RECENT DEVELOPMENTS IN SPACE DEBRIS ENVIRONMENT MODELLING, VERIFICATION AND VALIDATION WITH MASTER

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ABSTRACT

The MASTER (Meteoroid And Space debris Terrestrial Environment Reference) model is being developed by ESA (European Space Agency) and needs to be continuously maintained due to the dynamic nature of the space debris environment. The most recent version is MASTER-8 and it was released in March 2019. In this paper, it is shown how the model is being developed and the way the individual source models are verified and validated. This includes the revision of past breakup events, the addition and calibration of new events and the addition of an entirely new model to consider NaK leakage events. The approach to derive flux uncertainties in the model is described. An important aspect for many mission designs is MASTER's capability to provide flux projections for future dates. The current model assumptions are explained and potential improvements in that direction are outlined. Finally, an outlook will be provided on how MASTER is envisioned to become part of ESA's Debris Mitigation Facility (DMF).

Keywords: MASTER; Space debris; Modelling.

1. INTRODUCTION

One week after the successful orbit insertion of the second batch of 60 Starlink satellites, the train of satellites, resembling pearls on a string against the night sky and observed by many people with the naked eye, crossed the field-of-view of the Cerro Tololo Inter-American Observatory's (CTIO) survey camera DECam. The emotionally moving tweet by Clara Martínez-Vázquez on November 18, 2019[1] went viral, showing the exposure with 19 bright white lines correlated with the Starlink transit. The ensued public debate on the problem of light pollution was inextricably linked to the space debris problem and many questions have been raised. On many levels symbolic of the NewSpace era, the Starlink constellation not only contributed to literally visualise the problem, it also puts additional pressure on the already heavily congested low-Earth Orbit (LEO) and raises many new questions. Models of the space debris environment are the means to provide answers to many of those questions.

The development of the European MASTER (Meteoroid and Space debris Terrestrial Environment Reference) model began in 1987, triggered by the explosive breakup of an Ariane upper stage in November 1986. The need to understand the source mechanism behind this major pollution event, which resulted in about 500 catalogued fragments, prescribed the basic modelling philosophy behind MASTER: by simulating all known debris-generating events in space, a synthetic population can be established, which subsequently yields the associated space debris flux for a satellite mission thereby facilitating risk assessments. Moreover, if the model provides an accurate description of the environment and accounts for its underlying dynamics, predictions of the environment's evolution can be made. For the past two decades, the MASTER population and the underlying model have been used on IADC (Inter-Agency Space Debris Coordination Committee) level by all major space agencies to assess the effectiveness of mitigation measures and affirm the necessity of remedial action.

This paper starts with an introduction to the MASTER model in general. Followed by a detailed description of the changes that led to the release of the most recent version MASTER-8 in Section 2 and how the model was validated, it will be further discussed in Section 4 what those changes mean relative to the former version MASTER-2009. It has to be pointed out that previous papers over the last few years by the modellers have already provided first insights, including propagation aspects, the new NaK Leakage model or flux uncertainties [11, 34, 35, 13]. Moreover, an overview on the new model MASTER-8 has been presented in [12, 36]. This paper aims at providing a synthesis and at the same time to discuss the lessons learned in the current space debris modelling and mitigation context, which ultimately shapes the way forward for the MASTER model.

[1] https://twitter.com/89Marvaz/status/1196356715270291456

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1.1. MASTER history

In the wake of the 1986 breakup European efforts in the space debris domain gained significant momentum. Representatives from NASA, ESA and TU Braunschweig met for the first time in October 1989 in what was to become a series of semi-annual space debris modelling workshops [29]. To study the mechanism behind the explosive breakup and foster the development of an associated model, ESA awarded a first industry contract in 1991 to TU Braunschweig and the Battelle Institute. The insights gained from the laboratory experiments with upper stage scale models by Battelle were translated into a model providing statistical mass, size and added velocity (Δv) distributions.

The first MASTER beta version became available in 1995 and was distributed to a limited group of experts. It covered only the LEO region and accounted for space debris larger than 0.1 mm from launch activity, explosions and collisions from 106 past breakup events [30]. To consider impact risk from the natural meteoroid environment the Grün model was used [10].

After the first feedback had been received, the model went public in May 1997 [20]. It contained an update to 132 known fragmentation events and replaced the Grün with the Divine-Staubach meteoroid model [6].

A significant extension of the model occurred with the release of MASTER'99 [31]. The decision to describe the space debris environment for object sizes down to 1 μm size entailed providing source models associated with solid rocket motor (SRM) firing events, generating slag and dust particles, but also the NaK droplets which were hypothesised to originate from nuclear reactor core ejection events by the Soviet Union. The latter events were officially confirmed only in 2001 [1, 25]. Source models for paint flakes and ejecta particles were added, as well as the Jenniskens-McBride model to account for meteoroid streams [17, 24]. With the return of the Hubble Space Telescope's (HST) solar array via the Space Shuttle's first service mission (SM1) and the European Retrievable Carrier (EuReCa) in the early to mid 1990s, two additional validation sources became available and were included in MASTER's validation process for the small object population. Finally, this version also came with a Graphical User Interface (GUI).

With MASTER-2001, the model was extended to provide population files covering the entire history of space flight and, for the first time a long-term projection until 2050. The new NASA Standard Breakup Model (SBM) was implemented [18]. Moreover, the Program for Radar and Optical Observation Forecast (PROOF) was established to facilitate comparisons between ground-based measurements from survey campaigns with the modelled MASTER population in measurement space [3].

MASTER-2005 saw many improvements in the different source models. The breakup model was extended for the size regime below 1 mm. Following observations of the NaK population by NASA, the means to provide a more scientifically justified NaK source model and associated size distribution were in place. Upgrades also included the SRM, paint flakes and ejecta models [28]. The craters counted on the solar panel returned via HST's SM3B were included in the validation.

Following the discovery of a new population of High Area-to-Mass Ratio (HAMR) objects during dedicated surveys of high altitude orbits, MASTER-2009 introduced the new Multi-Layer Insulation (MLI) source model. Further improvements in the small size regime for fragmentation events were applied and the future population saw an extension down to 1 μm size regime [9].

The latest release was made in March 2019 and is called MASTER-8. The versioning scheme changed such that MASTER will now follow the *semantic versioning*[2], where major model upgrades will see an increment in the first digit. In that sense, MASTER-2009 is understood as 7.x, while the first release of MASTER-8 was the version 8.0.0. Patches include bugfixes that increment the last digit, while the center digit is incremented for changes in the software interface. The current version can be downloaded free of charge under a world-wide licence[3]. The changes in the latest model will be described in more detail in Section 2.

Today MASTER is used in mission design and risk assessment studies. It is used either as a stand-alone version or as the means to provide the background population or flux for more specific tools: the Debris Risk Assessment and Mitigation Analysis (DRAMA) suite relies on MASTER in its ARES (Assessment of Risk Event Statistics) and MIDAS (MASTER-based Impact and Damage Assessment Software) tools. It further supports vulnerability analyses in Systema-Debris, ESABASE2/Debris or the Particle Impact Risk and Vulnerability Analysis Tool (PIRAT) [5, 19]. Beyond the space mission and engineering context, MASTER is extensively used in academia, by insurers, economists and other groups to gain insights on the space debris environment.

1.2. MASTER population

The MASTER model provides space debris population snapshots at quarterly intervals up until its reference epoch which, in the latest version, is November 1, 2016. For the future projections, population snapshots are provided in yearly steps.

The population is built from nine different source submodels which are either *event-based (first order)* (launch and mission-related debris; fragmentations from explosions and collisions; MLI; SRM slag and dust; NaK coolant release and leakage), *continuous (second order)* (paint flakes) or *continuous (third order)* (ejecta). The paint flakes require the first order models to establish the

[2] https://semver.org
[3] https://sdup.esoc.esa.int

population of payloads and rocket bodies, whereas the ejecta model requires all the other sub-models to estimate the flux onto surfaces in space and provide resulting ejecta particles.

The major contribution for objects larger than a few mm are **fragmentation debris** from previous explosions and collisions. Due to the high impact velocity in LEO, wall penetrations and associated (sub-)system failures are likely in that size regime. Objects larger than about 1 cm are practically impossible to shield and can be considered lethal.

The second major contribution comes from **slag particles** as a result of SRM firings. They may reach object sizes up to a few cm and are typically released towards the end of the burn process with low additional velocity. Therefore, slag particles initially are encountered in the same orbital regions SRM firings take place. For objects larger than 1 mm in LEO, slag particles are second to fragmentation debris and third only to NaK droplets in altitudes around 900 km. In very low and high orbits (beyond LEO), slag particles are the major source of space debris in the 1 mm population. Evidence for SRM slag and dust particle impacts was found on returned surfaces and impact detectors such as the LDEF's (Long Duration Exposure Facility) Interplanetary Dust Experiment (IDE).

Radar measurements conducted by NASA in the 1990s indicated the existence of a population of metallic spheres in altitudes around 900 km. They were attributed to 16 reactor core ejection events by US-A type satellites which took place between 1980 and 1989 as a safety measure. The **NaK droplets** formed during the ejection as the primary coolant loop opened to space. The NaK population can be considered the most accurate source model in MASTER given the almost perfect match between the modelled and the measured size and velocity distributions [35, 22] and the detailed physical modelling of the released NaK mass and size limits based on orifice diameters and the application of the Rayleigh's capillary jet breakup mechanism for the released fluid. The maximum possible size is 5.5 cm. While the mm-sized droplets decayed very quick, today's population mainly consists of cm-sized droplets between 800 km and 900 km. They form the second largest contribution at those altitudes (about 10% of the total) and the third largest overall in LEO for objects larger than 1 cm. The mm-population of NaK droplets today is two orders of magnitude below the cm-population and will be entirely gone by 2040 [35]. The cm-population will remain in orbit for many more decades. An additional leakage model was introduced in MASTER-8 (see Section 2). The contribution by leakage compared to the released NaK populations in the 1980s is rather marginal. Figure 1 shows a comparison for the 1 cm population between fragments, SRM slag and NaK droplets.

After **MLI foils** were proposed as a possible explanation for the HAMR objects observed during high altitude surveys, a new source model was added in MASTER-2009.

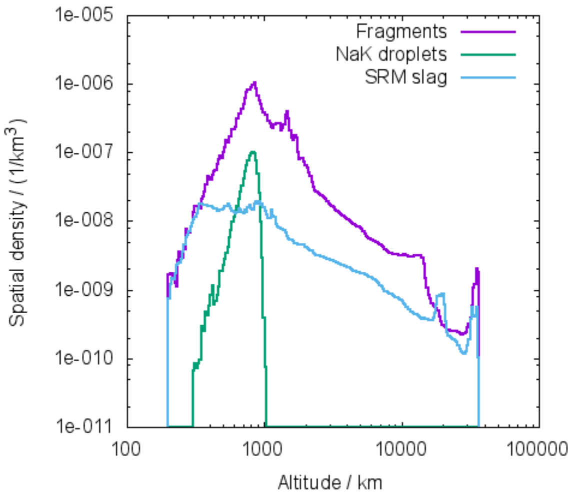


Figure 1: Spatial density for the population of objects larger than 1 cm. MASTER-8 at November 1, 2016.

They are assumed to be primarily the result of breakup events. Even though there are indications that MLI blankets may be released due to degradation processes, this part is currently not covered by MASTER. The number of MLI objects in total is small but as they are bright objects they are likely to be detected in sufficiently high numbers to warrant their consideration in the object correlation during the large object validation process. If MASTER would not consider them, it could lead to many false positives during the correlation and thus negatively impact other population source models in that size regime (mainly breakups) during the model calibration.

The sub-mm size regime where **ejecta** and **paint flakes** prevail down to about 50 μm. They are assumed to be continuously generated. As an example, on orbital altitudes of 800 km, ejecta in the size range of 0.1 mm exceed meteoroids by two orders of magnitude. However, ejecta and paint flakes are typically very short-lived in LEO and wiped from orbit by Earth's atmosphere during periods of high solar activity. An example is shown in Figure 2 for the number of ejecta particles in the range between 0.01 mm and 0.1 mm crossing the orbital altitude at 600 km.

In the size regime from 1 μm to about 50 μm, dust particles from SRM firings prevail. The 1 μm population represents the only size regime where the spatial density increases for altitudes higher than LEO (instead of decreasing, as is the case for larger object sizes) due to the accumulation over the space flight history.

In general, it can be said that the event-based modelling philosophy in MASTER seems to work well where sufficient documentation or evidence for events exist, especially as has been demonstrated with the NaK source model. At the same time this means that for higher orbits, like the Geostationary Earth Orbits (GEO), difficulties may be encountered as breakup events may go unno-

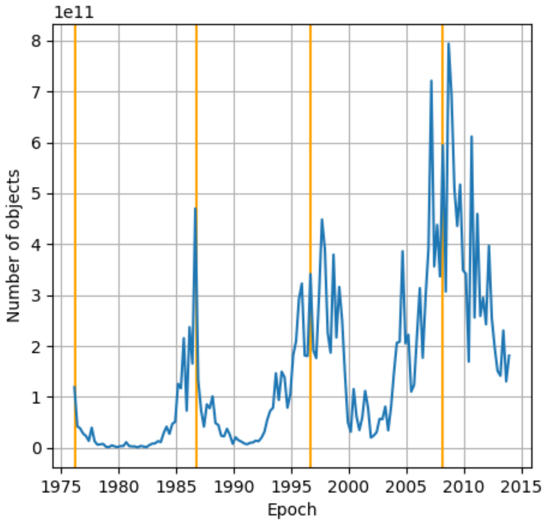


Figure 2: Variation of ejecta particles between 0.01 mm and 0.1 mm size at 600 km altitude. Orange vertical lines indicate the solar minimum date.

ticed due to sensitivity limits of ground-based sensors.

The modelling approach in MASTER also establishes confidence for extrapolation in space, time and size domains. For instance, the often mentioned *observation gap* (between 1 mm and 3 mm in LEO; 7 mm to 10 cm in GEO), which exists because of sensitivity limits for ground-based observations and too few craters counted from returned surfaces, can be bridged by means of extrapolation from the breakup model (coming from the larger objects) and the ejecta model (coming from the smaller objects).

2. UPGRADE TO MASTER-8

The recent upgrade towards MASTER-8 entailed many changes, with an overview given in the following. Major aspects are discussed in more detail in subsequent sections.

- Update of fragmentation events up to November 1st, 2016;
- Update of the SRM firing list;
- Implementation of uncertainty indicators as a function of orbital region and size;
- Introduction of a new sodium-potassium (NaK) leakage model as a partial source (part of the already available NaK model).
- Provision of a condensed population merging all individual sources into one population;
- Population validation taking into account the latest observational data;
- Introducing target orbit propagation, for instance facilitating flux assessments over time periods with significant altitude changes due to decay;
- Updated MASTER Application Programming Interface (API), which also provides the flux uncertainties;
- Update of the fragmentation modeling according to [21]
- Revision of the MLI model;
- Implementation of the Grün meteoroid model;
- Consideration of the meteoroids for spatial density (only Grün model);
- Flux evaluations in Earth-Sun-Lagrange points at 1 AU distance (only meteoroids);
- Extension of the target orbit mode. Altitudes up to 500,000 km can be simulated now, where space debris contributions end at $h_{GEO} + 1000$ km but meteoroids are considered beyond;
- Flexible reference epoch based on existing population files;
- Revision of future population approach, projections are now available until 2036;
- Revision of the GUI, introducing ”Basic Mode” and ”Expert Mode”.

A detailed assessment of orbit propagation aspects was conducated at the beginning of the upgrade activity [11]. Given that an excessive number of orbits need to be computed (even if representative objects are considered to reduce the objects to be propagated), a trade-off needs to be made to achieve acceptable accuracy but fast execution. It turned out that the currently used FOCUS-1 (Fast Orbit Computation Utility Software) propagator is up to the task. FOCUS uses the Adams-Bashforth/Adams-Moulton predictor/corrector numerical integration of the averaged classical orbital elements change rates, taking into account zonal harmonics (J_2 to J_5), atmospheric drag for an oblate atmosphere (MSIS-77), lunisolar and solar radiation pressure perturbations.

2.1. Update of event database

The **breakup event** database update resulted in 38 new events in the time period between May 1, 2009 and November 1, 2016, the reference epoch of MASTER-2009 and the upgrade model MASTER-8, respectively. Those events include the Proton ullage motors as a recurring class of objects suffering explosive breakups, totalling 12 events in that time span. Moreover, 25 historic events, which already existed in MASTER-2009 saw an update. Nine of those events were related to Ariane H10 upper stage breakups between 1984 and 2020 as identified in [8]. Three previously unconsidered historic events were added:

- Cosmos-1275 (1981-053A), breakup Jun 24, 1981;
- Agena-D (1970-025C), breakup Oct 17, 1970;
- Delta-P (1974-089D), breakup Aug 20, 1975.

After a significant increase in the catalogued number of fragments was observed over the years for both the Fengyun-1C ASAT from 2007 and the Cosmos-Iridium collision from 2009, those events had to be investigated in more detail. The general approach is to access publicly available orbit and object size information from the Two-Line Element (TLE) catalogue (or the related Space Situational Report (SSR)). This information is augmented with individual event analyses such as via NASA's Orbital Debris Quarterly News (ODQN). As soon as the number of confirmed detections (DC) is established from those sources, the SBM [18, 21] is applied and the power law scaled such that the cumulative number of objects matches with DC. An example for the Fengyun-1C ASAT is shown in Figure 3 At about 10 cm size, the

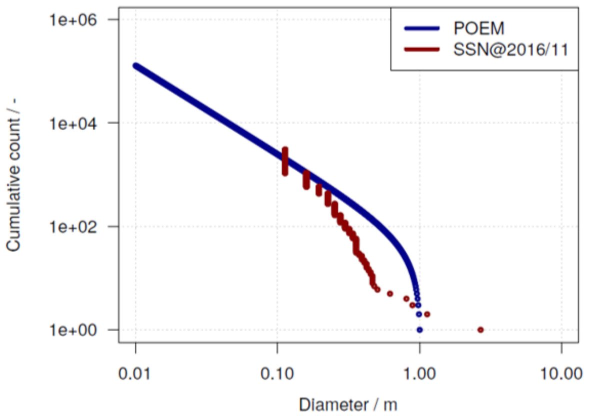


Figure 3: Cumulative number of fragments from the Fengyun-1C ASAT in 2007. Modelled population from POEM, catalogued objects from the SSR [14].

assumed sensitivity limit of the Space Surveillance Network (SSN), the modelled size distribution from the Program for Orbit Environment Modelling (POEM, which simulates MASTER's debris-generating events) and the size estimates from the known fragments match. What can be seen as well in Figure 3 is that the slope of the modelled power law does deviate from the observed one. This is indicative of a breakup mechanism not captured by the model. An attempt was made in NASA's Orbital Debris Engineering Model (ORDEM) to fit also the slope and thus tailor the breakup model for specific events [23]. This is currently not the case for MASTER. Another difficulty arises from the limited availability of size information. The public TLE catalogue nowadays comes only with the three categories SMALL, MEDIUM and LARGE, which for MASTER-8 got translated into the discrete accumulation of objects in certain size bins evident in Figure 3.

The updated numbers for the Fengyun-1C ASAT and Cosmos-Iridium events in MASTER-8 are shown in Table 1.

Name	MASTER-2009	MASTER-8
Fengyun-1C	1000	3425
Cosmos-2251	1050	1667
Iridium-33	467	628

Table 1: Update of major breakup events in terms of the number of catalogued space debris objects between the two models.

Both events happened before May 1, 2009, the actual reference epoch of MASTER-2009. However, due to the nature of the cataloguing process, it took many years (6 to 10 years for Fengyun-1C, 3 to 6 years for Cosmos-Iridium) to arrive at a reasonably converged number of fragments in the catalogue.

As of November 1, 2016, MASTER models 255 confirmed breakup events. It has to be pointed out that anomalous events or breakups resulting in only very few fragments, with no indication of any high energy event, are not considered in the model.

Two more recent major breakups are the DMSP-F13 and NOAA-16 explosions from February and November 2015, respectively. For the MASTER-8 upgrade, NOAA-16 was modelled with 357 DC, while the current catalogue (as of April 2021) already lists 458 objects (+28%). For DMSP-F13, MASTER-8 assumed 161 DC, while the catalogue now has 237 objects (+47%). This highlights the need for more regular model updates and at the same time to understand that there may be a significant lag until convergence can be achieved for a given event.

Mainly for high altitude orbits, the list of assumed breakups was revised to explain detections from latest survey campaigns (see also Section 3). This resulted in an additional 11 unconfirmed events which could be correlated with a potential parent satellite and 2 more hypothesised events that have no known parent object assigned [14].

The **SRM firing** database saw a significant update with many historical firings added that were previously not considered in MASTER-2009. The new firing list contains 2441 events compared to 1964 in MASTER-2009.

The **NaK release** event database did not see any update, but two new **NaK leakage** events were added (see also next Section).

2.2. NaK Leakage model

Sodium-potassium (NaK) droplets were released into the environment between 1980 and 1989 as the result of 16 reactor core ejection events for the Buk reactor type.

Each of the events released about 5.3 kg of droplets into space. As there were no further reactors launched of that type, they are considered a historic contribution.

Besides 31 launched Buk reactors, the Soviet Union also launched two thermionic converter reactors of the Topaz type in 1987 [34]. The Topaz reactors were launched into a sufficiently high orbit such that a reactor core ejection was not part of their design. The two satellites, Cosmos-1818 (1987-011A) and Cosmos-1867 (1987-060A) were operated for about 5 and 11 months, respectively, to continue orbiting the Earth dormantly for about two decades [26]. In July 2008, the SSN detected about 30 small debris objects in the vicinity of Cosmos-1818, among other very small objects that were difficult to monitor [26]. In 2014, a similar debris cloud was observed in the vicinity of Cosmos-1867 [27].

The analysis of both events revealed that droplets were released with additional velocities of up to 15 m/s in flight direction, indicative of a hypervelocity impact that might have severed the NaK supply pipes.

A new model to account for these leakage events has been added to MASTER. It assumes 250 g of total NaK mass for each event, distributing in sizes between 1.4 cm and 5.0 cm [34]. Compared to the NaK leakage event, these contributions can be deemed minor. At 900 km altitude, in the 1 cm regime, the NaK leakage droplets' contribution is two orders of magnitude below the one by NaK droplets generated during the reactor release events.

It is, however, interesting to note that ESA missions were encountering the catalogued droplets from both leakage events during their missions, detected as part of the nominal collision avoidance screenings. Conjunction Data Messages (CDM) were received since the launch of Sentinel-2A in June 2015. As of April 2021, there were 14,481 CDMs received, in 987 individual close approach events, between satellites of the ESA fleet and Cosmos-1867 coolant droplets. The majority of those CDMs were from encounters with Sentinel-2A (91%) followed by its sister spacecraft Sentinel-2B (6%). Similarly, droplets from Cosmos-1818 were chasing ESA satellites with a total of 11,635 CDMs received since June 2015 in 739 individual events. The shares are similar here: 92% of the received CDMs are attributed to Sentinel-2A and 8% to Sentinel-2B. So far, the collision probability was always below the manoeuvre threshold and no avoidance action has been taken.

2.3. Condensed population

Following the idea of a further population compression and to increase the processing speed on the user side, the *condensed population* was introduced as a combination of each single source contribution (excluding meteoroids). Like this, the user may decide whether to assess the total flux, where general properties (impact direction, for instance) of the previous sources are preserved, or perform a lengthier analysis if a resolution for individual sources is deemed necessary.

The previous diameter class discretisation in MASTER-2009 (and earlier versions) had 16 bins for each source irrespective of the size regime each source spans. In MASTER-8, all sources received a finer resolution with now 70 diameter bins to cover the size regime between 1 μm and 100 m.

2.4. Uncertainty modelling

The flux estimates MASTER provides are the result of a complex approximation and calibration process for different source models. Comparing the model output to actual measurements of the space debris environment will necessarily result in deviations. An approach to inform and constrain the model uncertainty is beneficial to MASTER users, for instance in mission design where flux-dependent margins could be applied in a less conservative way.

A first attempt to derive model uncertainties was made during the upgrade towards MASTER-8. It is based on the intuitive error ratio ϵ:

$$\epsilon = \frac{x_O - x_M}{x_M}, \quad (1)$$

where x_T is an observed quantity (e.g. number of craters counted on a surface in a certain size range) assumed to represent the true environment here, x_M is the equivalent quantity provided by the model (e.g. expected number of craters by the model for that surface in the size range under consideration). An additional assumption made is that the obtained value for ϵ can be interpreted as a worst-case deviation and hence defined as a 3σ deviation of an underlying normal distribution.

The requirement to have flux uncertainties provided along all dimensions of the model has to be reflected against the available sets of measurements. Significant gaps do exist, however in the available data (see also Section 3). Figure 4 shows the current data coverage across the two main dimensions *diameter* and *orbital regime*. For the LEO regime, the small object population is covered by LDEF, HST and EuReCa. With a transition region approximately between the class of diameters between 1 mm and 1 cm, the large object population is covered by radar campaigns through the Tracking and Imaging Radar (TIRA) and the European Incoherent Scatter Scientific Association (EISCAT). In high altitude orbits, the MASTER model currently relies on survey campaigns conducted with ESA's Space Debris Telescope (SDT) in Tenerife. Its limiting size threshold is at about 10 cm to 15 cm. To cover other areas (filled grey in Figure 4), reasonable extrapolations have to be applied currently. The entire Medium Earth Orbit (MEO) region would be covered by the application of the uncertainties obtained for LEO. The small object part in GEO would be covered by the small object population uncertainties obtained in LEO.

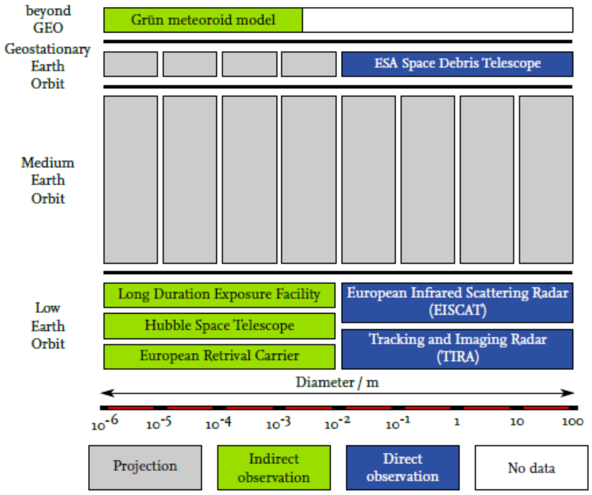


Figure 4: Coverage of size and orbital regimes through available validation sources in MASTER-8.

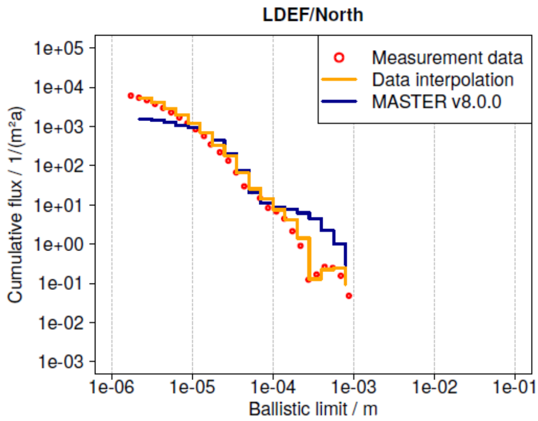
The detailed approach to derive uncertainties is documented in [13, 14]. The example provided in Figure 5 shall illustrate how the error ratio ϵ is derived. The observed cumulative flux, or the number of counted craters on LDEF's North surface, as a function of the ballistic limit (i.e. the size of an impactor beyond which a perforation of a surface can be expected) is shown in Figure 5a with red markers. To allow for a comparison with MASTER's discretised cumulative flux (blue graph), the observed flux needs to be interpolated first (yellow graph). This facilitates a direct comparison in measurement space to compute the error ratio. Figure 5b shows the individual deviations (blue graph) in the covered size regime. It was decided to compute both a positive and a negative error ratio per diameter decade. In this sense, all positive deviations are arithmetically averaged per decade to obtain $\epsilon(+)$ and all negative deviations likewise to obtain $\epsilon(-)$. This process is applied to all returned surfaces available in the MASTER validation. Similarly, the number of detections as a function of object sizes is used to obtain the error ratios for the large object population. The aggregated numbers as a function of diameter for the different orbit regions are shown in Figure 6. They are interpreted as multiplication factors to the nominal flux values obtained with MASTER to result in 1σ (one standard deviation) uncertainties. It is interesting to note that the mm-regime (1 mm to 1 cm decade) tends to show a clear overestimation of flux by the model (about 62%). This is at the same time a size region that is inherently difficult to observe and only very few impact craters are known compared to tens of thousands for smaller sizes. At the same time, it is also well within the sensitivity limit of ground-based radars observing LEO. The high uncertainty provided by the model is to some part also indicative of the existing observation gap, even if this is only one aspect.

Moreover, the large object population shows also rather high deviations in the LEO (and MEO) regime. It has to be noted that currently flux uncertainties are derived only for the non-correlated objects from measurement campaigns. It makes sense to assume that for the known population (i.e. catalogued objects) the deviation is zero. For the non-catalogued population, however, deviations may occur. And this is what is shown in Figure 6 for the large object population, i.e. it is not set in relation to the share of perfectly (in terms of numbers) known objects of that population.

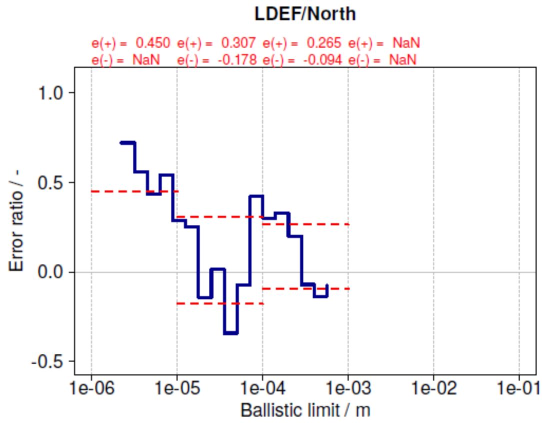
An important and challenging aspect is to combine the individually obtained error ratios to the aggregated numbers the model would provide. They need to be weighted according to the quality of the underlying data and their relevance or validity realted to the reference epoch of MASTER. The fact that uncertainties derived during the validation process are only provided at the most recent epoch (and not for the history) is a practical decision in view of the most common use cases of the model. In general, two different classes of weights need to considered: *intra-sensor* weights would relate different sub-contributions by the same sensor, such as individual tracking campaigns by TIRA or the different (but similar) surfaces by LDEF; *inter-sensor* weights are required to bring different sensors into relation. For instance, how much value would the aggregated contributions by TIRA make compared to those by EISCAT?

For the large object population, the intra-sensor weighting involved two criteria: first the age of a survey campaign, where older campaigns may be argued to be of less value compared to more recent ones because of the flux uncertainties being provided at reference epoch. However, one needs to be very careful here, as certain campaigns, even if older, may still have acquired important snapshots of the environment's features that more recent ones might not have. The second criterion is related to breakup events. Similar to the example of the cataloguing process of the Fengyun-1C ASAT and the Cosmos-Iridium collision breakup clouds, survey campaigns that are time-wise close to the breakup epoch might not yet give a clear picture of the number of fragments involved compared to later snapshots with wider separation of individual fragments. When it comes to inter-sensor comparisons one example was that Radar Cross-Section (RCS) information, used as a proxy for object size in the model, in the case of EISCAT was only obtained as a lower boundary. In the previously conducted campaigns, it was not possible to correlate a given detection with it's position relative to the radar main lobe's normal. This is different for TIRA and hence EISCAT was weighted less in the inter-sensor aggregation relative to TIRA. Overall, it can be stated that already for the limited amount of data sources used in MASTER's validation processes, the assessment of uncertainties requires significant care on many levels. Even if many of the computational aspects can be automated, the overall process remains quite labour-intense. More details on the weighting process and assessed data quality can be found in [13, 14].

The uncertainties for the meteoroids are based on [32] and work best with the Grün model underlying that assessment.

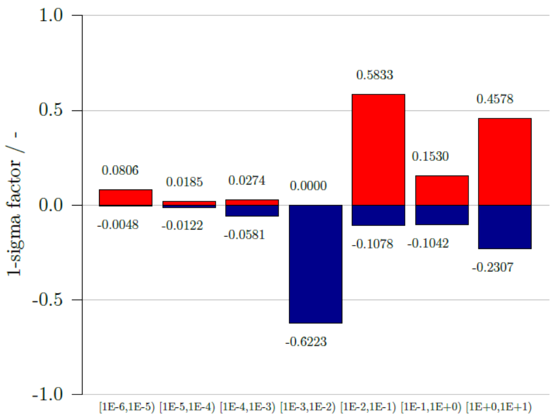


(a) Data vs. model comparison.

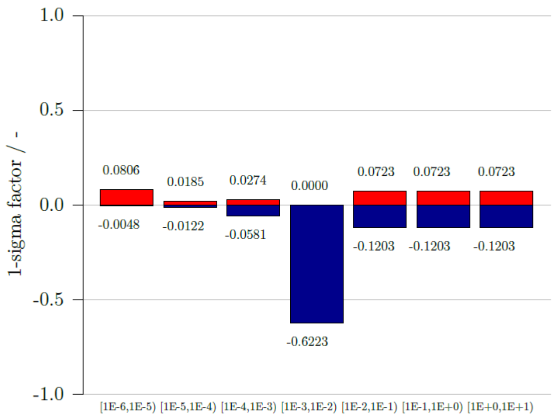


(b) Error ratio.

Figure 5: Example of the error ratio computation for the LDEF/North surface.



(a) LEO & MEO



(b) GEO

Figure 6: Flux uncertainty (1-sigma) multiplication factors per diameter decade (in meters).

2.5. Meteoroid models

The Grün model, which was already present in the early versions of MASTER, has been re-introduced with MASTER-8. It is considered simple but still reasonable to be applied for any space missions in Earth's vicinity. It supports the mission design process, as it is the currently recommended model by the European Cooperation for Space Standardization (ECSS) [7]. Flux assessments by MASTER can now also be performed for Earth-Sun Lagrange point orbits, representing the first development step towards facilitating mission analyses beyond Earth-bound orbits constrained by GEO as the outer boundary. In the current implementation, Lagrange point orbits are assumed to get the flux at 1 astronomical unit (AU).

2.6. Assumptions for the future projection

The future populations by MASTER are provided from the reference epoch 2016 until 2036 in yearly population snapshots for the condensed population but also the individual sources. The environment evolution is simulated by ESA's Debris Environment Long-Term Analysis (DELTA) tool. Based on an initial population, which is the one at MASTER's reference epoch, it would project scenarios defined along a certain parameterisation. Currently, this is being done for three different scenarios, referred to as the *Business-as-Usual* (BAU), *Intermediate Mitigation* (INTER) and *Full Mitigation* (FULL) scenarios, respectively. The differences between those three simulated scenarios are shown in Table 2. The explosion rate in the BAU scenario corresponds to an annual rate of 4.38 events [14] (in MASTER-2009 it was 5.46), based on the average breakup rate from an 8-year repetitive cycle which is also assumed for the launch traffic. For the latter, similar objects are being inserted into similar orbits for the entire projection span. The annual SRM firing rate significantly reduced compared to MASTER-2009: from 11.8 to 4.88. The disposal behaviour in the BAU scenario is derived from ESA's Annual Space Environment

Parameter	BAU	INTER	FULL
Explosion rate	100%	100%	linear decrease from 100% in 2017 to 5% in 2030
SRM firings	100%	linear decrease from 100% in 2020 to 5% in 2030	linear decrease from 100% in 2020 to 5% in 2030
MRO prevention	none	only payloads	payloads and rocket body
Rocket body de-orbit	25%	linear increase from 25% in 2017 to 50% in 2030	linear increase from 25% in 2017 to 90% in 2030
Payload de-orbit	10%	linear increase from 10% in 2017 to 40% in 2030	linear increase from 10% in 2017 to 90% in 2030
Re-orbit	75%	linear increase from 75% in 2017 to 90% in 2030	linear increase from 75% in 2017 to 100% in 2030

Table 2: Model parameters for the three future scenarios in MASTER-8.

Report[4]. DELTA is also assessing the collision probability during the simulation and would trigger a collision event when a drawn random number is above the threshold compared to the assessed collision likelihood between two objects. The results DELTA provides are then event lists for the entire projection span. Those are then provided to POEM to simulate the debris-generating events consistent with the MASTER model.

As the process is rather expensive in terms of computational resources, especially for the very small object populations (paint flakes, ejecta, as they are also higher-order models), the two main constraints introduced were on the projection span (20 years) and the number of Monte Carlo (MC) runs to account for the statistical nature of random processes inside a given scenario simulation. Each of the three scenarios was simulated along 20 MC runs. In total, the 60 MC runs are then processed with POEM for the 60 different futures of the environment. Only on the level of computing the probability density tables for MASTER, the scenarios are merged by applying an equal weighting. Given that the BAU scenario is representative of today's spaceflight activities, INTER and FULL are rather on the optimistic side and therefore the overall future scenario provided by MASTER can be considered rather optimistic. Especially, as the latest trends of the NewSpace era, including large constellations, are not yet reflected in the model.

An example of the merged scenario is shown for the evolution of explosion and collision fragments at altitudes between 700 km and 900 km in Figure 7. The large increase in collisional fragments results from the Fengyun-1C ASAT and Cosmos-Iridium events in 2007 and 2009, respectively. After those two events, a decline in collision fragment numbers can be observed, only to be caught up by the general growth rate due to collisions in the background population. For the explosion fragments, the MASTER-8 scenario saw a massive breakup in 2018 in one of the MC runs. While the averaging over 60 MC runs provides some smoothing, it is not sufficient to avoid

[4]The latest version can be found online: `https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf`

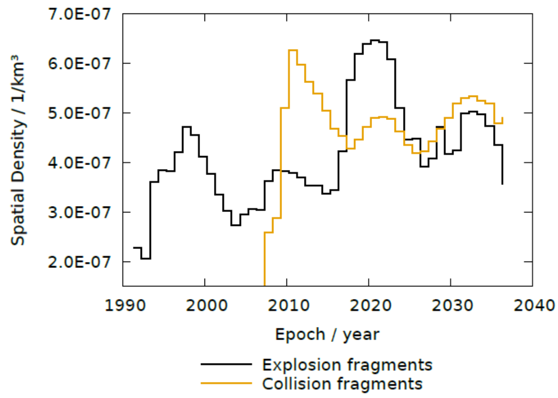


Figure 7: Evolution of the fragments (explosions and collisions) population larger than 1 cm in orbits between 700 km and 900 km in MASTER-8.

peak spatial densities as seen in Figure 7. At the moment the question remains open whether such events should be avoided and if so then to which extent in relation to the number of MC runs?

The different MC runs also serve in the assessment of future uncertainties provided by the model. They are derived as the standard deviation obtained from the 60 MC runs. The flux uncertainties derived via MASTER's validation process are combined with those of the future scenario by simple variance addition.

3. MODEL VALIDATION

The validation process for MASTER is sub-divided into the *small object* and *large object* branch. For any source of evidence, the model output is always translated into measurement space. For the large object population this is achieved by the PROOF tool. It takes a detailed parameterisation of a sensor (e.g. passive optical telescope or a tracking radar) and assesses the field-of-view crossings and detection probability for the objects from the MAS-

TER population. Those can then be compared to the actual measurements from any survey campaign. A difficulty here is that detailed knowledge on individual sensors is required such as the antenna pattern or the radar system description (incl. antenna constant, wavelength, transmitter power, number and duration of pulses). For the small object population, MASTER can be used to determine the impact flux in the case of a returned surface. The flux needs to be converted into damage features like impact crater size or holes generally by means of empirical ballistic limit equations (BLE) [16].

3.1. Large object validation

The large object validation is based on dedicated survey campaigns targeting the LEO and GEO regimes. For the validation in GEO, MASTER-8 relies on the SDT's annual survey campaigns conducted between 2001 and 2014. Detections are provided with a full set of orbital elements but generally a circular orbit is assumed. The main task lies in matching the distribution in the space defined by right ascension of ascending node (RAAN) and inclination, including the assessment of hypothesized events and their likelihood against observed object clusters by the SDT.

In LEO, there were in total 11 beam-park experiments (BPE), of 24 hourse each, conducted with TIRA since 2000. While the majority of them was east-staring, the latest one in 2015 was south-staring to attempt an access to low-inclination objects.

Moreover, since MASTER-2009, the measurements by EISCAT are also part of the validation. Between 2007 and 2009 there were in total 2424 observation hours spread over 101 days. For MASTER-8 an additional BPE campaign from October 2015 (4 days) could be used.

3.2. Small object validation

The small object population is validated by means of returned surfaces. While there have been measurements by in-situ detectors, none of them found their way yet into the MASTER validation process. This is currently under preparation for the next development step.

LDEF has been in orbit between 1984 and 1990 and provided a rich data set through the many surfaces and dedicated experiments that have been inspected for craters. The latter include the Interplanetary Dust Experiment (IDE), which also correlated impacts with timestamps and thus allowed to associated clustered impacts with individual SRM firings [33].

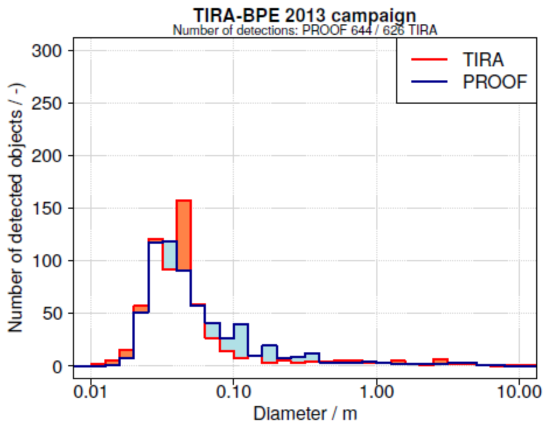
The HST was launched in 1990 and saw several service missions (SM) by the Space Shuttle during its operational lifetime. During the famous SM1 in December 1993, a corrective optics was installed for Hubble. At the same time, the solar panels contributed to the mission by ESA, were replaced and one of them recovered. During SM3B in 2002, the solar panels were replaced again, this time after spending about 8 years in orbit. Panels from both missions became accessible for impact crater counts.

In a similar manner, ESA's EuReCa mission was launched (or released by the Space Shuttle) in July 1992 to be recovered one year later again (July 1993). Also here, impact craters were counted in its solar panels.

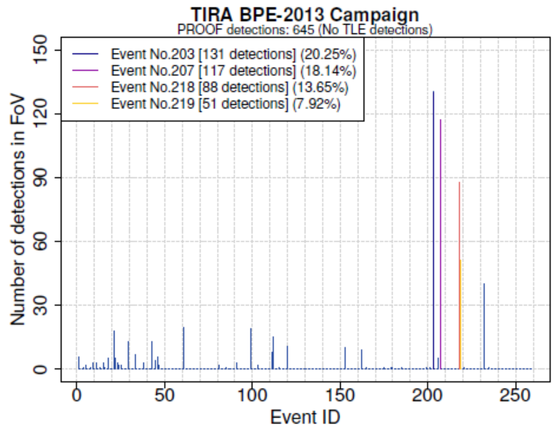
3.3. Validation cycles

The MASTER model validation is iterative and required in total 31 cycles for MASTER-8 to sufficiently converge. It usually involves an initialisation after the first update of the event lists. Upon comparison with the observations the results are screened for deviations and their potential cause. This may result in the calibration of model parameters (e.g. scaled number of fragments in the size distribution) and then a re-run of POEM to regenerate the clouds and propagate them again to the epoch of the measurement campaign(s). For the BPEs in LEO, the prevailing source to be calibrated is the breakup model. This is illustrated in Figure 8 for TIRA's east-staring BPE in 2013. In Figure 8a the number of detections as a function of diameter over an observation span of 24 h is shown. While overall the number of detections matches quite well (PROOF shows 644, while TIRA had 626), the distribution shows some deviations. To investigate the reason for this, one approach is to look at which objects were most likely crossing TIRA's field-of-view during the BPE. Figure 8b shows the simulated number of detections as a function of the breakup event. The major contributor here would be event no. 203 (which is Fengyun-1C), followed by no. 207 (Briz-M, 2006-006B), no. 218 (Cosmos-2251) and no. 219 (Iridium-33). These four events alone are responsible for 60% of the simulated detections. The calibration process would now involve re-assessing those four events first and see if this improves the result in the next iteration step. This is not always a very linear process, as changing model parameters might provide an improvement for one certain BPE, but may also have a negative impact on another experiment. Several metrics have been developed during the upgrade towards MASTER-8 to facilitate more automation in this optimisation. It will certainly be even more emphasized in the next model upgrade.

Another aspect in assessing the model's validity is to compare it to existing models. It turned out to be an enriching and rewarding collaboration with NASA's team working on ORDEM, as inter-model comparisons, especially when certain modelling aspects and considerations differ significantly, allow to point at weaknesses and opportunities that would be otherwise difficult to become aware of. The latest comparison between MASTER-8 and ORDEM-3.1 was carried out in [15].



(a) Detections vs. diameter



(b) Detections per POEM event

Figure 8: TIRA BPE-2013.

4. COMPARISON WITH MASTER-2009

Each model upgrade also involves the comparison to the former model to inform on the most relevant changes in terms of model output. There are several ways of approaching it. In a first step, it appears reasonable to compare MASTER-2009 and MASTER-8 at the reference epoch of the former (May 1, 2009) because then both models can be assumed validated. Such a comparison for the spatial density of the population larger than 1 cm as a function of altitude is shown exemplarily in Figure 9. The deviations are the result of either an update of

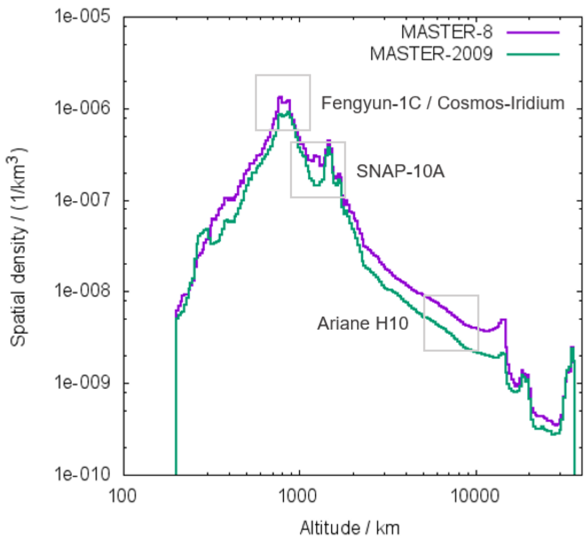


Figure 9: Comparison between MASTER-2009 and MASTER-8 at May 1, 2009, which is a validated population snapshot for both models (objects larger than 1 cm).

historic events that were already part of MASTER-2009 or were newly added. The latter category involves the group of Ariane H10 breakups mentioned earlier. It contributes to the increased spatial density seen primarily in the MEO region. And some H10 events may even still be missing, like the Ariane 4 upper stage that exploded in 1998 and got some attention recently after one fragment of that stage caused a Galileo satellite to conduct a collision avoidance manoeuvre in March 2021[5].

The increase in the most populated area between 700 km and 900 km is mainly due to the updates of the Fengyun-1C ASAT and Cosmos-Iridium collision events. Overall, this translates to a flux increase for a target satellite in that altitude of about 50%.

Finally, the MASTER-8 model included the breakup of the Snapshot satellite (1965-027A), which carried the SNAP-10A nuclear reactor, in an altitude of about 1300 km. Given more recent assessments [2], it might be that the satellite is shedding debris but a previously assumed high energy breakup might not be warranted and future model updates may see a decreasing contribution in that area again.

5. OUTLOOK

The most recent MASTER version was released in March 2019 as a result of more than 30 years of modelling activity. While distinct model versions have been released every few years, the relevant research activities as well as exchange and discussions in the community are a rather continuous process. Important next steps for the MASTER model have thus already been identified and are currently being studied and/or implemented.

During the population generation and the later validation for MASTER-8, several improvements have been identified. The catalogue correlation process is foreseen to be extended in order to include also other catalogues beyond TLE. One example is the Vimpel catalogue[6], which has

[5] https://twitter.com/eu_gnss/status/1369632284719079430

[6] http://spacedata.vimpel.ru/

very good coverage especially for higher altitudes. Individual breakup events were found to have significant impact on survey campaigns and it is therefore reasonable to introduce more tailored event-wise calibration. Both the correlation process and the event-wise calibration rely on size estimates for the fragments. Since this information is no longer shared publicly via the TLE catalogue, new sources need to be found. In view of upcoming commercial radar-based monitoring and tracking services, but similarly also for optical observers, modellers may need to reach out to those groups to see if such information may be provided as well.

In March 2021, we invited the community to a MASTER Modelling Workshop [4]. Many important inputs have been collected to initiate a revision of the future population modelling. Among others, this involves the modelling of large constellations and the number and design of different scenarios.

In the frame of the Debris Mitigation Facility (DMF), the MASTER flux browser (or the frontend users typically work with) will be embedded into a common framework with the other tools known from DRAMA. The motivation is to combine different debris mitigation related software to facilitate mission design in a digital engineering context. Beyond this, more validation sources are planned to be added to MASTER, especially for the small object population. While a preliminary assessment of the Micrometeoroid/Space Debris Detector (MDD) has been done already during the MASTER-8 activity, this shall be further extended to include sources like DEBIE, GORID and the Columbus survey. The population generation and validation process shall be further automated to enable faster population updates.

Beyond this, dedicated analyses will involve revisiting the population size binning, new propagation techniques and the re-assessment of existing events given new evidence (e.g. as mentioned for the Snapshot satellite).

The MASTER Modelling Workshop has confirmed that the community of model users and developers has grown significantly - and so did the use-cases. Not only may we expect a more diverse set of potential validation sources, including in-situ sensors, telemetry or anomaly reports indicative of impacts, etc., but also the need to address diverse groups of people working with the model. It includes economists, insurers, but also the astronomers who were shocked to see the impact constellations may have on their work. The MASTER model may support assessments of how space debris not only impacts spaceflight activity but also the society at large.

REFERENCES

1. Anon. Collisions between Nuclear Power Sources and Space Debris. `https://www.unoosa.org/pdf/limited/c1/AC105_C1_L246E.pdf`, accessed on April 5, 2021, 2001. AC.105/C.1/L.246.
2. Phillip Anz-Meador, John N Opiela, Debra Shoots, and J.-C. Liou. History of on-orbit satellite fragmentations, 15th edition. 2018.
3. Jörg Bendisch, Karl Dietrich Bunte, Heiner Klinkrad, Holger Krag, Clare Martin, Holger Sdunnus, Roger Walker, Peter Wegener, and Carsten Wiedemann. The master-2001 model. *Advances in Space Research*, 34(5):959–968, 2004.
4. Vitali Braun, Michael Clormann, Xanthi Oikonomidou, Silvia Sanvido, and Stijn Lemmens. Fostering Collaborative Concepts in Space Debris Mitigation. In 8^{th} *European Conference on Space Debris, Darmstadt, Germany*, 2021.
5. Karl Dietrich Bunte, Esfandiar Farahvashi, and Anatoli Miller. Methods to Reduce Uncertainties in Spacecraft Vulnerability Predictions. In 7^{th} *European Conference on Space Debris, Darmstadt*, 2017.
6. Neil Divine, Eberhard Grün, and Peter Staubach. Modeling the Meteoroid Distributions in Interplanetary Space and Near-Earth. In 1^{st} *European Conference on Space Debris, Darmstadt*, 1993.
7. European Cooperation for Space Standardization (ECSS). Space engineering - Space environment, June 2020. ECSS-E-ST-10-04C.
8. S K Flegel. *Multi-layer Insulation as Contribution to Orbital Debris*. Dissertation, Technische Universität Braunschweig, 2013.
9. Sven Flegel, Johannes Gelhaus, and Marek Möckel. Maintenance of the ESA MASTER model. *Final Report, ESA contract 21705/08/D/HK*, 2011.
10. Eberhard Grün, Herbert A Zook, Hugo Fechtig, and Richard Giese. Collisional balance of the meteoritic complex. *Icarus*, 62(2):244–272, 1985.
11. André Horstmann and Enrico Stoll. Investigation of Propagation Accuracy Effects within the Modeling of Space Debris. In 7^{th} *European Conference on Space Debris*, 2017.
12. André Horstmann, Christopher Kebschull, Sven Müller, Eduard Gamper, Sebastian Hesselbach, Kerstin Soggeberg, Mohamed Khalil Ben Larbi, Marcel Becker, Jürgen Lorenz, Carsten Wiedemann, et al. Survey of the Current Activities in the Field of Modeling the Space Debris Environment at TU Braunschweig. *Aerospace*, 5(2):37, 2018.
13. André Horstmann, Holger Krag, and Enrico Stoll. Providing Flux Uncertainties in ESA-MASTER: The Accuracy of the 1cm Population. In *First International Orbital Debris Conference (IOC), Houston, Texas*, 2019.
14. André Horstmann, Sebastian Hesselbach, and Carsten Wiedemann. Enhancement of S/C Fragmentation and Environment Evolution Models. *Final Report, ESA contract 4000115973/15/D/SR*, 2020.
15. André Horstmann, Alyssa Manis, Vitali Braun, Mark Matney, Andrew Vavrin, Derek Gates, John Seago, Phillip Anz-Meador, Carsten Wiedemann, and Stijn Lemmens. Flux Comparison of MASTER-8 and ORDEM 3.1 Modelled Space Debris Population. In 8^{th}

European Conference on Space Debris, Darmstadt, 2021.

16. Inter-Agency Space Debris Coordination Committee. IADC Protection Manual, June 2018. IADC-04-03, Version 7.1.
17. Peter Jenniskens. Meteor Stream Activity. *Astronomy and Astrophysics*, 287:990–1013, 1994.
18. Nicholas L Johnson, Paula H Krisko, J.-C. Liou, and Phillip D Anz-Meador. Nasa's new breakup model of evolve 4.0. *Advances in Space Research*, 28(9): 1377 – 1384, 2001.
19. Scott Kempf, Frank Schäfer, Martin Rudolph, Nathan Welty, Thérèse Donath, Roberto Destefanis, Lilith Grassi, Rolf Janovsky, Leanne Evans, and Arne Winterboer. Risk and Vulnerability Analysis of Satellites due to MM/SD with PIRAT. In 6^{th} *European Conference on Space Debris, Darmstadt*, 2013.
20. Heiner Klinkrad, Jörg Bendisch, H Sdunnus, P Wegener, and R Westerkamp. An Introduction to the 1997 ESA MASTER Model. In 2^{nd} *European Conference on Space Debris, Darmstadt*, 1997.
21. Paula Krisko. Proper Implementation of the 1998 NASA Breakup Model. *Orbital Debris Quarterly News*, 15(4), October 2011.
22. Paula Krisko, Andrew Vavrin, and Phillip Anz-Meador. NASA orbital debris large-object baseline populations in ORDEM 3.0. In *IAC-13-A6.P9,* 64^{th} *International Astronautical Congress (IAC), Beijing*, 2013.
23. Mark Matney, Alyssa Manis, Phillip Anz-Meador, Derek Gates, John Seago, Andrew Vavrin, and Yu-Lin Xu. The NASA Orbital Debris Engineering Model 3.1: Development, Verification, and Validation. In *First International Orbital Debris Conference (IOC), Houston, Texas*, pages 9–12, 2019.
24. Neil McBride. The Importance of the Annual Meteoroid Streams to Spacecraft and their Detectors. *Advances in Space Research*, 20(8):1513–1516, 1997.
25. Andrei Nazarenko, E Grinberg, V Nikolaev, A Gafarov, V Lukyashchenko, and M Yakovlev. Spacecraft with a Nuclear Power System and Problems of Space Debris. In 4^{th} *European Conference on Space Debris, Darmstadt, Germany*, 2005.
26. NASA Orbital Debris Program Office. New Debris Seen from Decommissioned Satellite with Nuclear Power Source. *Orbital Debris Quarterly News*, 13 (1), January 2009.
27. NASA Orbital Debris Program Office. Flurry of Small Breakups in First Half of 2014. *Orbital Debris Quarterly News*, 18(3), July 2014.
28. Michael Oswald, Peter Wegener, Sebastian Stabroth, Carsten Wiedemann, Jens Rosebrock, Clare Martin, Heiner Klinkrad, and Peter Vörsmann. The MASTER-2005 Model. In 4^{th} *European Conference on Space Debris, Darmstadt, Germany*, 2005.
29. David S F Portree and Joseph P Loftus. Orbital Debris: A Chronology. NASA/TP-1999-208856, NASA, 1999.
30. Holger Sdunnus and Heiner Klinkrad. An Introduction to the ESA Reference Model for Space Debris and Meteoroids. In 1^{st} *European Conference on Space Debris, ESOC, Darmstadt, Germany*, 1993.
31. Holger Sdunnus, Jörg Bendisch, Karl Dietrich Bunte, Heiner Klinkrad, and Peter Wegener. An Introduction to the Upgraded ESA MASTER Model. In *European Conference on Spacecraft Structures, Materials and Mechanical Testing, Noordwijk, Netherlands*, 2001.
32. Robert E Smith and B Jeffrey Anderson. Natural Orbital Environment Guidelines for Use in Aerospace Vehicle Development. Technical report, NASA Marshall Space Flight Center, Technical Memorandum 4527, 1994.
33. Sebastian Stabroth, Michael Oswald, Carsten Wiedemann, Heiner Klinkrad, and Peter Vörsmann. Explanation of the "May Swarm" signature in the LDEF IDE impact data. *Aerospace Science and Technology*, 11(2-3):253–257, 2007.
34. Carsten Wiedemann, Eduard Gamper, André Horstmann, Vitali Braun, and Enrico Stoll. Release of liquid metal droplets from Cosmos 1818 and 1867. In *IAC-16.A6.2.9,* 67^{th} *International Astronautical Congress (IAC), Guadalajara*, 2016.
35. Carsten Wiedemann, Eduard Gamper, André Horstmann, Vitali Braun, and Enrico Stoll. The Contribution of NaK Droplets to the Space Debris Environment. In 7^{th} *European Conference on Space Debris, Darmstadt*, 2017.
36. Carsten Wiedemann, André Horstmann, Sebastian Hesselbach, Vitali Braun, Holger Krag, Sven Flegel, Michael Oswald, and Enrico Stoll. Improvements and Updates in MASTER-8. In *IAC-20-A6.2.6,* 71^{st} *International Astronautical Congress (IAC)*, 2020.