. As the area-to-mass ratio for fragments between 1 mm and 1 cm is reduced, it can be assumed that these fragments will stay in orbit for extended periods of time.

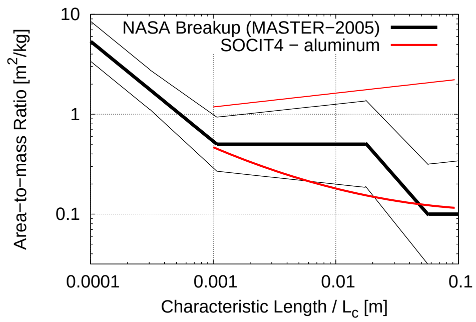

Figure 2. Area-to-mass ratio assignment for small particle regime for rocket bodies. Comparison of current implementation to the A/m-distribution for aluminum from the SOCIT-4 reanalysis [12].

NAK DROPLET MODELING

During the reactor core dismantlements of approximately 16 nuclear "Buk" reactors the primary coolant loop was opened. This lead to the release of the eutectic sodium-potassium NaK-78 which was used as coolant [18]. Modeling of this debris source for the *MASTER*-2005 model used a the total amount of NaK mass which was released during each event had been estimated to be about 8 kg [19]. Revised radar measurements [6, 7, 21] however indicate, that the total released mass may have been somewhat lower at approximately 5.3 kg per event. A closer look is therefore being taken at the mechanism behind the release of the liquid metal droplets. The Buk reactors used an expansion tank to compensate for the changing volume of the liquid coolant from temperature variations. Assuming that the reactor core is opened at the maximum temperature, not only the liquid metal surrounding the fuel rods and in the reactor head would escape into space, but also the equivalent volume in the preloaded expansion tank could be driven out of the cooling lines. This would result in a total release mass of 3.96 kg [20]. Additional effects such as the tumbling of the reactor which could result in additional outflow have not yet been taken into account. The current revision of the NaK model uses a total mass of 5.3 kg per event as this is in line with the conclusions drawn from the measurement data. This data represents intermediate results and may be subject to change in the further course of the ongoing contract.

MLI MODELING

During optical surveys of space debris in GEO transfer orbits using ESA's 1 m Ritchey-Chrétien Space Debris telescope (ESA-SDT), an unexpected debris population was discovered [15, 16]. The objects exhibit mean motions similar to GEO but have high excentricities and quickly changing orbit parameters. The objects also exhibit quickly changing brightness levels which may be explained through a tumbling motion. Since the beginning of these surveys in 1999, the source has been confirmed by other observations through e.g. Agapov et al. [1]. It had been proposed that plastic foil debris with very high area-to-mass ratios from GEO satellites could be forced into orbits with high eccentricities by solar radiation pressure. Further studies of the effect of solar radiation pressure on light objects lead to the development of a model for the simulation of such foil debris [14]. Subsequent comparison of the simulation results using this model to observation results performed with the ESA-SDT revealed an underprediction of the objects by the model [10]. It was therefore decided to introduce a modified version of the MLI-model into *MASTER*-2009. In this paper only a brief overview of the model is given along with the intended modifications compared to the model presented in 2006 by Oswald et al. [14].

Two different MLI-debris sources are modeled independently: an ageing-related, time dependent delamination process and the fragmentation of satellites. The delamination model is implemented without alterations. In response to the underprediction identified by Krag et al., the relevant model for fragmentation debris is revised. Figure 3 gives an overview of the revised MLI fragmentation model flow. Initially, the amount of MLI

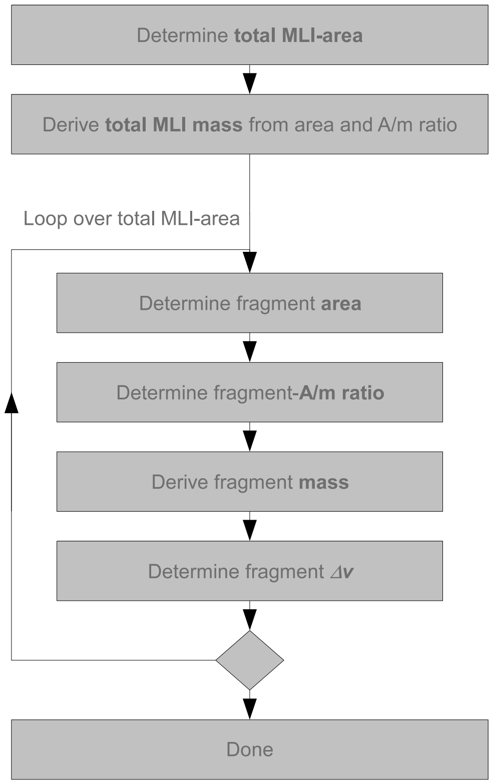

Figure 3. MLI-fragmentation model flow.

which was derived simply as a fraction of the beginning-of-life (BOL) mass of the satellite. In the current model, the total MLI-area is estimated from the surface area of a satellite and the number of insulating MLI-layers. The event list which is used for the simulation of historical fragmentations, no information is given on the size of the parent objects except the mass. The total surface area must therefore be estimated from the given mass. Equation (2) is an empirical equation [14] derived from satellite bus information and beginning-of-life mass given in ESA's DISCOS database (Database and Information System Characterising Objects in Space) [2].

$$(A/m)_{sat} = 0.01 + (20/(m_{BOL} + 2000)) \quad (2)$$

m_{BOL} is the beginning-of-life mass and

$(A/m)_{sat}$ is the surface area over the BOL mass. An additional change to the model is the seperation of the area-to-mass determination into two independent distributions for the outer cover layer and the inner reflector layers. This approach is already used for the delamination model. The probability density distribution for the area-to-mass ratio is given in Figure 4.

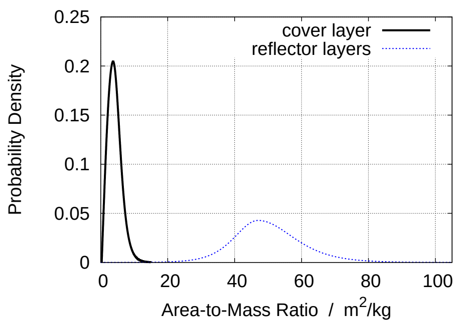

Figure 4. Probability density distribution for cover layer (solid line) and inner reflector layers (broken line).

FUTURE POPULATION

MASTER provides the user with the option to analyze the predicted evolution of the space debris environment within the frame of three scenarios: a business-as-usual scenario and two mitigation scnarios. These scenarios will be updated to reflect the latest trends in launch rates, fragmentation events and solid rocket motor firings. The population is produced using ESA's *DELTA* (Debris Environment Long Term Analysis) tool which has been developed by QinetiQ. In the *MASTER*-2005 release, the future space debris environement was provided down to a minimum diameter of 1 mm. For *MASTER*-2009 this limit will be brought into accordance with that of the historic population which is 1 μm.

DELTA currently implements payloads, rocket bodies and mission related objects, solid rocket motor slag, fragmentation debris from explosions and collisions which are determined through simulation of the population. The submillimeter population for these sources as well as those which are currently not considered by *DELTA* such as solid rocket motor dust, paint flakes and ejecta as well as the newly implemented Multi-Layered Insulation, will be produced with ESA's *POEM* (Program for Orbital Debris Environment Modeling). This program is the core software which is used to produce the historical *MASTER* population through simulation of all known historical events.

USER PROVIDED FRAGMENTATIONS

The space debris population used in the *MASTER*-2005 model uses accurate information on four orbital parameters: perigee altitude, orbit eccentricity, orbit inclination and argument of perigee. The orbit normal vector which is described in the inertial space through the right ascension of the ascending node along with the true anomaly describing the precise location of an object within an orbit are not included. For flux calculations the *Flux Browser* then randomly determines information on the right ascension for all objects based on a uniform distribution over the entire range of 0 to 360°. This process is repeated several times to arrive at an averaged flux. This approach results in statistically robust long-term flux predictions onto target satellites. Recent events have however made a method for determining the short and medium term flux from individual fragmentation events highly desirable.

The time-development of a fresh cloud may be roughly divided into three stages: In the first stage after a fragmentation, the debris orbits the earth in an expanding and contracting cloud. Accurate modeling of this stage requires information on the right ascension of ascending node of each fragment along with the true anomaly. As the orbit period of a fragment from a LEO event is on the order of a 90 minutes, a time resolution on the order of minutes is required. In a second stage, the different orbiting periods of the debris causes the fragments to form a ring around the earth. As the debris is distributed roughly uniformly within this ring, information on the exact position may be omitted while retaining the information on the orientation of the orbital plane. For a 1 cm debris fragment, the NASA Breakup Model gives a mean Δv of approximately 0.2 km/s for an explosion event. Assuming one posigrade and one retrograde debris object, the time until one object overtakes the other can be estimated. For a LEO event, this occurs after roughly five hours. For GEO events, this stage will take place within 30 hours. All objects with higher or lower orbit periods at this time will be located somewhere in between. These times can be used as rough estimates for the transition time between the first and second stage. Perturbative forces will then cause the right ascension of ascending nodes of the fragments to drift apart until the debris is evenly distributed around the earth in a spherical torus. As this drift rate is limited to a maximum rate of a few degrees per day, the transition time between the second and third stage lies on the order of months and a time resolution on the order of days is enough for accurate flux determinations during this period.

For *MASTER*-2009, an additional source has been added which allows the user to include individual fragmentation clouds. Dayly population files include additional information on the right ascension of ascending node. This makes a detailed flux and spatial density analysis of the second stage of a fragmentation event possible. Detailed flux analyses from fresh clouds over an extended period of time also requires the orbit propagation of the target orbit. This is realized through the inclusion of simple analytical equations for the drift rate of the right ascension of ascending node and the arguement of perigee according to equations (3). Population files for contemporary events will be made available for download from the *MASTER* webpage.

$$(\Delta\Omega)_{day} = -9.96^\circ \cdot \frac{(R_E/a)^{7/2}}{(1-\epsilon^2)^2} \cdot \cos i \qquad (3)$$

$$(\Delta\omega)_{day} = 4.98^\circ \cdot \frac{(R_E/a)^{7/2}}{(1-\epsilon^2)^2} \cdot \left(5\cos^2 i - 1\right)$$

MASTER FLUX BROWSER

Postprocessing of the particle flux onto a target spacecraft or through an inertial volume is sometimes required. This is currently possible by selecting an additional output file which contains all relevant cell passage events, the so called CPE files.

The *MASTER Flux Browser* shall be improved to allow for further processing of the data output by damage assessment tools. In this context, a common data interface was agreed by IADC members based on a concept developed by RWTH Aachen University [17]. The finalized STENVI implementation shall allow for an output file for each target surface to be specified by the user via the existing surface description input file of the command-line and GUI version of the *Flux Browser*.

In addition to the STENVI interface, it is intended to ease the implementation of the new *MASTER Flux Browser* into other space environment tools like ESABASE2/DEBRIS. Here, an input option allows for a flux analysis of only a defined range in orbital arc of the target spacecraft orbit. Since the current version of the callable *Flux Browser* does not allow for a multi-dimensional spectrum output for a restricted orbital arc, this input feature will be implemented into the new version.

MASTER-2009 WEB SERVICE

A dedicated *MASTER* & *PROOF* website will be hosted by ESA. The site will provide the following services and features:

- Online version of *MASTER*-2009
- Population files of contemporary fragmentation events for download
- No login requirement
- Software updates to the 2005 and 2009 versions of *MASTER* and *PROOF*

The online version of *MASTER*-2009 will use the same graphical user interface (GUI) as the DVD version and will replace the current MARWIN application. For a maximum amount of commonality, the structure of the GUI is rewritten around a controller which handles all data transfer between the GUI, the *MASTER* model, all data files and GNUplot which is used to produce of the graphical output. This allows the software to be used on a local system or on a remote system with only the GUI being accessed by the user. The new software architecture is shown in Figure 5. Once the user has entered the simulation data, the input data is sent to the remote server where the *MASTER* software is exectuted and all plots are produced. The resulting graphics are then displayed in the GUI viewed by the user and may be downloaded by the user.

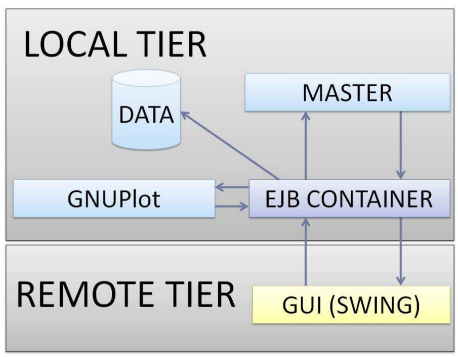

Figure 5. Future software architecture with local and remote tiers for application with the MASTER *web service.*

In the case of major new fragmentation events such as the recent collision between the Iridum-33 and Cosmos 2251 satellite, these events will be simulated, propagated from the moment of the event onward to a future epoch and then converted into *MASTER* population files. The user can then download a .zip file containing all population of that event. Unlike the background debris population, these files include information on the right ascension of ascending node to give an accurate representation of the evolution of a fragmentation event (see Section). Therefore, files will be provided for dayly epochs.

SUMMARY

The major changes which will be implemented in the *MASTER*-2009 model have been presented. The new model will implement upgrades in all major software tools. Updates of the underlying physical models will increase the quality of the underlying population. A new source is introduced to model highly visible Multi-Layered Insulation debris based on two independent creation mechanisms. A major new feature will be the possibility to analyze individual fragmentation events taking into account the dayly development of the cloud geometry. Provision of cloud populations for major events from the *MASTER* website will allow satellite operators to estimate the risk for operational satellites presented through individual events for the near and medium term. The *MASTER* website will include a new online version of the *MASTER* GUI using the same front end as the DVD-based version thus making it possible to perform satellite flux analyses from anywhere in the world.

ACKNOWLEDGMENT

The results presented in this paper were achieved under the ESA contract 21705/08/D/HK “Maintenance of the ESA MASTER Model.” All responsibilities for the contents of this publication reside with the authors.

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