# FLUX COMPARISON OF MASTER-8 AND ORDEM 3.1 MODELLED SPACE DEBRIS POPULATION

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## ABSTRACT

In this paper, the modelled debris fluxes by ESA's Meteoroid And Space debris Terrestrial Environment Reference (MASTER-8) model and NASA's Orbital Debris Engineering Model (ORDEM) 3.1 are compared. At first, the basic modelling approaches for both models are presented to explain the fundamentally different model philosophies and help the reader to comprehend and interpret the obtained results. Then, the flux results of both models for three different orbits are presented and analysed. They are discussed and set into perspective. A conclusion is drawn at the end of the paper, highlighting the ongoing cooperation of both agencies responsible for their models.

## 1 INTRODUCTION

With ESA's Meteoroid And Space debris Terrestrial Environment Reference (MASTER-8) model [1] and NASA's Orbital Debris Engineering Model (ORDEM) 3.1 [2], the two premier orbital debris engineering models have been officially released. The two models come with significant enhancements and now represent the state-of-the-art orbital debris modelling for their respective agencies. Both models provide the community with estimates of the space debris environment from low Earth orbit (LEO) up to at least geostationary altitude.

Modelling the space debris environment is a complex task and requires a thorough understanding of orbit dynamics, the physical characteristics of debris generating events, and data of sufficient quality for model tuning and validation. Since not all debris objects can be tracked on a regular basis, due to their complex orbits or small size, there is limited data on the space debris environment for some size and altitude regimes. In particular, objects with a diameter between 1 mm and 1 cm cannot be tracked, yet they can cause significant mission-ending damage if they impact operational satellites. Furthermore, detection data for millimetre-sized debris is rare, so it is inherently difficult to validate this diameter range for space debris models. Due to persistent fragmentation events and the growth of launched objects, the risk of collisions is steadily increasing. Space debris models are therefore required to assess the mid-/long-term (i.e., decade time scales) collision risk and evolving orbital debris environment. Engineering models, like MASTER-8 and ORDEM 3.1, provide an interface to assess the condition of the environment as well as the interaction of the space debris environment with satellite missions. Having two independent and fundamentally different space debris models available, it is therefore of great interest to understand how they compare. Differences between the two models point to aspects of space debris modelling that might not be fully understood. They uncover modelling limitations and drive collaborative research to improve our understanding of how to most accurately model the orbital debris environment. Also, they could indicate a range of uncertainty in a specific area, particularly those regions where more data on the orbital debris environment may be needed. Commonality of results indicates that the actual space debris environment is modelled sufficiently well in terms of the validity of flux assessments. Because the threat from space debris is a global issue, converging modelling results benefit global space safety. At the same time, there could be a persistent area of limited knowledge where different

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model estimates might diverge, giving an idea of the potential range in uncertainties.

The goal of this paper is to compare MASTER-8 and ORDEM 3.1, primarily in terms of flux assessments. The comparison will provide an analysis of similarities and differences that lead to an objective assessment on regions where the space debris environment is well-modelled, as well as regions where additional information may be needed.

At first, the general modelling approaches for both models are briefly described. This is followed by a selection and justification of test cases that are used for the simulations. Afterwards the results are presented and discussed, and a conclusion is drawn at the end of the paper.

## 2 APPROACHES FOR POPULATION GENERATION

### 2.1 Modelling approach in MASTER-8

The MASTER population is an event-based simulation of all known events that generate debris and objects that are part of the U.S. Space Surveillance Network (SSN) catalogue, which provides coverage of objects with diameters down to approximately 10 cm in LEO and 1 m in geosynchronous Earth orbit (GEO). Different models are used to simulate the artificial objects and their orbital evolution over time. These models are called “sources” because they assign an origin to each individual object and consist of fragments, solid rocket motor (SRM) slag and dust, Sodium-Potassium (NaK) droplets, paint flakes, ejecta, and Multi-layer Insulation (MLI) objects. The objects from each source are characterized by having individual release mechanisms, as well as orbital distributions, material composition, and size and mass distributions. Dedicated radar and telescope observation data is used to calibrate the model for objects larger than 1 cm in LEO and larger than 10 cm in GEO. For calibrating the small-sized objects, below 1 cm, impact data from returned surfaces are analysed. Because the >1 cm object population is dominated by fragments, the fragmentation event database was updated to include new events, as well as re-evaluate past events. Special attention was drawn to re-evaluating the Fengyun-1C (FY-1C) anti-satellite test from 2007 and Cosmos-Iridium collision event from 2009 since these events have dominated the fragment population because of their severity. After 2009, and as of November 1, 2016, the two largest fragmentations in terms of number of tracked debris are the Briz-M explosion in 2012 and the NOAA-16 explosion in 2015. In total, there are 261 confirmed fragmentations in the database up to November 2016. [1]

The generation process of the historic population, which is valid up to the latest reference epoch (November 1, 2016), follows an iterative procedure consisting of three steps:

1. Object generation
2. Correlation
3. Validation

The MASTER population consists of objects larger than 1 µm. Every object is generated with the Program for Orbital Environment Modelling (POEM) by an event-based approach which means that every object can be linked to a certain event, e.g., a fragmentation, an SRM firing or just a normal launch event. This discrete background population is then transformed into a spatial distribution on a 3-dimensional grid of cells holding the mean residence probability of all crossing objects along with information on their orbital parameters and material properties. This not only allows the calculation of flux onto specified surfaces on an arbitrary orbit for a certain diameter spectrum, but also any kind of geometric information like impact direction, impact velocity, etc.

The object generation (step 1) is subdivided into the individual sources which are: Launch- and mission-related objects, Fragments, NaK droplets, SRM firing remainders, MLI fragments, paint flakes, and ejecta. Each source has its own characteristics in terms of size distribution, preferred orbital regime, material properties, and consequently individual dynamic orbital motions. In certain orbital regimes, distinct sources dominate specific size intervals in terms of numbers, e.g., fragments dominate the 1 cm population in LEO and SRM dust particles dominate the 1 µm population in GEO.

Launch- and mission-related objects refer to all payloads and rocket upper stages, as well as any nominally released debris, with no discrimination made whether satellites are operating nominally or considered defunct. These objects are taken from the Two-Line Element (TLE) catalogue. Fragments are modelled by using a modified version of the NASA Standard Satellite Breakup Model (SSBM) [3], where the overall size distribution is scaled to best match the number of catalogued fragments. Based on fragmentation type, mass, and object type, a diameter distribution is used to sample distinct fragments. In the MASTER population, fragments are generated with diameters down to 1 µm. Mass density is drawn from a diameter-dependent probability density distribution that centres around 2.7 g/cm³, with a maximum cut-off at 4.0 g/cm³ and decreasing densities for large diameters [1]. Fragmentations are subdivided into explosions and collisions which yield different underlying diameter distributions. Fragments have the highest number contribution for objects larger than 1 cm in general and dominate the 1 cm environment in LEO. NaK droplets originate from nuclear reactor (Buk) core ejections of the Radar Ocean Reconnaissance Satellite (RORSAT) satellites as well as leakage events from TOPAZ reactors.

They are modelled based on the Rosin-Rammler equation under consideration of liquid dynamics. Due to their origin, NaK droplets are only present on a narrow inclination band of approximately 65° in altitudes between 900 km and 950 km and contribute to the 1 cm to 5 cm diameter regime. They inherit a constant material density of 0.9 g/cm³ and exhibit diameters of up to a few centimetres. Objects originating from SRM firings can further be subdivided between dust and slag. Dust refers to micrometre sized aluminium oxide ($Al_2O_3$) particles as part of exhaust gas of solid-propellant rocket motors. The motors usually contain around 18% aluminium oxide of the total propellant mass. The objects are modelled based on an empirical function fitted against experimental data derived from the Payload Assist Module (PAM-A) and ground-/in-flight tests of different motors by the Institute of Space and Astronautical Science (ISAS). Dust particles have a mean material density of 3.5 g/cm³ and dominate the LEO population for objects larger than 1 µm. Slag particles refer to liner material residuals and exhibit significantly larger diameters than dust particles while having slightly lower mean material density of 2.7 g/cm³ and a maximum diameter of a few centimetres. Multi-layer insulation fragments refer to High Area-to-Mass Ratio (HAMR) objects that can be observed mainly in geostationary altitudes. These objects consist of thin insulation material originating from fragmentations and exhibit Area-to-Mass ratio (AMR) up to 100 m²/kg. Their size can exceed 10 cm which is especially visible in the GEO regime. Paint flakes are pieces of paint, released as a result of surface degradation, from payloads and rocket stages that have been in orbit for an extended period. They are generated based on an interaction of the space environment with the outer surfaces of those satellites. The driving factors can be summarized as atomic oxygen, thermal cycling and ultraviolet radiation. The size distribution ranges from 2 µm to 200 µm and their material density is set to 4.7 g/cm³, the mean value of zinc (7.1 g/cm³), titanium (4.5 g/cm³), and aluminium (2.7 g/cm³). One of the most complex modelling approaches for a debris source is for ejecta. They refer to feedback objects that are generated when present debris impacts satellite surfaces, releasing new objects. Ejecta are generated from 1 mm down to 1 µm with a density of 2.5 g/cm³ for brittle targets and 4.7 g/cm³ for ductile targets.

Having generated the objects of all source types, step 2 of the population generation iteration is carried out: the correlation. With the TLE catalogue providing most of the on-orbit objects with diameter larger than approximately 10 cm, the simulated objects need to be correlated to not artificially increase the total number of objects. The correlation takes simulated objects larger than 1 cm and correlates it to the TLE background population. After this step, there are still objects in the population that are larger than 10 cm, in addition to the TLE objects. Because the TLE catalogue only contains approximately 60% of the actual objects in space [4], the simulated objects try to fill this apparent gap.

The extensive validation procedure (step 3) uses a set of available measurement data to calibrate the model to the data. The validation data consists of dedicated space debris observation campaigns conducted by the Tracking and Imaging Radar (TIRA), the European Incoherent Scatter Radar (EISCAT) and ESA's Space Debris Telescope (SDT). The beampark experiments of TIRA provide measurement data on objects with diameters down to 1 cm in LEO. For MASTER-8, over 250 hours of observation time was considered. The EISCAT radar also provides measurement data on 1 cm sized objects in LEO, and 2424 hours of observation data was used during the validation of MASTER-8. For the GEO regime, the SDT provides magnitude measurements of objects larger than approximately 10 cm. The SDT provides data from annual observation campaigns with a couple of nights per campaign. In addition, analysis of impact features on the Long Duration Exposure Facility (LDEF), the Hubble Space Telescope (HST) and the European Retrieval Carrier (EuReCa) yield validation data for the small sized debris, i.e., objects with diameters below 1 mm, in the LEO region. LDEF was exposed to the debris environment for almost six years and yielded impact data, including impact impulse measurement data and partial chemical analysis of the impacting objects. Impact data on EuReCa are used for validation with an on-orbit duration of 10 months. A large amount of impact data was gathered from the solar panels of the HST. During two Service Missions (SM) 1 and 3B, impact data of almost 12 years could be acquired. During the calibration phase, the model parameters are adjusted so that the model output matches the validation data as close as possible. One of the most important parameters is the fragmentation event history where each fragmentation is modelled based on the reported number of detected objects, the majority of which are usually catalogued.

When the validation cycle is finished, the population is transformed into all cells of the 3-dimensional grid around Earth, as stated at the beginning of this section. The flux on a specific target orbit is obtained by multiplying the spatial density of objects in each crossed cell with the mean target orbit velocity in the cell.

## 2.2 Modelling approach in ORDEM 3.1

The fundamental capability of ORDEM is providing fluxes (number per $m^2$ per year) of debris for a given year. Fluxes are calculated as a function of cumulative size, meaning the fluxes are presented for a given size and larger. This is based on the risk assessment view that if an impact from a debris particle of a given size will critically damage a spacecraft component, so will larger debris. Eleven half-decade size thresholds, or fiducial points, are considered in calculating and presenting the cumulative fluxes: 10 µm, 31.6 µm, 100 µm, 316 µm, 1 mm, 3.16 mm, 1 cm, 3.16 cm, 10 cm, 31.6 cm, and 1 m. Fluxes at points between these are calculated by interpolation.

Fluxes are modelled for objects greater than 10 µm in LEO (altitudes below 2000 km) and greater than 10 cm in GEO. Note that while geosynchronous transfer orbit (GTO) and GEO orbits physically overlap, the dynamics (including perturbation forces and impact velocities) as well as the physical size and structure of satellites within the GEO region are unique. Thus, ORDEM provides debris fluxes in GEO only for sizes of 10 cm and larger. Any fluxes below 10 cm at altitudes above LEO are due solely to high-eccentricity debris sources.

ORDEM 3.1, like ORDEM 3.0 [5], includes a breakdown of debris into material density categories to help characterize the potential debris risk posed to spacecraft. Five populations are modelled and identified in the output flux breakdown, including intact objects (spacecraft and rocket bodies); low-density (LD, 1.4 g/cm³) fragments; medium-density (MD, 2.8 g/cm³) fragments and degradation debris; high-density (HD, 7.9 g/cm³) fragments and degradation debris; and NaK coolant droplets (0.9 g/cm³) from the RORSAT class of spacecraft. Note while these material density categories represent a range of values, the specific values indicated here are those used for risk assessments.

ORDEM is a data-driven model, using measurement data from *in situ* and ground-based radar and optical sources to scale initial reference models of the orbital debris environment. The NASA LEO-to-GEO Environment Debris (LEGEND) model [6] provides the baseline for most sub-populations in ORDEM. This reference population consists of many orbits with specified orbital elements, the number of objects on each orbit, as well as physical characteristics such as size (characteristic length), mass, area-to-mass ratio, and material-type assignment for each object. The historical population is based on a database of known launches, breakups, and manoeuvres, as maintained internally by the NASA Orbital Debris Program Office (ODPO). Fragments from confirmed historical fragmentation events are created using a special version of the NASA SSBM, which extends the standard model to incorporate material density assignments for fragments less than 10 cm based on percentages derived from analysis of fragments generated by the Satellite Orbital Debris Characterization Impact Test (SOCIT) series [7] as well as known satellite material breakdowns [8]. In LEO, LEGEND models fragments down to 1 mm in diameter, and assigns material densities according to fragment size and area-to-mass ratio. In GEO, LEGEND models fragments down to 10 cm, and assigns MD designations to all fragments. For the future projection in ORDEM 3.1 (2016 through 2050), objects were added to the population assuming a repeat of the previous 8-year launch traffic cycle and a post-mission disposal success rate of 90% for rocket bodies and spacecraft. Future collisions and explosions were modelled statistically, with collisions between objects greater than 10 cm modelled according to the "cube" collision assessment algorithm in LEGEND [9].

The initial LEGEND-generated LEO populations 1 mm and larger in ORDEM 3.1 were scaled using 2013–2015 data from the Haystack Ultra-wideband Satellite Imaging Radar (HUSIR), operated by the Massachusetts Institute of Technology Lincoln Laboratory, which provides data for LEO debris down to approximately 5.5 mm below 1000 km altitude. Several special populations of objects were modelled separately in ORDEM 3.1. These special populations are designated by criteria such as unique cloud attributes, a notable release mechanism, anomalous or significant production of fragments, or lack of a readily identifiable source or production mechanism. These populations were scaled statistically based on comparisons to the HUSIR data and include 10 customized LEO breakup events, the major breakup clouds from the FY-1C anti-satellite test and the Iridium 33/Cosmos 2251 accidental collision, debris from shedding events by the SNAPSHOT vehicle and Transit series of spacecraft, and the NaK droplets that were released from RORSATs.

The ten breakups are specific historical breakup events that were identified as requiring custom adjustments to the nominal breakup model, based on comparisons to HUSIR data, and were assigned size-dependent scale factors to adjust the overall number and the slope of the cumulative size distribution of fragments smaller than 10 cm. Comparisons of the major breakup clouds of FY-1C, Iridium 33, and Cosmos 2251 to HUSIR data led to scaling the overall number of fragments and incorporating momentum transfer effects. In addition, comparisons to the HUSIR 2013–2015 data, which represent the state of the clouds after nearly a full solar cycle, showed that the fragments for these breakups, in particular Iridium 33, appeared to be decaying at a faster rate than predicted by the models. Enhancements were made to the area-to-mass ratios of debris in these clouds to capture this behaviour. The SNAPSHOT/Transit shedding events were initially modelled using the NASA SSBM with a maximum separation velocity of 5 m/s, and final modelled clouds were developed using a Bayesian approach [10]. The NaK population – the only special population explicitly identified in the ORDEM output – was revised for ORDEM 3.1 to be in steady state, based on analysis of the latest available HUSIR data [11]. The LEO populations were validated against independent 2016–2017 datasets from HUSIR as well as the Goldstone Solar System Radar, which provides a unique capability to detect orbital debris population sizes down to an approximate size of 3 mm for altitudes less than 1000 km.

LEO degradation debris less than approximately 3 mm in ORDEM 3.1 were scaled using data from impacts to the

U.S. Space Transportation System (STS) orbiter vehicle (i.e., the Space Shuttle), as archived by NASA's Hypervelocity Impact Technology (HVIT) group. Data on impacts to the shuttle windows and radiators from STS missions 71 through 133 (1995–2011) were used for scaling an initial small particle degradation model. The initial production model produces a size-dependent number of particles from 10 µm to 3 mm, proportional to the surface area of the intact parent object, which are released with zero delta velocity. Both MD and HD particles are produced from each parent object, though the production rates for each density family were scaled separately according to the number of each type of impactor observed based on chemical analysis of the impact craters. The predicted impact rate of these modelled particles on the STS for each mission (including year, epoch, and spacecraft orientation) was computed, and the number of predicted damage features of various sizes was calculated using empirical damage equations [12]. A similar analysis was used for ORDEM 3.0, but for ORDEM 3.1, the analysis was expanded so that each STS mission and each window and radiator element was fitted independently to better preserve altitude and directionality effects. The degradation model populations were validated using new data from impacts to the HST, specifically the MLI cover on HST's Bay 5 (exposure time covering 1990–2009) and the Wide Field Planetary Camera 2 (WFPC-2) radiator (exposure time covering 1993–2009).

For the GEO region, the population of objects smaller than the SSN threshold (approximately 1 m) was characterized using data from Michigan Orbital DEbris Survey Telescope (MODEST) observation campaigns in 2004–2006 and 2007–2009. Several new analysis techniques were employed in building the GEO component of ORDEM 3.1, including a filter based on the angle between the orbital plane and the stable Laplace plane to extract objects most likely to be GEO fragmentation debris. In addition, because objects detected by MODEST that are not correlated to the TLE catalogue are assigned orbital elements based on a circular orbit assumption, a new approach was developed to assign non-circular orbits to the fragmentation debris observed by MODEST, based on correlations determined from modelled GEO breakups. During validation of the ORDEM 3.1 GEO population using an additional MODEST dataset covering 2013–2014, differences identified between the model and data led to the inclusion of two simulated GEO breakups with breakup time and orbital parameters assigned to best match the data.

## 3 SIMULATION CASES

To compare both models, a set of simulation cases was defined that covers a broad spectrum of the modelled debris population (Tab. 1).

The sun-synchronous orbit (SSO) case has been selected to compare the model outputs in the most critical region of space, i.e., with the highest accumulation of objects. Results for the International Space Station (ISS) orbit are intended to inform the statistical risk for ISS operations from the ESA and NASA perspectives. The GTO simulation case has been selected to cover all altitudes from LEO up to GEO.

*Table 1: Simulation cases identified for the flux evaluations.*

| | **#1 SSO** | **#2 ISS Orbit** | **#3 GTO** |
|---|---|---|---|
| **Semi-major axis** | 7171 km | 6771 km | 24 000 km |
| **Eccentricity** | 0.0001 | 0.0001 | 0.73 |
| **Inclination** | 98° | 51.6° | 28.5° |
| **Argument of perigee (ω)** | 0° | 0° | 0° |
| **Right ascension of the ascending node (Ω)** | 0° | 0° | 0° |

In addition to the main flux analyses, spatial density evaluations for the LEO regime (200 – 2000 km) are performed to further analyse the two models. Results are obtained for diameter thresholds of 1 mm, 3.16 mm and 1 cm.

All simulations are performed for the year 2016, which is the most recent historic reference population for MASTER-8 and the first year of the future projection for ORDEM 3.1. All simulations assume a spherical target geometry, i.e., the flux is integrated over all directions.

## 4 RESULTS AND DISCUSSION

This section directly compares the results of all simulation cases for both MASTER-8 and ORDEM 3.1. Note that MASTER-8 outputs cumulative fluxes for diameters between 1 µm and 100 m, while ORDEM 3.1 outputs cumulative fluxes for diameters from 10 µm to 1 m. Having two fundamentally different models, deviations in results are expected. Still, when the difference in results appear to be within reasonable margins, the common assessment can be considered to describe the actual space debris environment. At the end, each model provides its agency's best estimate of the orbital debris environment. One model may be more accurate in one regime while the other may be more accurate in another, and it is expected that the truth lies somewhere in between.

The results of the first simulation case (sun-synchronous orbit) are shown in Fig. 1. At a diameter of 1 m, the flux results of each model are almost identical. In LEO, most objects with such a large diameter are tracked and hardly any additional simulated objects are introduced by either model. Down to approximately 4 mm, both models show slightly different results, still less than an order of magnitude, with ORDEM 3.1 showing lower flux. At 1 cm, a critical diameter threshold for collision risk estimations, MASTER-8 indicates a flux which is higher by a factor of 2.3. At around 2 mm, both models yield the same result, following ORDEM 3.1 with a higher flux down to 10 µm. Modelling the sub-millimetre diameter regime is complex and relies on sparse data against which to calibrate models. Still, both MASTER-8 and ORDEM 3.1 show a consistent trend of levelling off for the flux evolution towards the micrometre regime. However, ORDEM 3.1 shows a flux almost 2 magnitudes higher than MASTER-8.

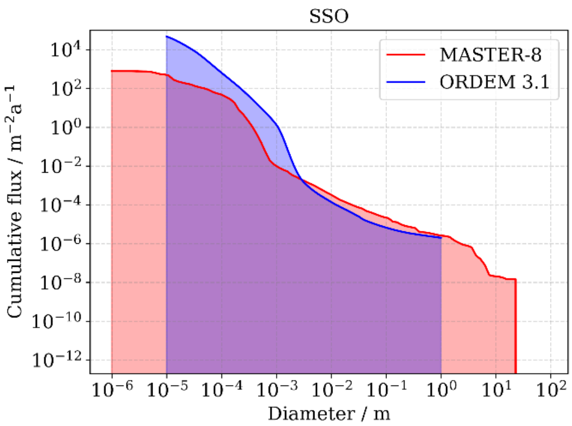


*Figure 1. Cumulative total flux for a sun-synchronous orbit at 800 km altitude.*

The flux breakdown by model sub-population provides some insight into the underlying flux behaviour. The MASTER-8 source populations are shown in Fig. 2, and the ORDEM 3.1 flux breakdown by material density is shown in Fig. 3. Note “M” represents MASTER and “O” represents ORDEM in Fig. 2 and 3, respectively. The sub-populations for MASTER-8 shown in Fig. 2 are explosion fragments (“EXPL”), collision fragments (“COLL”), launch- and mission-related objects (“LMRO”), NaK, SRM slag (“SRMS”), SRM dust (“SRMD”), paint flakes (“PAFL”), ejecta (“EJEC”), and MLI. Fig. 3 shows the breakdown by the five density families for ORDEM 3.1: NaK, intact objects (“IN”), LD, MD, and HD. Naturally, the fluxes greater than approximately 10 cm are dominated by the intact object (launched payloads and upper stage) population. In MASTER-8, the main contribution in the shown sub-millimetre regime is the ejecta population (M/EJEC curve in Fig. 2). It is the dominant source on the SSO from 1 mm down to 10 µm. Below 10 µm, the SRM dust particle (M/SRMD in Fig. 2) contribution shapes the flux result. The ORDEM 3.1 MD population (O/MD curve in Fig. 3) dominates for sizes smaller than approximately 500 µm and larger than approximately 1.8 mm, with the main contribution coming from the HD population (O/HD curve in Fig. 3) for sizes in between. The behaviour of the HD population leads to the bend in the ORDEM 3.1 curve around 1 mm. Between approximately 5 mm and 2 cm, the NaK population rivals the HD population. The LD population is a minor contribution.

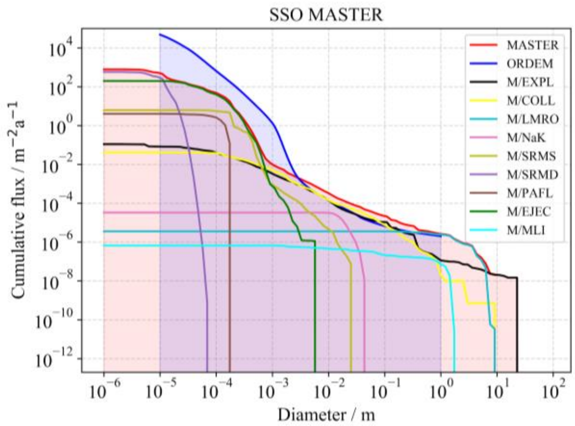


*Figure 2. MASTER-8 plot with source population breakdown for a sun-synchronous orbit at 800 km altitude.*

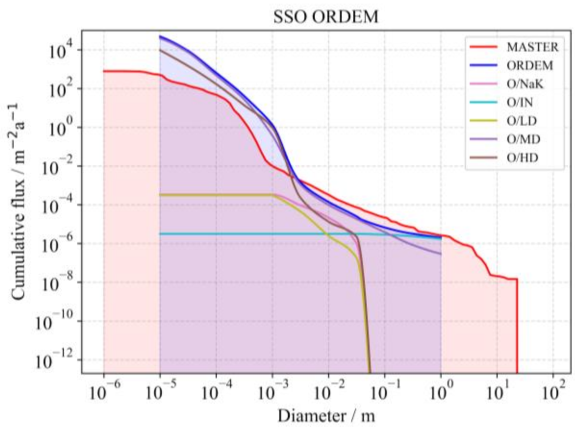


*Figure 3. ORDEM 3.1 material density population fluxes for a sun-synchronous orbit at 800 km altitude.*

The result for the second simulation case (ISS Orbit) is shown in Fig. 4. This case shows the same features as for the SSO simulation case. However, MASTER-8 shows a slightly higher flux at 1 m than ORDEM 3.1. There is a consistent trend from 1 m down to approximately 2 mm almost maintaining the same logarithmic offset as at 1 m. Down to 10 µm, the flux obtained by ORDEM 3.1 exceeds MASTER-8 results consistently, with up to 2.5 orders of magnitude at 10 µm. With ORDEM 3.1 showing a continuous logarithmic diameter distribution for objects smaller than 3 mm, MASTER-8 shows a step-like behaviour with three steps at around 500 µm, 200 µm, and 10 µm. These are due to individual source contributions from paint flakes, SRM slag, and SRM dust. Each source has its own orbital dynamics because of the area-to-mass ratio of individual objects. For a nominal ISS orbit at around 400 km altitude, atmospheric drag plays a major role in the number evolution of the objects which leads to different re-entry behaviours of the different sources. Combined with individual release mechanisms for each source, the present step-like pattern is as shown. For ORDEM 3.1, similar to the SSO case, MD dominates for sizes smaller than approximately 400 µm and larger than approximately 1.8 mm, with the HD population dominating in between and driving the bend in the ORDEM 3.1 curve around 1 mm.

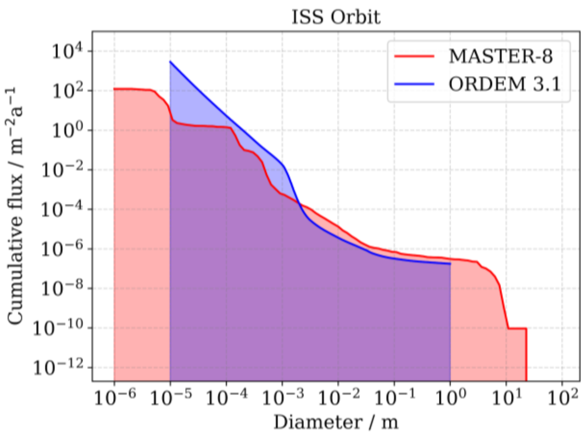


*Figure 4. Cumulative total flux for a nominal ISS orbit.*

The result for the third and last simulation case (GTO) is shown in Fig. 5. At a diameter of 1 m, the flux results of each model are almost identical. Similar to the SSO simulation case, both models show slightly different results down to approximately 2 mm, with ORDEM 3.1 showing lower flux. At the 1 cm threshold, MASTER-8 indicates a flux which is higher by a factor of 3. Below 2 mm and down to 10 µm, ORDEM 3.1 flux exceeds the MASTER-8 flux between a factor of 2 to 10. The two strong slopes in the MASTER-8 flux between 1 mm and 100 µm are predominantly due to SRM slag objects. Between 100 µm and 10 µm, a superposition of SRM slag and ejecta dominates the flux. Below 10 µm, SRM dust is the dominant source of objects. As with the SSO and ISS cases, the ORDEM 3.1 flux is driven by the MD population for sizes smaller than approximately 500 µm and larger than approximately 1.8 mm, with HD the main contribution in between.

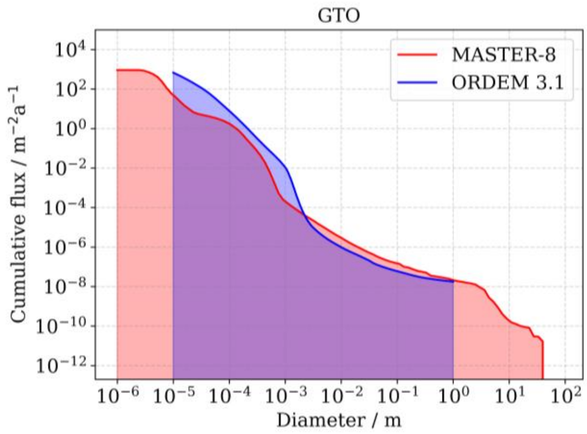


*Figure 5. Cumulative total flux for a typical GTO with an apogee altitude of 35 149 km and a perigee altitude of 109 km.*

For further analysis, spatial density spectra provided by MASTER-8 and ORDEM 3.1 are presented. Figs. 6, 7, and 8 show the spatial density for objects greater than 1 mm, 3.16 mm, and 1 cm, respectively, in LEO. As expected from the flux results of LEO orbits, MASTER-8 shows slightly higher spatial densities at 3.16 mm and 1 cm. This may be partly due to the reanalysis of the major breakup clouds for ORDEM 3.1, which led to enhancements to the area-to-mass ratios of debris in these clouds to capture the faster apparent decay rates of the fragments. At 1 mm, ORDEM 3.1 is higher by up to 2 orders of magnitude. The ORDEM 3.1 millimetre-size population was scaled to fit data from impacts to the STS radiators and windows, while the populations greater than approximately 5 mm were scaled to match the HUSIR data. This leads to the steeper slope in fluxes from approximately 2 mm down to 1 mm and the larger spatial densities in this size regime.

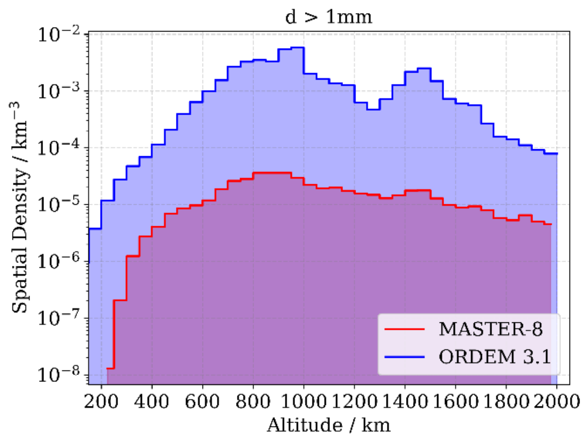


*Figure 6. Spatial density in LEO for objects with a diameter larger than 1 mm.*

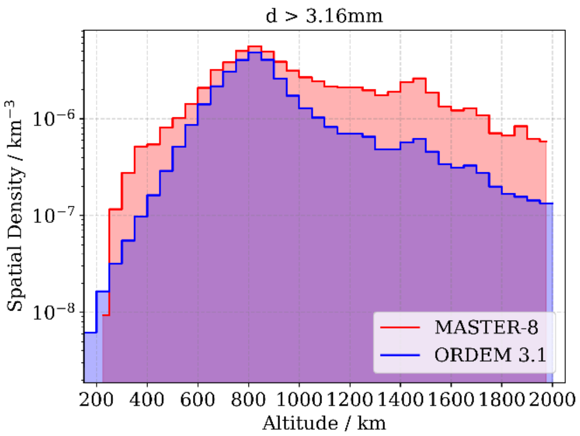


*Figure 7. Spatial density in LEO for objects with a diameter larger than 3.16 mm.*

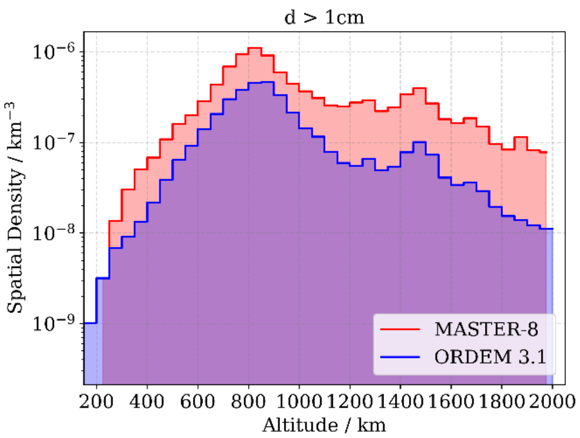


*Figure 8. Spatial density in LEO for objects with a diameter larger than 1 cm.*

To better understand differences and similarities between the models, a comparison to data on impacts to the HST Bay 5 MLI and WFPC-2 radiator is also presented in Fig. 9. This data was used for ORDEM 3.1 validation and represents the newest-available in situ data from the HST altitude. Note that MLI impacts have not yet been analysed to characterize trace residues and assess impactors as micrometeoroid (MM) or OD. Thus, the comparison is presented against a total (MM + OD) environment, with the MM component modelled by the NASA Meteoroid Environment Model Release 2.0 (MEM R2). The exposure time of the HST Bay 5 MLI ranged from 1990 to 2009, so the MASTER-8 and ORDEM 3.1 fluxes are presented as the average of the HST average annual orbits over that time. Since the MLI impacts have not yet been characterized, the MLI curve presented is an average of two scenarios, assuming all impactors as either MD (nominal material density 2.8 g/cm³) or HD (nominal material density 7.9 g/cm³) in interpreting particle diameter from the impact feature size. The uncertainties in the particle diameters span the range in uncertainties from the MD and HD assumptions. The limiting size of the MLI impactors is based on the transition zone from penetrations to craters. Note that the particle size interpretation for the MLI impacts is based on laboratory impact tests conducted using large particles (much greater than the MLI thickness), and the results were extended to all size impactors, with the assumption that the transition zone and penetration behaviour is similar to that of aluminium plates. At the time of ORDEM 3.1 validation, 11 WFPC-2 radiator impacts were assessed, and impactors characterized as MM or OD, with corresponding material density assessments, and those are accounted for in the presented particle diameters. MASTER-8 and ORDEM 3.1 both show very good agreement to the data where the data is most complete: approximately 100–300 µm. As with the flux and spatial density results, the difference between the models grows where the data is lacking, in particular near 1 mm. Near 1 mm, the MASTER-8 + MEM R2 curve is close to the MEM R2 curve, indicating that the MASTER-8 debris flux is lower than the modelled micrometeoroid flux for these sizes. In contrast, the ORDEM 3.1 debris flux is significantly higher at these sizes.

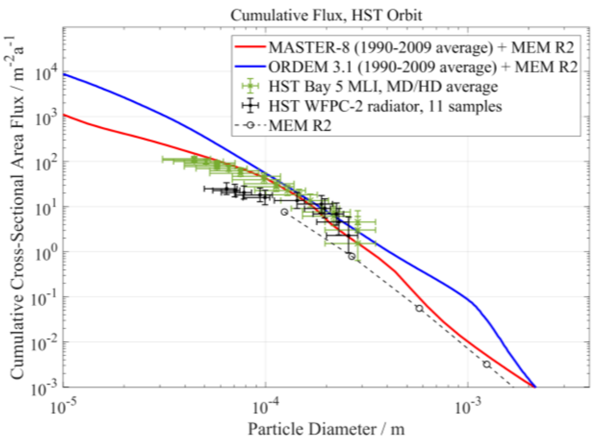


*Figure 9. Comparison of the cumulative cross-sectional area flux vs size between MASTER-8, ORDEM 3.1, and impact data from the HST Bay 5 MLI and WFPC-2 radiator. The MASTER and ORDEM curves include the meteoroid flux estimates from the MEM R2 model. The MLI data points represent an average from assuming all impactors as either MD or HD. The MEM R2 model results are also shown for reference.*

## 5 CONCLUSION

Collaborative efforts between ESA and NASA have been ongoing to assess similarities and differences in the models used to characterize the evolving space debris environment. This study serves as the first cooperative effort to compare and investigate differences in the modelling approach and resulting debris fluxes of the two premier orbital debris engineering models, MASTER-8 and ORDEM 3.1. At a high level, these models are similar, both in function and in development. Modelling the debris populations begins with building environments of intact objects and fragmentation, anomalous, and degradation debris based on supporting models and data. There are also distinct differences between the models. MASTER-8 models populations by source (fragments, SRM slag and dust, NaK droplets, paint flakes, ejecta, and MLI fragments). ORDEM 3.1 also uses a breakdown by source (intacts, fragmentation debris, degradation debris, and NaK) to build the underlying populations, however the model outputs flux by categories of low-density, medium-density, high-density, NaK, and intacts.

While there are some similarities between these underlying populations (for example, both models include a distinct NaK component), a direct comparison of the source models is not immediately possible from the model output. Nevertheless, comparing the superposition of all sub-populations allows for a direct comparison and an assessment of the common view of the space debris environment. The comparisons presented herein are similar to comparisons done between the previous versions of both models, MASTER-2009 and ORDEM 3.0 [13]. This is expected, as the new versions of both models are fundamentally the same as the previous versions, while utilizing updated datasets for building and calibrating debris populations. The regions of similarities and differences between the models identify critical orbit and size regimes where there are currently insufficient measurements. Of note, the agreement between the models is best where there is good data on the orbital debris environment, as evidenced by the comparison of the models to the HST MLI and WFPC-2 impact data. There are also clear differences in the flux estimates by the two models mainly in orbit and size regimes that are only poorly covered by underlying measurement data, particularly in the critical millimetre size range and at SSO altitudes. These comparisons create incentives to collect measurement data in the identified target orbits and size regimes.

Orbital debris is a global issue, so collaborative international studies, as prepared for this paper, will continue in the future to improve our understanding of the orbital debris environment.

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