Deutscher Luft- und Raumfahrtkongress 2010
DocumentID: 161277

New developments in the modeling of the space debris environment

Sven Flegel[a], Gelhaus J.[a], Wiedemann C.[a], Möckel M.[a], Vörsmann P.[a], Krag H.[b], Klinkrad H.[b]

[a] *Institut für Luft- und Raumfahrtsysteme, Technische Universität Braunschweig , Hermann-Blenk-Str. 23, 38108 Braunschweig, Germany*
[b] *Space Debris Office, ESA/ESOC, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany*

Abstract

In order to estimate the risk for satellites to collide with space debris or meteoroids, software is used which simulates earth's particulate environment. The underlying population represents the core of these programs. It is established via a fusion process which combines measurement data with simulation data. With time, knowledge of the space debris environment increases so that the population can be refined. ESA's *Meteoroid and Space Debris Terrestrial Environment Reference* (MASTER) Model is one of the most widely used programs which serves this purpose. In the frame of the contract "Maintenance of the ESA MASTER Model," the entire historical population up to the year 2005 was revised. The history was extended up to May 1st, 2009 and predictions of the future evolution were updated according to current trends.

The current paper compares the population of the MASTER-2005 model with that of the new MASTER-2009 model. Changes in the representation of the historical population evolution are discussed which result from revised modeling of independent debris sources. The newly established population between May 2005 and May 2009 is then compared to the predictions of MASTER-2005. An emphasis is put on the validation of the method which is used in deriving the traffic definitions of the business-as-usual scenario. Initial results for the future debris population evolution conclude this paper.

Keywords: MASTER-2005, MASTER-2009, Space Debris

1. Introduction

The population of the MASTER model combines data from in-orbit objects and simulations. It aims at giving a realistic representation of the historical space debris environment since 1957. Predictions for the future debris environment up to 2060 are made for different traffic scenarios. Data sources for in-orbit objects are the Two-Line Elements and the Satellite Situation Report which are published by the USSTRATCOM over the Space-Track website /13/, Jonathan McDowell's Satellite Catalog /7/ and ESA's Database and Information System Characterising Objects in Space (DISCOS) /2/. Only a small part of all objects orbiting earth are however included in these databases so that an alternate source of information is required. In the MASTER population, these gaps are filled by simulation of all known space debris sources. The software used in this process is the *Program for Orbital Debris Environment Modeling* POEM. The debris sources included in MASTER-2009 are the clusters from the two Westford-Needle experiments which were performed in the early 1960s, payloads, rocket bodies and mission related ob-

Email address: s.flegel@tu-bs.de (Sven Flegel)

jects, explosion and collision events, solid rocket motor slag and solid rocket motor dust, ejecta, paint flakes, Sodium-Potassium droplets and multi-layer insulation. A full description of the initial sources is given in the MASTER-2005 Final Report /8/. The updated models will be published in the MASTER-2009 Final Report to be released this autumn. The model for the release of multi-layer insulation foils has been adapted from /3/ and updated and will be presented at the 61st International Astronautical Congress in Prague, September 27 to October 1, 2010.

2. New developments for MASTER-2009

Since the release of MASTER-2005, changes have been introduced into the modeling of the space debris population. The most prominent changes and the effects on the space debris environment are discussed here.

2.1. Sodium-Potassium Droplets

In the time frame of 1980 to 1988, the former Soviet Union operated radar ocean reconnaissance satellites of the type RORSAT. These satellites used a nuclear BuK-reactor for power supply and operated in low earth orbits close to 250 km alitude. At the end of the operational lifetime, the reactor cores were ejected whereby some of the liquid coolant, consisting of a eutectic sodium-potassium (NaK) alloy, was released. The coolant formed into spheres of sizes between some hundred nanometers and a few centimeters.

In the MASTER-2005 model, a total mass of eight kilograms was estimated to be released during each of these events /8/. Revised radar observations and other information later required an update of the model. The adapted model, which is used in MASTER-2009, reduced the total ejected NaK mass from eight kilograms to 5.3 kilograms. The size distribution was subsequently changed so that the number of the larger NaK spheres is similar to the MASTER-2005 results, but the total number of spheres with diameters below one centimeter is considerably reduced /9/.

The changes to the NaK model has a large effect on the total number of sub-millimeter size objects. These however all decayed due to atmospheric drag in the 1990s. The only remaining objects at the MASTER-2009 reference epoch of May 1st, 2009 are objects larger than one millimeter. The number at this epoch has decreased from 23,900 objects in MASTER-2005 to 18,410 objects in MASTER-2009.

2.2. Fragmentation Events

Individual historical fragmentation events have been adjusted to better match measurement results. In all, nine events which occured before May 1st, 2005 were adapted. Adaptations included the number of large fragments produced, time of event and orbit position.

In terms of simulation, the small size regime has been changed to incorporate new findings from Krisko et al. /5, 6/ involving the SOCIT-4 ground test. The SOCIT test series analyzed the fragmentation of Transit navigation satellites in a ground based laboratory. In these tests, only the SOCIT-4 test characterized small size fragments. Reanalysis of the SOCIT-4 data with respect to different materials showed that the predominant material of fragments with a small characteristic length was phenolic/plastic. In the SOCIT-4 tests, the source for these fragments had been the electronic circuit boards. Krisko et al. presented the possibility of seperating payloads and rocket-bodies in terms of their material make-up for fragmentation simulation. The idea was based on the assumption that the electronics-to-structure ratio is higher for satellites than for rocket-bodies. After testing this idea, the fragmentation model in MASTER-2009 was adapted to incorporate these material properties. For payloads, the material density of small size fragments was shifted from aluminum with a mean density of 2.7 g/cm^3 towards plastic with a mean density of 1.9 g/cm^3. Material density of rocket body fragments between 1.1 mm and 5.6 cm was shifted from that of plastic towards that of aluminum.

These changes resulted in a decrease in spatial object density for micrometer sized objects by 10 % in LEO. For the 1 mm to 5 cm size range, the spatial object density increased by 20 % /4/.

2.3. Solar Radiation Pressure Effect

The orbits of all objects created by POEM are propagated with a semi-analytic propagator. A comparison was performed between this tool and numerical propagators. All available numerical propagators exhibited a higher effect of solar radiation pressure (SRP) by a factor two so that for MASTER-2009 it was decided to adopt this factor.

The effect of SRP increases with increasing area-to-mass ratios. For these objects, the SRP leads to a periodic eccentricity build-up. For some objects on initially geostationary orbits, the perigee may sink into the atmosphere, leading to a fast decay of the object. The largest effect of the introduced change is seen in solid rocket motor dust and slag and ejecta with sizes *below* one millimeter. For all three sources, the decay rate at these sizes increased, which lead to a reduced number of in-orbit objects.

2.4. Multi-Layer Insulation

Multi-Layer Insulation has been added as a new source for space debris in the MASTER-2009 model following results of several observations of recent years /10, 11, 1/. Initial observations of this debris were made with ESA's 1 m Ritchey-Chrétien Space Debris telescope (ESA-SDT) during surveys of space debris in GEO transfer orbits. These objects exhibited mean motions similar to GEO but had high eccentricities and quickly changing brightness levels which could be explained through a tumbling motion.

Multi-Layer Insulation is used on satellites for thermal insulation of the satellite bus and for shielding of radio frequency antennae from solar radiation /12/. These insulation systems commonly consist of multiple layers of metalized polymers with varying thicknesses between 6 μm and 250 μm. Two processes were identified by which these objects may be released from satellites: i) through fragmentation events ii) through ageing related delamination. The corresponding very high area-to-mass ratios of these foils ranges up to 111 m^2/kg /3/.

2.5. Solid rocket motor retro firings

Two major updates were performed on the solid rocket motor (SRM) firing list. 45 new known events for the time frame of May 2005 to May 2009 have been included. For the years 1970 to 2005, a new group of firings was included. This group contains retro firings from photo film capsules which were ejected from Russian reconaissance satellites and deorbited using small SRMs. These firings occured at very low altitudes below 300 to 400 km so that almost no slag or dust from these events is in orbit today. These events were however detected by the Long Duration Exposure Facility (LDEF) which was in orbit between 1984 and 1989. Results have been previously published by Stabroth /14, 15/.

3. Historical Population before 2005

The current section takes a look at the changes between the MASTER-2005 and MASTER-2009 representations of the historical population since the beginning of man's utilization of space in 1957 up to 2005. An emphasis is put on object diameters larger than 1 mm. For object sizes larger than 1 mm, the time evolution of the spatial object densities for LEO altitudes between 186 and 2186 km is shown in Figure 1. Paint flakes and SRM-Dust do not contribute to these size ranges and are not shown here.

Explosions. Minor changes in the evolution of the explosion fragments are visible in the 1960s, the early 1980s and after the year 2000. The first feature represents the fragmentation of the first recorded space explosion ever of the Thor Ablestar rocket body 1961-015C. During the population validation for MASTER-2009, it was decided to reduce the number of large fragments of this event to

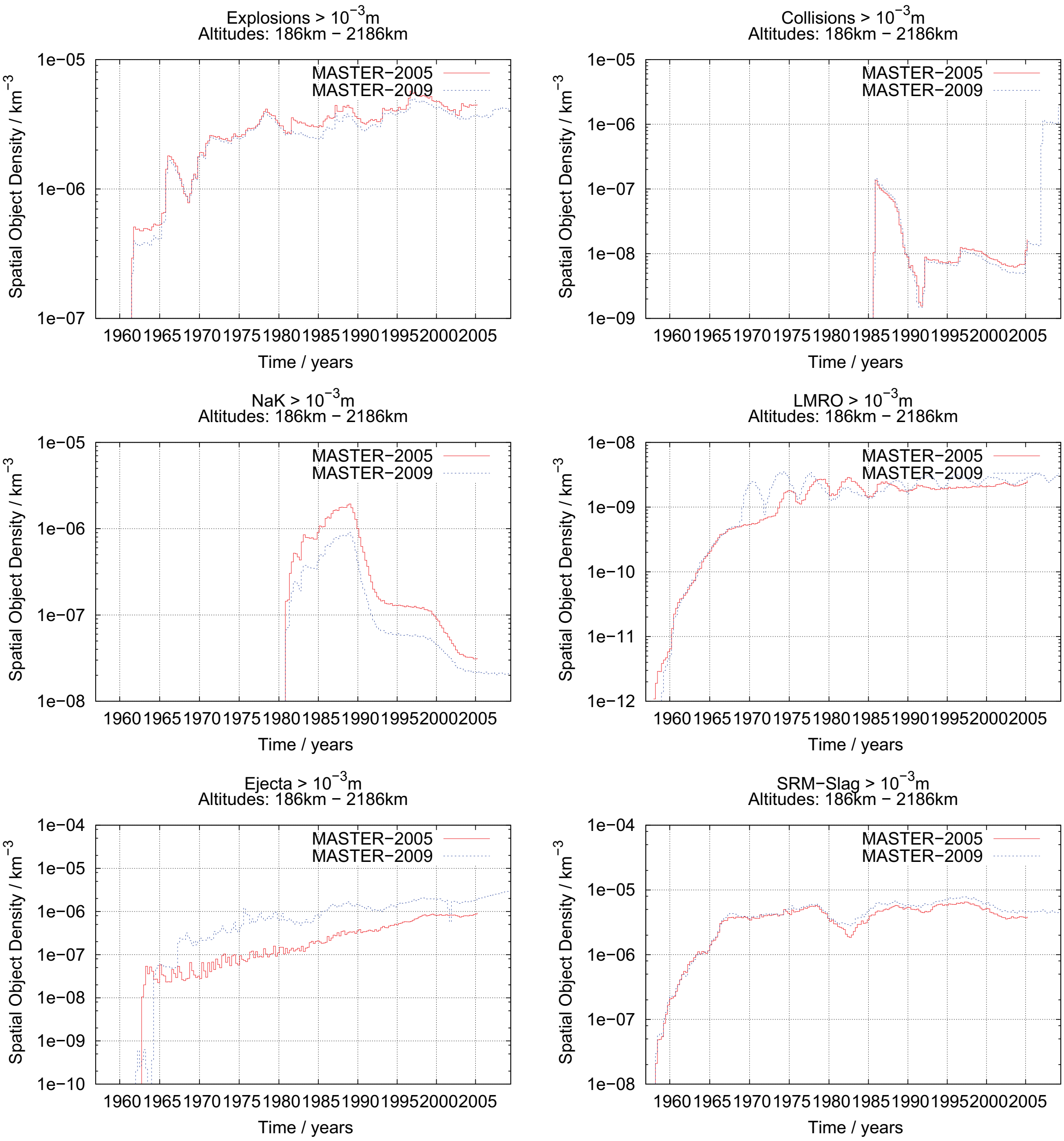

Figure 1: Spatial object densities vs. time for LEO altitude region.

better match measurement results from debris observation campaigns with the Tracking and Imaging Radar TIRA from the Fraunhofer-FHR (former FGAN). Several other events in the 1980s were reduced in a similar fashion leading to the changed evolution. For the time frame after 2000, artificial events had been introduced in MASTER-2005 to account for detection features near a doppler inclination of 90 degrees. Personal communication with radar experts revealed that the signal-to-noise ratio decreases for doppler inclinations near 90 °. As no additional information could be found to support these features to correspond to actual fragmentation events, it was decided to remove these artificial events again for MASTER-2009.

Collisions. The anti-satellite event of the Feng-Yun satellite in early 2007 is clearly visible here. The spatial object density for objects larger than 1 mm increased by roughly two orders of magnitude. Another slight increase is seen in 2008 after the collision of the Cosmos-2251 and the Iridium-33 satellites. The fragmentation event of the 1989-001H ullage motor in 2003 had been included in the collision population and is now moved to the explosion population. The event occured on a highly eccentric orbit with its apogee altitude near 18,700 km. The resulting alitude dependent change is presented in Figure 2.

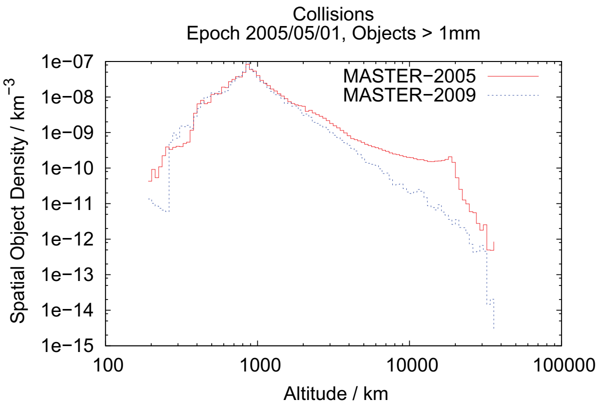

Figure 2: Spatial object densities vs. Altitude.

NaK. The reduction of the total ejected mass from 8 kg to 5.3 kg is most clearly visible for diameters above 1 mm while the density above 1 cm remains almost unchanged. The step like decline of these objects results from the periodically changing atmospheric drag due to the solar cycles.

LMRO. The mean evolution for the launch- and mission related objects remains unchanged from MASTER-2005. The pulsating evolution which is superimposed over the mean trend is produced by the copper needles from the two Westford Needle experiments which were performed in 1961 and 1963. These needles were released at an altitude near 3600 km which is well above the upper limit of the low-earth orbit environment. Due to their small size of around 1 mm and high reflectivity however, they are highly susceptible to solar radiation pressure effects. The eccentricity of their orbits oscillates, bringing the perigee altitude into the LEO region. The increased effect of the solar radiation pressure discussed in Section 2 leads to the more pronounced features visible in Figure 1.

Ejecta. The ejecta population exhibits the same increase over time as the MASTER-2005 environment. Small ballistic parameters for these objects feature a high susceptibility to solar radiation pressure and atmospheric drag. This is evident for instance in the relatively larger time-dependent oscillations seen in Figure 1.

SRM-Slag. The retro firings from the Russian reconnaissance satellites in the 1980s are the only noticeable change in the historical evolution of this source. The plot suggests a reduced use of these SRMs for LEO applications after 2005.

Multi-Layer Insulation. MLI was first detected during observation of the GEO region and during GTO observation campaigns. The derived model for MASTER-2009 simulates the production of these debris objects at all altitudes. The total spatial object density is comparable to that of the LMRO population for 2009 (Figure 3 top). The high inherent area-to-mass ratios of many of these objects results in quick deorbit rates. This is visible especially in the fast reduction of the spatial object density over time after peaks produced by fragmentation events. At the reference epoch of May 1st, 2009, the simulated object population shows a sharp decline towards lower altitudes below the most densily populated region of 900 km. A second lower peak is visible at about 1400 km. The number of in-orbit objects in MEO altitudes surpasses that of the LMRO. The pronounced dip between the 25,000 km circular MEO region and the GEO region at 36,000 km typically visible in all other sources is missing for the MLI due to the high temporal variability of the orbit eccentricity.

Table 1: DELTA mitigation traffic scenarios for MASTER-2009

	Intermediate Migitation - MIT1	Full Mitigation - MIT2
Explosion Traffic	reduced steadily to 5 % by 2020	reduced steadily to 5 % by 2020
SRM Firings	reduction from 100 % in 2020 to 5 % in January 2030	reduction from 100 % in 2020 to 5 % in January 2030
MRO prevention	total prevention after 1 January 2015	total prevention after 1 January 2015
RB Deorbit	–	for perigee < 2000 km, 100 % success rate after 1 January 2015
PL Deorbit	–	for perigee < 2000 km, 100 % success rate after 1 January 2020
RB & PL Reorbit	–	for GEO objects in accordance with IADC guidelines: 100 % success rate after 1 January 2020

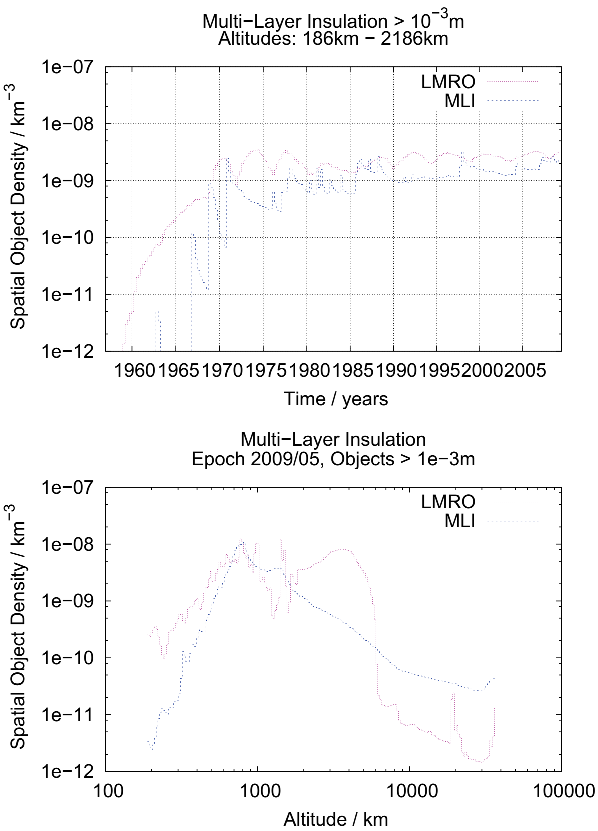

Figure 3: Spatial object densities vs. time and alitude for MLI and LMRO.

4. Future Population

The future evolution of the space debris environment is simulted using ESA's Reference Tool DELTA. The tool was developed by the UK company QinetiQ. It uses extensive launch traffic information with correlation of launchers, rocket bodies and mission related objects to certain payloads. In the course of the current contract all traffic tables were updated. Future population evolution is based on 20 Monte-Carlo runs for which intermediate results are presented here. For further information, the reader is referred to the MASTER-2009 final report which will be published on the MASTER-2009 DVD to be released in autumn 2010.

4.1. Traffic Scenarios

For MASTER-2009, the three future traffic scenarios used in MASTER-2005 were adapted to the new time frame. All three scenarios follow the same launch rate and differ only in the applied debris mitigation definitions. The business-as-usual (BAU) scenario uses no mitigation measures. Table 1 contains the definitions of the two mitigation scenarios.

4.2. Validation of Business-as-Usual Traffic Model

In the following section, the population for the time frame May 2005 to May 2009 will be looked at. Specifically, the predicted population evolution from MASTER-2005 will be compared with the true evolution which has been updated in the

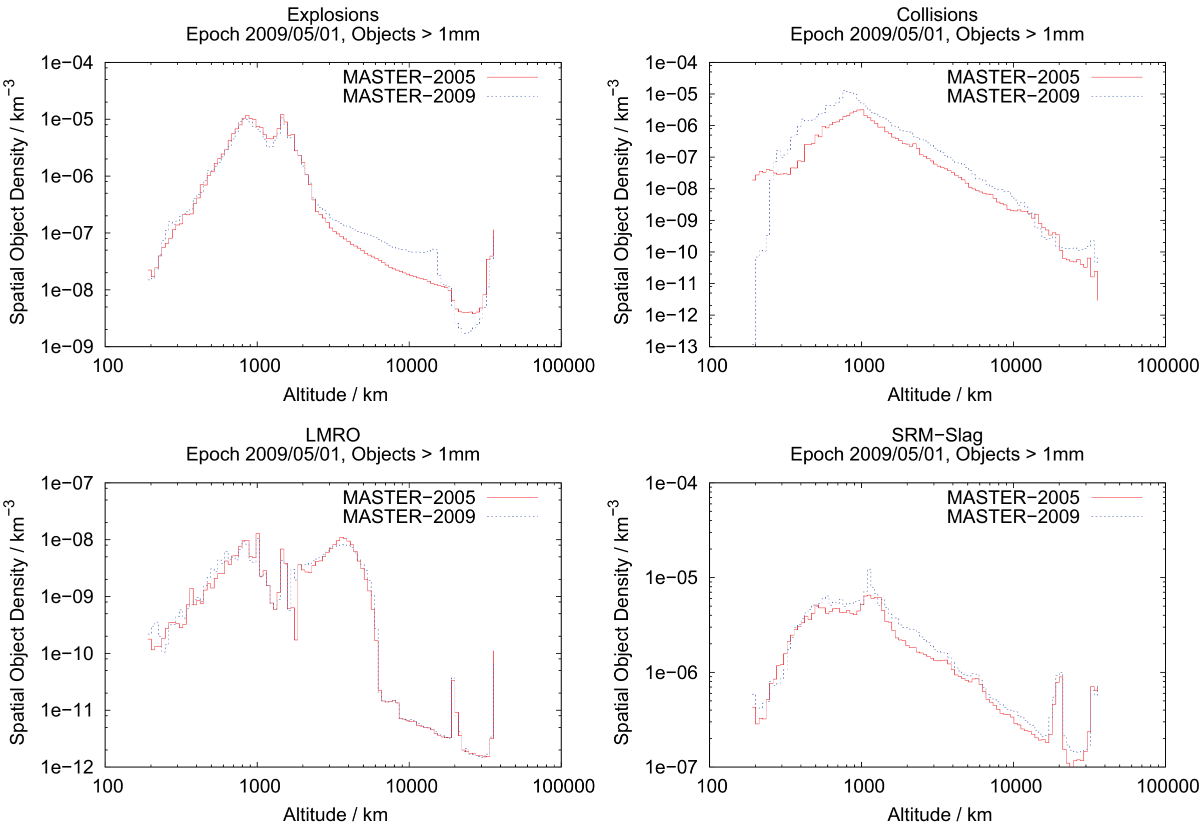

Figure 4: Comparison of MASTER-2005 prediction and MASTER-2009 simulation for May 1st, 2009. Spatial object densities vs. altitude.

MASTER-2009 model. To this end, the debris sources

- explosion fragments
- collision fragments
- launch- and mission related objects and
- solid rocket motor slag

are taken into account. The sodium potassium droplets are not compared, as these rely solely on a historic source without new contributions in the time frame 2005 to 2009. The spatial object densities for all altitudes and objects larger than 1 mm are compared for May 1st, 2009 in Figure 4.

Explosions. The predicted spatial object density around 1,000 km matches the population derived for MASTER-2009 well in all size regimes. The explosion of the Briz-M upper stage in early 2007 lead to the production of a large number of fragments on highly eccentric orbits. The spatial object density between 18,000 and 20,000 km is not effected by the Briz-M fragments and shows a good match between the predicted and true data. The object density between 20,000 and 30,000 km is lower than predicted.

The mass of the Briz-M upper stage was in excess of 11 tons. Most explosions involved objects with significantly lower masses. This specific event represents an exception to common explosion events and cannot be used in the establishment of any business-as-usual scenario. The spatial object density in MEO above the influence altitude of the Briz-M fragments is crucial for determination of the fidelity of the basis for the business-as-usual scenario. As the spatial object

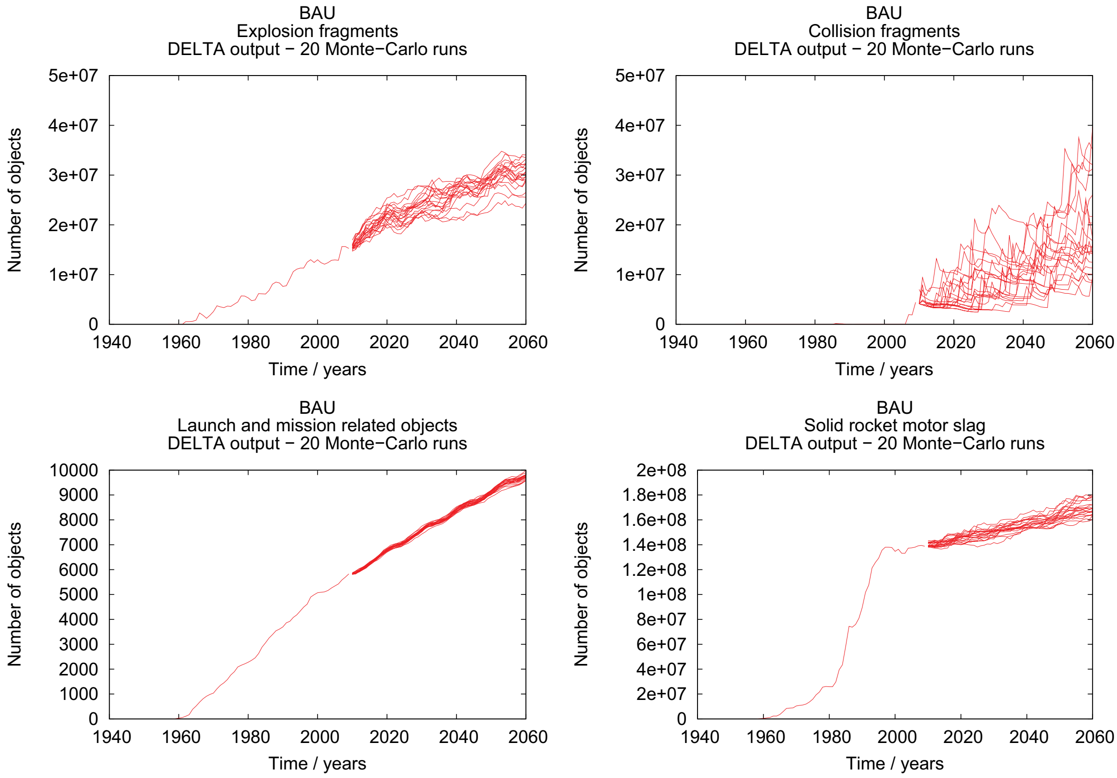

Figure 5: BAU - DELTA population from 20 Monte-Carlo Runs over time.

densities match well in this range, the assumptions for the explosion prediction up to 20,000 km are deemed valid.

Collisions. The collisions are determined by DELTA. The current comparison therefore is performed for purely academic reasons as the results are not used as parameters for the scenario definitions. The largest spatial object density in MASTER-2009 is located at around 800 km altitude; the altitude of the Feng-Yun 1C collision event. In MASTER-2005, the highest density was predicted at slightly above 1000 km alitude.

LMRO. The predicted distribution of launch- and mission related objects match the MASTER-2009 population density well. The basis for the scenario definition used in MASTER-2005 was thus used for the LMRO prediction for MASTER-2009 as well.

SRM-Slag. Above 700 km, the spatial object density of SRM-Slag is higher in MASTER-2009 than in MASTER-2005. This deviation is also present at the epoch May 1st, 2005. The basis for the scenario definition of the business-as-usual scenario is therefore seen as valid and was again used for MASTER-2009.

The performed comparisons show that the method by which the business-as-usual traffic scenario had been defined for MASTER-2005 is sufficient for medium term prediction of the space debris environment. This same methodology was therefore adopted for MASTER-2009. In MASTER-2009 as in MASTER-2005, the projection of the events and launch rates are derived from the eight years preceding the reference epoch (here May 1st, 2009).

4.3. *Business-as-Usual Population Evolution*

Figure 5 shows the results from the 20 Monte-Carlo runs with respect to the total number of an-

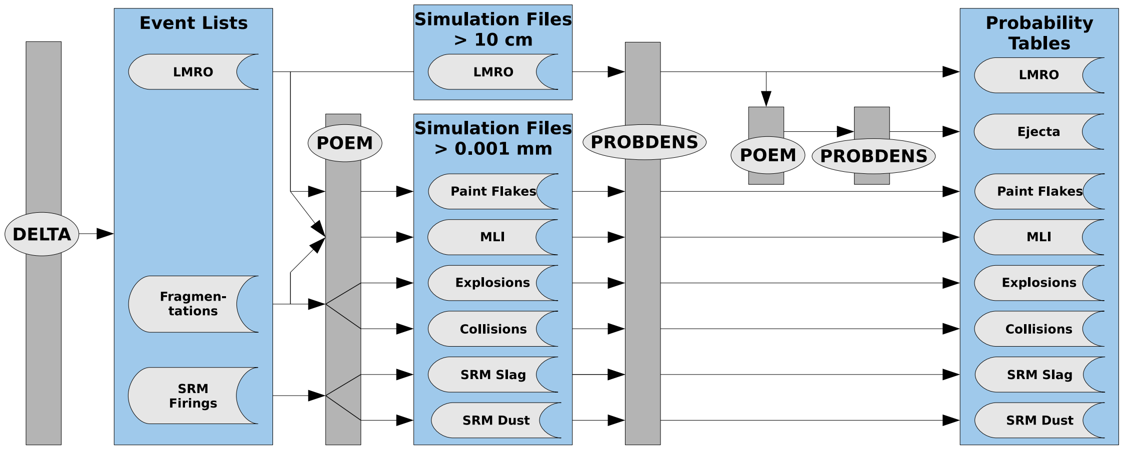

Figure 6: Schematic of the method used for the future sub-millimeter population simulation for MASTER-2009.

nual inorbit objects. The largest spread is obvious in the collision fragments which shows a total spread of up to a factor five. The collisions are simulated in DELTA by calculation of orbit intersections. Fragmentation clouds are created based on collision probability for individual events.

Explosions. For the 20 Monte-Carlo runs, DELTA simulates an annual mean of 5.6 ± 0.4 events including atmospheric breakups. For comparison, in MASTER-2005, 4.5 events were simulated annually which does not include atmospheric breakups.

Collisions. An average of 14.7 ± 4.5 collisions were triggered during the 51 simulation years from 2009 to 2060. In MASTER-2005, 13 collisions were simulated in the BAU scenario. This signifies a slight overall increase. The high standard deviation is also visible in the population growth for the 20 Monte-Carlo runs.

Launch- and Mission Related Objects. On average, 69 payloads are launched per year which does not include constellation payloads. 18 additional constellation payloads were launched on average per year. For the new MASTER release, the constellation launches were seperated from the background traffic to include typical launch patterns for constellations.

Solid Rocket Motor Firings. The simulated annual average of solid rocket motor firings is 12.9. The events are distributed uniformely over the simulation time frame which is apparent in the increase in the SRM particles in Figure 5.

5. Future Sub-Millimeter Population

One requirement for MASTER-2009 was that information on sub-millimeter objects had to be available for the future population. DELTA simulates the space debris environment down to 1 mm. Purely small size debris sources such SRM-Dust, Ejecta or Paint Flakes are not included. Several methods were investigated in order to make sub-millimeter information available. In the end, it was decided to use the event lists produced by DELTA as input for the POEM software which is used to create the historical population. Figure 6 shows the method by which the future population is thus created. The PROBDENS tool creates statistical representations of the population created by POEM. These are required by the MASTER FLUXBROWSER which is also used in POEM to simulate the Ejecta debris.

6. Summary

The MASTER-2009 population has been presented. Changes in the representation of the population up to 2005 due to updates in the simulation process have been discussed. Changes include a reduction in the total ejected mass of Sodium-Potassium coolant during reactor core dismantlement of BuK reactors. The simulation of the small size fragmentation events has been seperated for payloads and rocket bodies to account for differences in material makeup. Additional solid-rocket motor firings were included representing retro firings from photo film capsules which were ejected from Russian reconaissance satellites. Also, a new debris source was added for Multi-Layer Insulation. The method used for the definition of the Business-as-Usual scenario was validated by comparison of the projected population evolution from MASTER-2005 to actual data up to 2009. Intermediate results were presented for the future debris population evolution and the method was outlined by which the future sub-millimeter population are currently being simulated.

Acknowledgment

The work presented in this paper was performed under ESA contract No. 21705/08/D/HK "Maintenance of the ESA MASTER Model." Liability for the results in this paper resides with the authors of this paper.

References

1. **Agapov, V., Molotov, I., Titenko, V.**, *Analysis of the results of the 3 years observations of the GEO belt and the HEO objects by the ISON network*, Proceedings of the 59th International Astronautical Congress, Glasgow, Scotland, 29. September - 03. October 2008, IAC-08-A6.1.2
2. *Database and Information System Characterising Objects in Space (DISCOS)*, Provided by European Space Operations Centre (ESOC), Darmstadt, Germany, http://mas15.esoc.esa.de:9000/
3. **Flegel S.K.,***Modelling the High-Area-to-Mass Ratio Debris Population in GEO*, Studienarbeit at the Institute of Aerospace Systems, June 2006, R-0603-S
4. **Flegel S.K., Scheidemann P., Gelhaus J., Wiedemann C., Vörsmann P., Oswald M., Stabroth S., Klinkrad H., Krag H.,** *The MASTER-2009 Fragmentation Model for the Small Size Regime*, presented at the International Astronautical Congress in Daejon, South Korea, 2009, IAC-09-A6.2.3
5. **P.H. Krisko, Y.-L. Xu, J.N. Opiela, M.J. Matney,** *Material Density Distribution of Small Debris in Earth Orbit,* in: Proceedings of 59th International Astronautical Congress, Glasgow, Scotla
6. **P.H. Krisko, M. Horstman, M.L. Fudge,** *SOCIT4 collisional-breakup test data analysis: With shape and materials characterization,* Advances in Space Research 41 (2008) 1138- 1146, doi:10.1016
7. **McDowell J.**, http://planet4589.org/jcm/jmcdowell.html, accessed February 2010
8. **Oswald M., Stabroth S., Wiedemann C., Wegener P., Martin C., Klinkrad H.,** *Upgrade of the MASTER Model - Final Report*, ESA contract number 18014/03/D/HK(SC), April 26, 2006
9. **Wiedemann C., Flegel S., Johannes G., Klinkrad H., Vörsmann P.,** *Size Distribution of NaK Droplets for MASTER-2009*, published in proceedings of the 5th European Conference on Space Debris, Darmstadt, Germany, 30 March - 2 April 2009, ESA SP-672
10. **Schildknecht, T., Musci, R., Flohrer, T.**, *Properties of the High Area-to-Mass Ratio Space Debris Population at High Altitudes*, Advances in Space Research, Vol. 41, Issue 7, 2008, p. 1039 - 1045, doi:10.1016/j.asr.2007.01.045
11. **Schildknecht, T., Flohrer, T.,Musci R., Jehn, R.**, *Statistical analysis of the ESA optical space debris surveys*, Acta Astronautica 63 (2008), p. 119 - 127, doi: 10.1016/j.actaastro.2007.12.035
12. *Product Bulletin*, Sheldahl® Technical Materials, December 2008, http://www.sheldahl.com
13. *Space Track - The Source for Space Surveillance Data*, Responsibility of United States Strategic Command (USSTRATCOM) since 22 December, 2009, http://www.space-track.org
14. **Stabroth S., Oswald M., Wiedemann C., Klinkrad H., Vörsmann P.,** *Explanation of the "May Swarm" signature in the LDEF IDE impact data*, Aerospace Science and Technology 11 (2007), 253-257, doi:10.1016/j.ast.2007.02.003
15. **Stabroth S.,** *Dust Particle Impacts due to Re-entry Firings of Solid Rocket Motors*, Dissertation, ZLR-Forschungsbericht 2009-06, Shaker Verlag Aachen 2009, ISBN 978-3-8322-8268-4