PROPULSION-RELATED ORBITAL DEBRIS

M. Oswald, S. Stabroth, C. Wiedemann, P. Vörsmann
Technische Universität Braunschweig, Institute of Aerospace Systems, Braunschweig, Germany

P. Wegener
Wegener Aerospace Consult, Braunschweig, Germany

Orbital debris is posing an increasing threat to all unmanned und manned space activities. With the number of objects steadily increasing since the launch of Sputnik 1 in 1957, collisions that damage or even disable spacecraft have become more likely. As of today, the US Strategic Command Catalogue contains about 13,000 objects which are big enough to be regularly tracked. However, this is just the tip of the iceberg. Due to the limitations of the radars and telescopes used to maintain this catalogue, only a small percentage of debris that might pose a threat to spacecraft can be regularly tracked. Models of the debris environment such as the Meteoroid and Space Debris Terrestrial Environment Reference Model of the European Space Agency (ESA-MASTER) suggest that there is a total number of 580,000 objects with diameters larger than 1 cm in Earth orbit.

MASTER is based on the simulation of debris-generating events like on-orbit explosions and collisions, solid rocket motor firings, coolant releases, debris impacts, and spacecraft surface degradation. Based on the generation of initial debris clouds, a propagation of the debris particle orbits to all future epochs is performed, delivering a simulated orbital debris population for both past and future epochs. In MASTER, this information is used to deliver information on the debris flux to be expected for a certain mission scenario. The modeling results are validated against observation data gathered by TIRA, Goldstone, Haystack, and Cobra Dane radars. In addition to that, observations by the ESA Space Debris Telescope, the CCD debris telescope, and the Liquid Mirror Telescope are used. For the validation of the small particle debris environment modeled in MASTER, data on actual impacts on returned space hardware is used. The solar arrays of the Hubble Space Telescope returned by the Space Shuttle on missions STS-61 and STS-109, the EURECA satellite, and the Long Duration Exposure Facility are sources for impact data.

ESA-MASTER will be developed to its next release, MASTER-2005. The contract for the upgrade was awarded to the Institute of

Aerospace Systems at the Technische Universität Braunschweig together with QinetiQ.

This paper will deliver an analysis of the effects of the usage of solid rocket motors for orbit transfers with respect to the orbital debris environment of the Earth.

The MASTER Tool

Since 1995, the European Space Agency successfully procures the development of the European environment model MASTER. With its capability to analyze debris and meteoroid flux, MASTER is a widely used and globally accepted software. It has become a synonym for risk assessment rather than for a complex environment model.

MASTER is not just the designation of the new user branch of the software to be introduced in MASTER-2005, it also stands for a number of tools that are involved in a complex process to generate the required databases. This so-called “developer's branch" constitutes the scientific core of MASTER and is invisible to the user. As the underlying model is continuously being improved, driven by new findings and the changing environment, MASTER is regularly upgraded.

Currently the '2005 version of MASTER is under development by a consortium led by the Institute of Aerospace Systems at the Technische Universität Braunschweig supported by QinetiQ (UK) under ESA contract. It facilitates the following major improvements:

- Revision of the majority of source models
- New flux browser, providing more accurate flux data at higher speed
- Revised event database
- Revised traffic models

The History of MASTER

The original modeling philosophy of MASTER, to consequently pursue a deterministic approach towards a realistic description of the Earth's particulate environment is maintained to the current date.

It is based on the semi-deterministic treatment of all debris sources. The generation of debris is described in specific algorithms for each debris source. Individual objects described by a set of orbital elements at the epoch of generation and a number of other properties are generated in the simulations. In the following processing step, the orbits of all objects are propagated to predefined epochs.

The first release of MASTER was issued in 1995. It was a Beta version only offered to a restricted number of users for evaluation. It only considered the trackable population and objects above 100 microns generated by 121 on-orbit fragmentations. The Grün meteoroid model was used to consider the natural debris sources. The model allowed the computation of flux to a unit sphere. In 1997, the first official release of MASTER was issued by ESA/ESOC. The main difference between the newer version and its predecessor was the replacement of the Grün meteoroid model by the Divine-Staubach model.

MASTER-99 included a large number of improvements. Based on the same semi-deterministic concept as the previous versions, this version incorporated a number of new source terms, namely solid rocket motor slag and dust, NaK droplets, paint flakes, and ejecta particles. Its predecessors have also suffered from the fact that a lower size threshold of 100 microns made it difficult to compare the model output with measurements from returned space hardware. Thus, the threshold has been lowered to 1 micron in this new version. For the first time, the model also considered meteoroid streams. Both the Jenniskens-McBride and the Cour-Palais stream models were included.

MASTER-2001 further increased the value of the model by providing some unprecedented features: All past MASTER models had required periodic updates of the underlying database, and flux and spatial density results could only be provided around a fixed reference epoch, given once for each release. MASTER-2001 has the ability to provide flux and spatial density results for any point in time with comparable reliability and information content. This major improvement was accompanied by the introduction of the West Ford needles as a new source term.

Solid Rocket Motor Firings

MASTER-2001 had considered 1,032 solid rocket motor firings. These are important contributors to the orbital debris environment. Upon burnout of such engines, particles consisting of Al_2O_3 and burned liner residual materials spill out of the nozzle. These slag particles can be up to some centimeters in diameter and can be found near the target orbits of the inserted payloads. SRM firings are also responsible for the generation of small dust particles: In the exhaust gas of solid rocket motor (SRM) firings, a considerable amount of very small aluminum oxide (Al_2O_3) particles is generally included. In order to increase motor performance and to dampen burn instabilities, aluminum is used as an additive in the propellant. During the burn process most of this aluminum is transformed into Al_2O_3. A large number of small dust particles (< 1 µm up to about 50 µm) is generated continuously during a burn. At the end of a burn, a second group of much larger fragments from an Al_2O_3 slag pool clustering inside the motor leaves the nozzle.

SRM Dust Generation Mechanisms

Fundamental publications related to the modelling of SRM dust originate from the publications of Mueller and Kessler [1] well as Akiba and Inatani [2]. Mueller and Kessler's assumptions are based on investigations with the PAM-A (Payload Assist Module) motor originally performed by Burris [3], and are then applied to the IUS (Inertial Upper Stage) and SSUS (Spinning Solid Upper Stage) motors. The resulting distribution function is a fit to experimental data of Varsi [4]. Akiba and Inatani have performed many ground- and in-flight tests using ISAS motors (Institute of Space and Astronautical Science) and two-phase flow analysis to obtain sampling data. The distribution function postulated by Akiba and Inatani exists only in raw-data format.

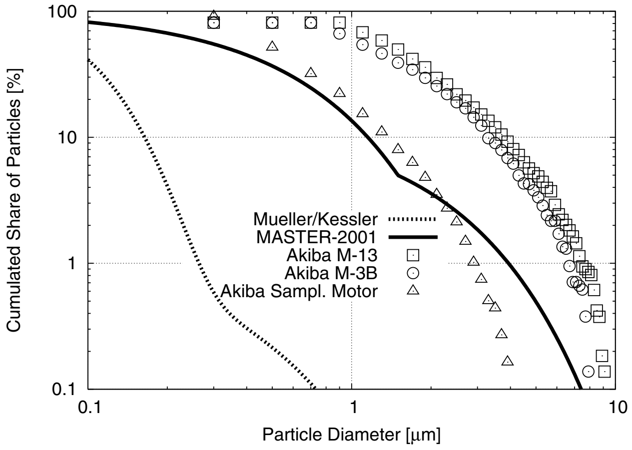

Fig. 1: Overview of SRM dust size distributions [11]

A comparison of the distributions (see Fig. 1) shows that both models expose fundamental differences in the share of large dust particles greater than about 0.5 microns. Akiba and Inatani find a certain dependency of the distribution of such particles on the nozzle throat diameter and thus on the size of the motor. The distribution postulated by Mueller and Kessler remains several orders of magnitude below the data of even the smallest engine investigated by Akiba and Inatani.

A viable solution for the diameter distribution is an approximation by two sections of an exponential law approach below and above a certain switch particle diameter d°. The distribution function currently used by the SRM dust module in MASTER-2001 is written as the normalised object number and can be interpreted as the fraction of objects larger than a certain diameter:

$$\hat{N}_d(d) = \begin{cases} e^{-b_1 d} & \forall d \le d^\circ \\ e^{b_2(d^\circ - d) - b_1 d^\circ} & \forall d > d^\circ \end{cases} \qquad (1)$$

$\hat{N}_d$ = Normalised object number
d = Object diameter [µm]
$d°$ = Switch diameter [µm]
$b1, b2$ = Function parameters [1/µm]

The database presented by Akiba and Inatani seems to be more reliable than the report to which Mueller and Kessler refer, because it is based on their own analysis. Therefore, it has been chosen to adopt the slope of the sampling motor distribution for very small dust particles below 1.5 microns. Since the model is intended as a generic approach to the historic SRM dust generation, the distribution also has to reflect larger particles as generated by huge orbital stages like the IUS. Therefore, the distribution is continued using the slope of the larger motors investigated by Akiba and Inatani. This is additionally supported by results of Hörz [5], who found evidence for aluminium oxide dust particles clustering on the nozzle surface. This leads to larger aggregates being continuously shed throughout the burn. Therefore, the default dust size distribution model calls for the function parameters being set to:

$$b_1 = 2.0\frac{1}{\mu m} \qquad b_2 = 0.5\frac{1}{\mu m} \qquad d° = 1.5\ \mu\mathrm{m} \qquad (2)$$

Fig. 1 additionally shows the resulting relation for the MASTER-2001 approach graphically in comparison with the existing distributions. Proceeding from this normalised size distribution, absolute particle numbers can be calculated with the knowledge of the total dust particle number released per SRM burn. Knowing the qualitative size distribution as described above, this number can be derived from the mass of Al_2O_3 available for the dust production following the generation of slag objects. This is an issue of mass balancing between the two modelled Al_2O_3 debris sources. More detailed information on the implementation of an SRM particle generation approach into the MASTER model can be found in Wegener [6].

SRM Slag Size Distribution

Some investigations have been made in the past concerning the ejection of slag particles from solid rocket motors after passing the nozzle throat, particularly after burn-out. As a result of limited amount of data, only two very crude slag ejection models exist for the time being - one approach by NASA and one by the MIT/Lincoln Laboratory (MIT/LL). The two slag ejection models are based on different observation techniques. The approach by NASA was derived from optical observations of statically fired SRMs, originally described by Siebold [7] and Anderson [8]. In contrast, the MIT/LL law as described by Bernstein and Sheeks [9] is based on the observation of ascending sub-orbital launch vehicles using ground-based radar devices and infrared telescopes. While the ground tests involved STAR-48 and STAR-63 motors with propellant masses of about 2,000 kg and 3,700 kg respectively, the radar observations refer to a 4-nozzle engine design loaded with 1,680 kg of propellant. Both models are restricted to particle diameters above 5 mm due to measurement limitations.

For the implementation in MASTER-2001, the size distribution of objects larger than a threshold diameter of 5 mm is a combination of both NASA and MIT/LL models. The most significant discrepancies between the two models concern the number of slag particles set free. The ground tests revealed a lower limit of 400 particles with an average

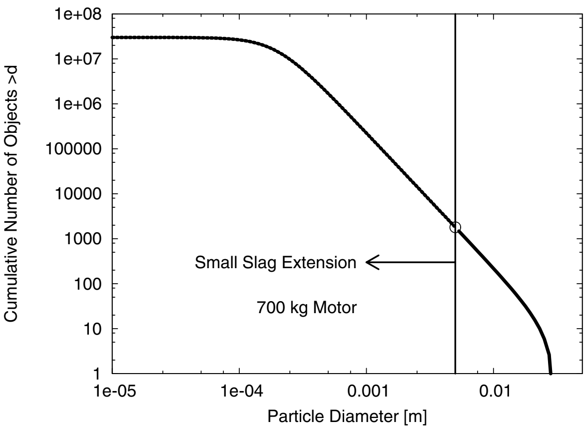

Fig. 2: Cumulative size distribution for the standard slag model and the small slag extension [11]

diameter of 1.5 cm, but this number may be one order of magnitude too small [7]. A typical observation conducted by MIT/LL rendered about 900 objects ranging from a lower limit of 5 mm to the largest objects believed to have diameters of about 3 cm.

The discrepancies can be resolved by scaling the observed cumulative object numbers and ranges to the propellant mass of a STAR-37 reference motor with 700 kg propellant mass and assuming a baseline of 1,800 particles greater than 5 mm, which is a compromise with the aim to meet measurement data. The number distribution is proportional to $1/d^3$, hence follows a $1/m$ relationship (see Fig. 2). It is assumed that 50% of the particles are created from propellant material (Al_2O_3 density $3.5\,g/cm^3$) and 50% are created from liner material (density 1.8 g/cm^3), which is used to fix the solid propellant on the insulation layer. In addition, the current model in MASTER-2001 suppresses the generation of slag larger than a limiting diameter threshold of 3 cm, since the maximum size of slag particles is clearly limited by the nozzle's throat diameter, which on average is smaller for orbital kick stages than for large rocket boosters or upper stage motors.

It is possible that particles smaller than 5 mm can leave the nozzle without being noticed because of the maximal resolution of the observation instruments. An extensive investigation of an impact crater found on a Space Shuttle Orbiter window after mission STS-50 showed that the impactor had a size between 100 to 150 microns and the chemistry of this object was aluminium oxide [10]. Solid rocket motors are the only possible source for particles of that composition. Due to this evidence, it turned out to be desirable to include also these smaller particles into the model. There are no clues yet for the distribution of diameters below the 5 mm observation threshold. The formation of slag within the combustion chamber is followed by a complex two-phase flow, leading to a possible shattering of droplets. The number of these sub-millimetre slag objects released during one burn may be very high, while the contribution of the objects to the totally ejected slag mass remains rather low.

The approach chosen in MASTER-2001 for objects below 5 mm allows a smooth fade-out to lower diameters, thus avoiding discontinuities in the overall population distribution (see Fig. 2). In order to preserve continuity with the standard diameter distribution function, the switch diameter between the branches is chosen as the reference diameter for both parts of the distribution [11]. The tail-off of the diameter distribution should be at about 150 microns (the diameter of the particle impacting on the Shuttle window).

Contribution to the Environment

According the the ESA-MASTER-2001 Model, SRM slag is the major contributor to the above-1mm orbital debris environment up to 500 km altitude and in the region between 1200 km altitude up to the geostationary ring.

A large portion of the 1,032 firings that have occurred until the reference epoch of MASTER-2001 took place at inclinations near 28 degrees. The major contributor are the US space activities that employ a wide range of solid rocket motors for orbit transfer maneuvers, including GEO insertion burns.

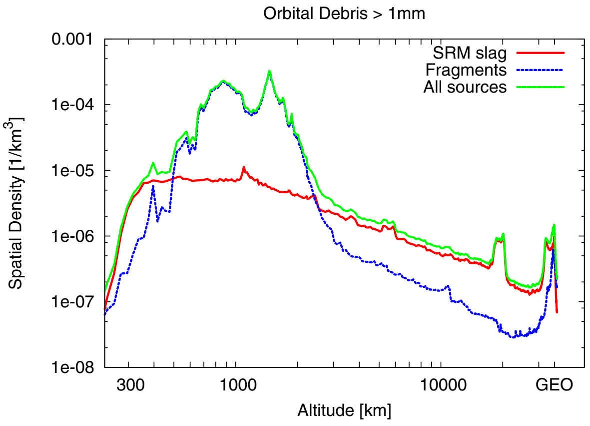

Fig. 3: Contribution of SRM slag to the orbital debris environment according to ESA-MASTER-2001

Conclusions

Propulsion-related orbital debris is a major contributor to the orbital debris environment. In this paper the approach pursued for modelling solid rocket motor slag and dust released during firings has been described. The new ESA-MASTER-2005 model will consider a large portion of the methods described here. MASTER-2005 is currently being developed by the Institute of Aerospace Systems at the Technische Universität Braunschweig under ESA contract.

References

[1] Mueller A. C. and Kessler D. J. The effect of particulates from solid rocket motors in space, *Advances in Space Research*, Vol. 5, 1985, pp. 77-86, 1985.

[2] Akiba R. and Inatani Y. Behavior of alumina particle exhausted by solid rocket motors, *Proceedings of the Workshop on Space Debris*, ISAS, Kanagawa, Japan, 1990.

[3] Burris R. A. Orbiter surface damage due to SRM plume impingement, *MDTSCO Design Note No. 1.4-3-016,* 1978.

[4] Varsi G. Particulate measurements, *Space Shuttle Environmental Assessment Workshop on Stratospheric Effects*, JSC TM X-58198, 1977.

[5] Hörz F., Bernhard R. P., See T. H. and Kessler D. J., Metallic and oxidized aluminum debris impacting the trailing face of the long duration exposure facility (LDEF), *Space Debris*, Vol. 2, No. 1, pp. 51-66, 2002.

[6] Wegener P., Krag H., Rex D., Bendisch J. and Klinkrad H. The orbital distribution and dynamics of solid rocket motor particle clouds for an implementation into the MASTER debris model, *Advances in Space Research*, Vol. 23, No. 1, pp. 161-164, 1999.

[7] Siebold K. H., Matney M. J., Ojakangas G. W. and Anderson B. J. Risk analysis of 1-2cm debris populations from solid rocket motors and mitigation possibilities for geotransfer orbits, *Proceedings of the First European Conference on Space Debris*, ESA SD-01, Darmstadt, Germany, 1993.

[8] Anderson B. J., Ojakangas G. W. and Anz-Meador P. D. Solid rocket motor contribution to large-particle orbital debris population, *Journal of Spacecraft and Rockets*, Vol. 33, No. 4, pp. 513ff., 1996.

[9] Bernstein M. D. and Sheeks B. J. Field observation of medium-sized debris from postburnout solid-fuel rocket motors, *Proceedings of SPIE*, 3116-32, 1997.

[10] Jackson A. and Bernhard R. Large solid rocket motor particle impact on shuttle window, *The Orbital Debris Quarterly News*, Vol. 2, No. 2, pp. 3-4, 1997.

[11] Wegener P. Modelling and validation of the space debris flux onto satellites, *ZLR-Forschungs-bericht*, 2004-12, 2004.