FOSTERING COLLABORATIVE CONCEPTS IN SPACE DEBRIS MITIGATION

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ABSTRACT

Our common understanding of the space debris environment is reflected by models which identify the environment's source and sink mechanisms and allow us to study its interaction with satellite missions as well as the potential evolution. The European model MASTER (Meteoroid And Space debris Terrestrial Environment Reference) is being developed at ESA (European Space Agency) since the early 1990s and needs to be continuously maintained due to the dynamic nature of the space debris environment. The target orbit flux estimates provided by MASTER are used in mission design and risk analyses in general by a diverse spectrum of users worldwide. The modelled space debris population and its evolution over time enables one to study the impact space debris mitigation has on the environment and dedicated tools have been developed for such assessments, bundled in ESA's DRAMA (Debris Risk Assessment and Mitigation Analysis) software. The MASTER model has been extensively validated by ground-based radar and telescope measurement campaigns for the large size population, and by means of studying impact features on returned surfaces for the small size population. Historically, the model's development was mainly driven by the public sector – and rather constrained to a technical academic viewpoint - through cooperation between ESA and different research institutes and agencies. Recent developments in the commercialisation of the space sector, involving the design and operation of further ground- and space-based sensors, but also the additional contributions by academia in the public sector, give solid reason to assume an even more diversified approach in the near future with stronger partnership opportunities – the way information is collected and how we transfer the obtained knowledge into the models. That approach will certainly entail more stakeholder participation and at the same time add significant complexity only to be tackled by transdisciplinary thinking. In this paper, the ideas and first implementations of ESA's Space Debris Office to accommodate for more participative approaches in the domain of space debris mitigation are presented. How can we, in our role as an Agency, connect various stakeholders, facilitate exchange and let everyone contribute such that we all benefit from the resulting models? Starting from outreach and education, over experiment design, to collection of observations and measurements - how can all those pieces be aligned to shape a comprehensive picture? Among the first steps in facilitating user collaboration with DRAMA was the development of DRAMA's Python package adding more visibility into how the tools are working. Very positive feedback has already been received, including improvements and additions by users. This is a very encouraging aspect, which is further driving the evolution of DRAMA and its transition into the Debris Mitigation Facility (DMF) with a broadly extended open source and community approach. Finally, today's space mission design relies on flux assessments for a future space debris environment. Naturally, the associated prediction models are quite complex and inherently uncertain. We therefore aim to increase collaborative approaches not only for enlarging the user community and adding new functionalities in support of the user needs, but also for strengthening verification, validation and, in the end, the broad acceptance of the model predictions. To that end, a first MASTER Modelling Workshop was held in March 2021 to foster stakeholder-based collaborative concepts. In this paper, we summarise the findings of that workshop.

Keywords: MASTER; Space debris; DRAMA; DMF.

1. INTRODUCTION

In what could have been another pleasant revolution after more than eight months dormantly orbiting the Earth, the Ariane rocket body, carrying the two European satellites Viking and SPOT-1 into orbit, violently exploded on November 13, 1986, during its ascending path about 800 km above the eastern part of Africa [13]. Only a few minutes later the fresh debris cloud, which eventually consisted of 497 catalogued fragments, was initially detected passing through the field-of-view of the U.S. FPS-79 radar at the Pirinçlik Air Base, Turkey. It took another about 8.5 hours until it was re-acquired over the U.S. AN/FPS-85 radar site in Florida. On that same day NASA (National Aeronautics and Space Administration) Administrator James Fletcher and ESA (European Space

Proc. 8th European Conference on Space Debris (virtual), Darmstadt, Germany, 20–23 April 2021, published by the ESA Space Debris Office
Ed. T. Flohrer, S. Lemmens & F. Schmitz, (http://conference.sdo.esoc.esa.int, May 2021)

Agency) Director General Reimar Lüst were meeting amidst a tense period of negotiations about ESA's role in the envisioned space station programme. ESA's provocative step to be treated as a mature and equal partner in the multilateral space station cooperation made Fletcher observe that the "European approach is inequitable. In measurable ways, the Europeans want to take far more out of the Station than they are bringing to it" [24]. In that meeting on November 14, 1986, Fletcher informed Lüst of the breakup [28]. In retrospect, this can be perceived as an important moment for the Europeans to identify as responsible and reliable partners. Lüst did not hesitate too long in what was literally a big-bang initiating European space debris modelling activities. In May 1988, he established ESA's Space Debris Working Group (SDWG), chaired by Prof. Rex from the Technische Universität Braunschweig (TU-BS), an expert in the space debris domain from earlier involvement in the risk assessments for the uncontrolled re-entries of Kosmos-954, Kosmos-1402 and Skylab. The SDWG published their report *Space Debris* in 1988 to raise public awareness on the threat to the near-Earth environment posed by space debris [5, 28]. In the foreword to that report, Lüst says that "by our failure to take preventive measures, future generations will inherit an ominous legacy" [28]. As a peculiar twist of fate, his foreboding materialised when a fragment of the Ariane breakup severed the boom of the French Cerise satellite in 1996 in what became the first collision between a known piece of fragmentation debris and an active satellite. By the mid-1990's, ESA had already introduced a passivation procedure to all launched Ariane upper stages based on the support and knowledge transfer in the transatlantic cooperation with NASA colleagues and their lessons learned with Delta upper stages previously. Furthermore, semi-annually modelling workshops were held between ESA, NASA and TU-BS since 1989. They eventually led to the establishment of the Inter-Agency Space Debris Coordination Committee (IADC) in 1993 and were essential in the development of the European Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model which saw its first public release in 1997. After an initial understanding of breakup mechanisms and their contribution to the space debris environment had been reached, modelling efforts continued in a collaborative manner between the major space agencies. Additional source models, such as the NaK droplets released as a by-product from Soviet nuclear reactor core ejections or solid rocket motor (SRM) dust and slag particles were hypothesized, studied and confirmed to become part of subsequent model releases. The latest model MASTER-8 was released in 2019.

In the meanwhile, the space debris environment continued to grow significantly, despite the international recognition of the problem through the endorsement of the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS), Space Debris Mitigation Guidelines by the UN General Assembly in 2007 [32] and considerable mitigation efforts undertaken by the community. In February 2009, the two satellites Iridium-33 and Cosmos-2251 collided at about 790 km altitude, producing thousands of fragments to give a certain taste of the transition from an explosive past enriching the near-Earth environment, thereby setting the scene for a future evolution driven by collisions, an effect described by Kessler and Cour-Palais [15]. In line with Kessler's statement from 1994 that "simple, meaningful environment models are no longer possible" [28], those models attained a high degree of complexity over time in an attempt to accurately reflect on the environment's diverse source and sink terms. This also strengthened the confidence in their predictiveness of potential futures assuming certain traffic scenarios. Not only were modellers able to show evidence for the collisional cascading in their simulations of a business-as-usual scenario. Even more worrying was the sustained collisional growth of the near-Earth environment even if space flight activities would be entirely discontinued [23]. While those studies demonstrated the need for Active Debris Removal (ADR), it doesn't come without a certain sense of irony that parallel developments in space hardware miniaturisation and increased commercialisation of the space sector (generally referred to as *NewSpace*) are now boosting the number of objects inserted into the environment far in excess of earlier traffic and without any indication of restraint, especially with the onset of the deployment of the Starlink constellation in 2020, as shown in Figure 1.

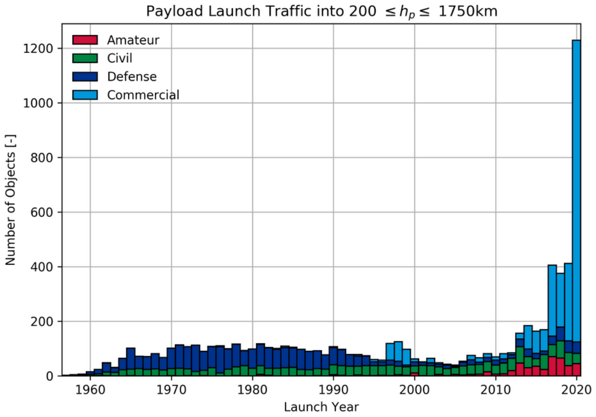

Figure 1: Number of satellites annually inserted into the Low-Earth Orbit (LEO) over time.

While it seems to be a very unlikely scenario at the moment that a substantial amount of people would start imagining a pleasant life without the need for infrastructure in orbit, space debris modelling will remain an important task. In view of the space debris history and the present situation, the following observations can be made to emphasize the need for and justify such modelling activities:

Mission operations: with a growing population, especially for the sub-catalogued debris, which can be lethal to sizes down to about 1 mm, it is important for a model to provide accurate estimates of the expected impact flux. Not only does this facilitate shield design and improved vulnerability assessments but, more importantly, also mitigates the risk that impacts would render satellites inoperable with a further degradation of the environment.

Mitigation & Remediation: to make reasonable predictions of potential futures and hence provide the means to study the impact of mitigation measures; to inform standardisation bodies on a technical level; and to identify the minimum required remediative measures to prevent collisional cascading, a model has to be verified, validated and its inherent assumptions critically reflected even beyond the technical level.

Socio-economic dependency: as global societies continue to aim for global connectivity of technologies, as well as their increasing autonomy, the dependency on space infrastructure will grow [4]. The more society becomes dependent on such infrastructure, e.g. in terms of economy and security, the higher will be the latent risk emanating from space debris - either through collisions or through the re-entry and potential damages or casualties on ground. In a context of increased societal awareness of the problem, any model prediction would be more widely exposed and scrutinized. This may have a significant impact on the model credibility and acceptance.

Growing complexity: the MASTER model has been developed for about 30 years in a more or less centralised approach by ESA. Contrary to the notion that a model over time could converge to perfection with increased knowledge, the model evolution shows that complexity has rather increased significantly. Partly because certain aspects could no longer be left in the realm of ignorance. In addition, space flight activities and related domains on the ground have seen many new actors joining over the past decades. Not only does this significantly expand interconnectivity and relationships resulting in increased space traffic, but it also multiplies the associated pollution of the space environment. Consequently, the potential users of the model increase and a more diverse set of use-cases and model needs results.

Recognizing the societal dependency on orbital infrastructure and the need to anticipate undesired consequences, the way forward in space debris modelling and mitigation appears to align well with the rationale behind the European Commission's Responsible Research & Innovation (RRI) framework [27]. RRI is characterised by four dimensions [16]: **Anticipation** requires us to consider various possible scenarios for the space debris environment and to reflect on the dynamics shaping our modelling work; **Reflexivity** urges us "to blur the boundary between our role responsibilities and wider moral responsibilities" [16]; **Inclusion** aims at broader public participation in our activities to identify desirable outcomes for the society, opposed to or balancing expert-driven top-down decisions; **Responsiveness** demands to alter our path if necessary and avoid undesired technological outcomes, linked to "questions of ethics, values, transparency, norms, accessibility or risks" [16].

The aforementioned considerations were the main motivation to host the first MASTER Modelling Workshop from March 2-4, 2021. The goal was to initiate the discussion on how collaborative approaches can be established within the community, the latter being a quite diverse group of space debris experts, users and non-professional actors. As a simplified instructive example, Figure 2 shows how the different groups involved in space debris modelling are interconnected. The *Model* (in our case MASTER) provides flux estimates to inform *Mission* designers on associated risk and support in more resilient platform designs. On the other side, *Measurements* are collected by active and passive means and serve in the validation and calibration process of the *Model*. A circular relationship can be established by identifying the potential support missions can provide to the measurement community, e.g. by hosting sensors or even through enhancing the capabilities of their satellite such that it starts *sensing* impacts to be detected on-ground through analysis of telemetry, orbit and attitude determination data. This example shows why a space debris model is more than a *digital twin* of the space debris environment. While the mechanical description is one part and fits that analogy, the rather challenging aspects go well beyond *digitalisation* and require care and agency in the existing and evolving relationships. For the workshop, we therefore asked two questions:

- Who are the stakeholders, how are we connected and how would we raise the awareness of everyone's activities?
- Where is the potential to improve stakeholder participation in all essential areas in space debris modelling?

In practical terms, the proposed stakeholder participation approach relies significantly on the willingness and ability of everyone involved (or not yet involved) to contribute. Considering that most of us are embedded in governance and economic schemes incentivising rather the opposite - namely short-term and disciplinary thinking - such an approach will require us to start the transition from asking "what's in it for *me* (or *my* organisation/country etc.) today?" towards "what's in it for *us* tomorrow?". And there is a chance of achieving this when we start to identify a common purpose in the activities we are all engaged in: to provide future potential for innovation in the realm of space technologies, a sustainable space environment is in the interest of everyone and means that *us* necessarily includes *me*. Or to say it in Jensen's words: "But what if the point is not to rule, but to participate? What if life less resembles the board games *Risk* or *Monopoly*, and more resembles a symphony? What if the point is not for the violin players to drown out the oboe players (or worse, literally drown them or at least drive them from the orchestra, and take

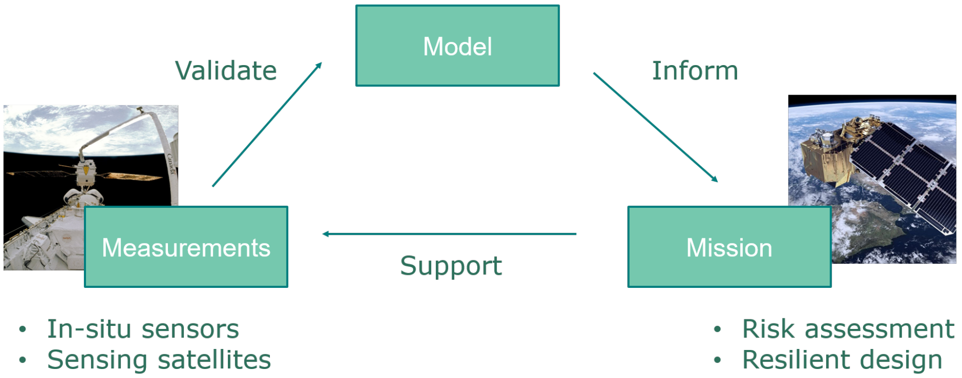

Figure 2: Example for the interaction and agency in the space debris modelling context.

their seats for more violin players to use), but to make music with them? What if the point is for us to attempt to learn our proper role in this symphony, and then play that role?" [12]

The next sections discuss the results of the MASTER Modelling Workshop and the first steps made by ESA towards collaborative modelling and mitigation in the frame of the Debris Mitigation Facility (DMF).

2. MASTER MODELLING WORKSHOP 2021

The MASTER Modelling Workshop was held virtually from March 2-4, 2021, organised by ESA's Space Debris Office (SDO) in cooperation with Michael Clormann from the TU Munich's Munich Center for Technology in Society (MCTS). Each day of about 4 hours had a different focus, where the participants were following selected presentations in the first half to set the context for the second half of the day: here, the participants would break-out into smaller groups and discuss among each other key questions related to space debris modelling. To facilitate interactive collaboration, the MURAL[1] digital workspace tool was used in those sessions. An example for a mural the participants created in one session is shown in Figure 3. The main topics for each day and the topics for each moderated group session were defined in advance by the organising committee. The participants were assigned randomly to the different sessions, with a few manual optimisations to attain a good mix of domain experts and people not necessarily familiar with a given topic (or even from an entirely different domain) in the same group. After about 60 minutes in the break-out groups, the participants met again in the main virtual room to present the outcome of their discussions to the larger group and allow for questions and feedback.

The three days had between 80 and 100 participants each, with professional backgrounds including mission design, economics, space agencies, space debris modelling, project management, space debris observation and monitoring, system engineering, telecommunications, insurance, and also many trainees and students, some being exposed to the modelling activities of the community for the first time.

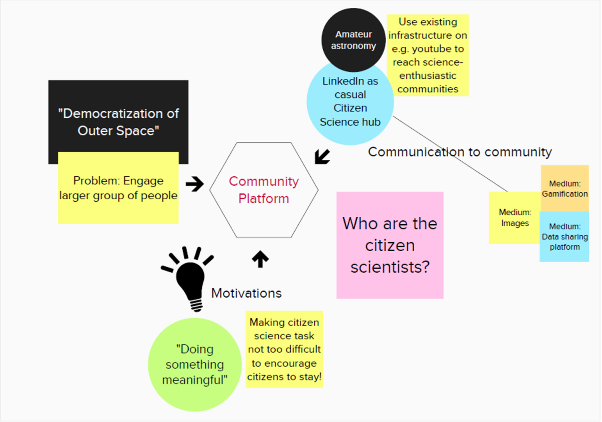

Figure 3: Mural created in a break-out group session at the workshop on the first day. The moderated discussion here was about citizen involvement and possible support from the general public.

In the following, a synthesis of the various presentations, group discussions and additional feedback received is presented for the three thematic days.

2.1. Day 1: Measurements & Validation

The first day was all about the measurements that are required to shape our understanding of the environment and create the basis for model development and validation. As larger objects are typically monitored by ground-based sensors and detailed object and orbit information is available (for instance via the public Two-Line Element (TLE) catalogue), modelling efforts are rather targeting the so-called *sub-catalogued* debris, typically below sizes of a few centimetres in LEO, which was also the focus in this workshop. Those measurements fall into five main categories:

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[1] https://www.mural.co

Remote sensing includes Beam Park Experiments (BPE) and dedicated survey campaigns with ground-based radars and telescopes. In the validation process of MASTER, several such BPEs by Fraunhofer's Tracking & Imaging Radar (TIRA) as well as radar detections from the European Incoherent Scatter Scientific Association (EISCAT) are used. Moreover, for higher altitudes in the vicinity of the geosynchronous orbital region, ESA's Optical Ground Station (OGS) in Tenerife, Spain, is regularly employed during surveys to collect information on objects in that region down to about 15 cm size. Space-based radars and telescopes dedicated for debris detections are currently being evaluated in concept studies and might represent additional options in the near future.

Active sensors come with a variety of designs, including impact ionisation detectors, like the Geostationary Orbit Impact Detector (GORID) flown in 1996 on the Russian Ekspress-2 satellite, or sensitive foils, such as the Debris In-orbit Evaluator (DEBIE) flown on the PROBA-1 satellite and the International Space Station. The advantage of these sensors is that measurements are time-tagged. In the case of the Interplanetary Dust Experiment (IDE) flown on the Long Duration Exposure Facility (LDEF) between 1984 and 1990, short-term flux variations were registered, which could later be correlated with SRM firings [31] and help in the validation process for individual firing events. One disadvantage is that detailed chemistry to support establishing the impactor's origin is limited.

Passive sensors usually come with larger areas and less complexity when compared to active sensors, like with LDEF's Chemistry of Micrometeroids Experiment (CME). Typically they come with very low energy consumption but require a sample return mission. For the MASTER validation, data from LDEF is being used.

Opportunistic returns are any recovered materials with earlier space exposure not specifically designed to collect impacts. Craters have been counted on returned solar panels from the Hubble Space Telescope as well as the European Retrievable Carrier (EuReCa) and are considered in the MASTER validation process.

Photographic surveys were already conducted during the Shuttle era, e.g. when approaching the Mir [6]. The recently conducted impact crater survey of the outer hull of the International Space Station's (ISS) Columbus module after ten years of exposure revealed many impact craters with the evaluation of the results still on-going [29].

2.1.1. Measuring the sub-catalogued population

Several concepts currently under design for planned missions or awaiting flight opportunities were presented during the workshop, such as the Orbital Dust Impact Experiment (ODIE), a retrievable passive detector developed by the University of Kent [33]; the Solar panel-based Impact Detector (SOLID) developed by the Deutsches Zentrum für Luft- und Raumfahrt (DLR) as an active detection layer below the solar cells, flown recently on TU Berlin's Technosat [1]; the Austrian Particle Impact Detector (APID) as a piezo-electric active sensor in combination with a short-wave radar planned to be flown on board the Austrian Debris Detection Low Earth orbit Reconnoiter (ADLER-1) in late 2021 by the Österreiches Weltraum Forum (Austrian Space Forum, ÖWF) [2]; and the DEbris Density Retrieval & Analysis (DEDRA) sensor, an impact ionisation sensor based on the Munich Dust Counter (MDC) planned to be flown on the Munich Orbital Verification Experiment (MOVE-III) satellite [26]. Recognising the diverse parallel developments with a common objective to sample the space debris environment, a further strong argument for a participative approach can be made: to bring different actors together with the common purpose to improve the knowledge on the environment and facilitate the incorporation of the measurement data into the MASTER model validation. Ideally, such a community would coordinate (or orchestrate) different missions to cover spatial (e.g. LEO, MEO or GEO) and time domains as good as possible. Moreover, exchanging on the lessons learned in sensor design (for instance, to use a Palladium coating preferred over Gold, as was used on-board LDEF, in the ODIE design to improve chemical residue analysis), the measurement process and associated constraints as well as learning what modellers expect establishes the need for a community approach.

In order to maximise scientific output from a statistical significance point of view, any in-situ instrument (whether active, passive or opportunistic) would have to be designed to maximise the expected number of impacts which implies large surface area and exposure time. This conflicts with the trend of satellites becoming smaller and spending less (operational) time on orbit. To compensate for that trend, it appears natural to use as many flight opportunities as possible for various sensors. In practical terms, ESA presented at the workshop the Distributed Space Weather Sensor System (D3S), which includes hosted payloads and a small satellite mission, targeting the small debris environment via instrument developments in accompanying ESA technology programmes.

Another aspect discussed by the participants was the possibility to screen telemetry data down-linked from operational satellites for potential impacts. The higher the sensitivity of instruments on-board (e.g. for the attitude control system) the higher the likelihood of detecting impacts in the data. This involves reaching out to the owner/operator community and to think together about incentives to exchange that information for model improvement. Current barriers for such an exchange may exist due to the data sensitivity, but it was also mentioned during the workshop that the owner/operator community

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[2] https://adler.oewf.org/

might not be aware of the potential behind the data in the modelling context.

2.1.2. Observation gaps

Considering that ground-based capabilities to monitor (or survey) the debris population reach sensitivity limits in the centimetre (cm) or even millimetre (mm) regime in LEO, this size domain can be perceived as the transition region towards favouring space-based (or in-situ) measurements. From a space mission risk perspective, even mm-sized objects can penetrate common wall designs, while smaller objects are typically shielded off and rather lead to surface cratering and associated degradation effects. It is therefore often argued that a better understanding of the mm-regime, especially in the so-called *observation gap* between 1 mm and 3 mm (in LEO) or 7 mm to 10 cm (in GEO), is of utmost importance to assess mission vulnerability. The problem is that the expected number of impacts in that regime for any typical sensor deployed will be very low. Furthermore, especially for the active sensors, a significant flight heritage comes from sampling the meteoroid environment (like in the case of the MDC). The question then is: how can those sensors contribute in a meaningful way to our understanding of the mm-regime if they only measure in the tens to hundreds of microns domain? Or asking differently: would we be able to learn or say something about the mm-region without having direct evidence from that same region? The modelling philosophy behind MASTER is to apply size distributions for individual source terms. In Figure 4 an example for the MASTER-8 reference population on November 1, 2016 is shown. For the current space debris population, the mm-regime presents us with another kind of transition: while explosion fragments are the dominating source contribution down to object sizes larger than about 0.5 mm, for even smaller objects, the ejecta population starts to prevail the flux observed by a satellite. For instance, at 1 mm, the difference between explosion fragments and ejecta is about one order of magnitude. An MDC collector flown in LEO and measuring in the size domain of tens of microns would ultimately establish supporting evidence for the ejecta size distribution. A calibration process or model tuning would ultimately result in an update in the mm-regime as well, under the assumption that the model's size distribution is justified. At the same time, when approaching from the larger size regime, improvements in breakup modelling and (ground-based) observations in the cm-regime provide evidence to support the extrapolation of the size distribution power law well into the mm-regime. It is therefore possible to leverage on the knowledge attained from measuring dust-sized ejecta particles as well as for larger fragments and establish confidence in the mm-regime even before having any measurements in that region. For the ejecta model, this may also include model improvements for cratering mechanisms and surface materials currently used. Similarly, for explosion fragments, potential improvements include single event calibration and reconstruction as a common practice in model validation. Of course, this does not weaken the need to pursue measurements in the mm-region. In fact, a model could inform on the inherent model uncertainty for different orbit and size regimes to indicate the need for better observation coverage by asking, for instance, how much monitoring is required to reduce the uncertainty by a certain factor.

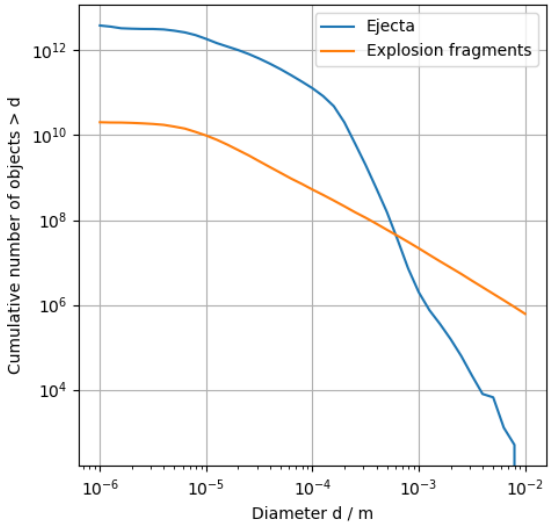

Figure 4: Cumulative number of ejecta particles as a function of size at MASTER-8 reference epoch (Nov 1, 2016).

2.1.3. Data accessibility

Another important aspect discussed during the workshop is data accessibility. Especially radar data may be subject to export control and not readily available for model validation. Moreover, limited knowledge of the actual properties of employed radar systems for the same reasons impedes the modelling of such systems to attain reasonable comparisons between actual and modelled debris populations in the measurement space. And while the participants shared the view that data policies should already be established early enough to facilitate its usage in the model validation, there are also examples of how to make use of certain knowledge without direct data availability. As an example, the size distribution of MASTER's NaK population was calibrated on a derived graph from the measured distribution [17].

2.1.4. Involving the community

What does it mean in practical terms to achieve a broader community involvement? Several examples were discussed, such as the relationship between modellers and mission designers: the understanding of the model characteristics may diverge, for instance when a mission designer would reasonably assume the same quality behind the model's validation irrespective of the considered object size and orbit regime. The recently introduced flux uncertainties in MASTER-8 give a first insight to better account for design margins. The need to have different space debris models was discussed: as long as there are large knowledge (or observation) gaps, resulting in deviations between model and reality, different model assumptions and philosophies provide the means to inform the community of such discrepancies and potential ways to improve. If knowledge gaps would decrease, the different models can be expected to converge. This has been demonstrated in comparisons between MASTER and NASA's Orbital Debris Engineering Model (ORDEM) [18, 7]. Considering the co-evolution of ORDEM and MASTER, with the latter's history outlined earlier, and especially in view of the many bilateral modelling workshops through the 1980's and 1990's but also continuing exchanges these days, the existence of these two models alone is a very encouraging example for what can be achieved collaboratively.

With a growing number of observers in academia, in networks like the International Scientific Optical Network (ISON), and in planetary defense, meteoroid science and space weather groups, the need to raise awareness towards their potential contribution to space debris modelling was discussed. A potential approach could be a community platform serving as a general information hub, but also as a *stack exchange* platform where users and developers can discuss ideas, use-cases, problems and software issues together. The first step towards such a platform is currently being made in the DMF development (see Section 3).

Involving the general public was another key aspect discussed. With the on-going yet sometimes unfulfilled goal of democratisation in the NewSpace era, the level of interest to get involved in modelling aspects may also be increasing. Enthusiastic communities could be identified and reached with citizen science experiments, tutorials or gamification. The DMF user platform may facilitate broader participation.

2.2. Working with MASTER

On the second day the emphasis shifted towards the output side of the model to identify use-cases and discuss how they are currently met or how they could be improved.

2.2.1. Mission design

One of the most common use-cases for the MASTER model, which historically has grown in parallel to the model's use in understanding the environment and assessing mitigation options, is to conduct space debris and meteoroid risk assessments during mission design. While at earlier project phases coarse system parameters allow for initial assessments using the DRAMA/MIDAS (MASTER-based Impact and Damage Assessment Software), more detailed risk and vulnerability analyses for mature and complex satellite designs are facilitated through dedicated applications like Systema-Debris, ESABASE2/Debris or the Particle Impact Risk and Vulnerability Analysis Tool (PIRAT) [3, 14]. Several participants pointed out how useful a standardised output from the model is, referring to the Standard Environment Interface (STENVI) supported by MASTER. Even though being a de-facto standard, STENVI may come with different flavours [25, 10] and therefore the need for an actual standardisation has been emphasized. This would include suggested support of different reference frames and interplanetary missions. Regarding the latter, the analysis of meteoroid flux in Lagrangian orbits has been introduced with MASTER-8, but additional use-cases were found in the meantime such as the support of Earth flybys (a recent case was BepiColombo in April 2020) or exploration missions in general that either interfere with Earth's space debris environment or are considered for meteoroid impact assessments only when outside Earth orbits.

The discretisation of the MASTER population was discussed, including spatial, temporal and object size classes. The reasoning or the justification for the discretisation offered by the model is not always understood and could be supplemented with additional analysis, documentation and practical guidance. One example for the latter could be to inform on how the model would be most reasonably used for multi-year missions given the yearly population snapshots by MASTER. As the software automatically selects the yearly population file closest to the epoch under consideration, results may become sensitive when the epoch under consideration falls in between two adjacent population files.

MASTER provides the background population for the DRAMA/ARES (Assessment of Risk Event Statistic) software, where the resulting flux coming from the model for a given target orbit is paired with catalogue uncertainty information to evaluate operational collision avoidance strategies [2]. ARES has gained popularity recently with the emerging requirement for satellite owner/operators to prepare a collision avoidance plan and manage on-orbit collision risk actively [11]. As an example, the collision avoidance support planning for the ESA missions XMM and Integral (both in high-eccentricity orbits) was presented during the workshop, using ARES and the newly developed Python package in DRAMA, which supports parametric analyses. In the case of XMM and Integral, an acceptable collision probability level, serving as the manoeuvre threshold, was analysed with respect to the mitigated risk and established for the seasonal crossings of the protected regions in LEO and GEO. As such missions can be operational over decades (XMM was launched in 1999), re-assessments of the mission-terminating risk may show significant variations with ongoing model evolution, but also the evolution of the environment itself.

During the group discussions, participants recognised the value in stronger engagement and exchange with mission designers. This could be possible via surveys, dedicated fora and workshops or a regular newsletter. The advantages of early involvement of expert users from the community became already apparent during the development phase of MASTER-8, where users provided feedback and communicated their needs as alpha testers. A detailed and publicly available development roadmap could facilitate such involvement and ensuing communication would make sure model developers understand the main use-cases of the model to address the primary needs of the user community. Moreover, exchange along those lines may contribute to trust and confidence building within the community and enable the exchange of very useful but otherwise sensitive and thus typically undisclosed information from observed satellite anomalies or telemetry data. Mission designers and operators would benefit from a spirit of transparently sharing best practices, recommendations and use-cases involving MASTER.

2.2.2. Environmental impact assessment

While the main focus in mission design is the actual satellite and its interaction with the environment, another very important branch that has grown considerably over the years is the assessment of the environment's evolution in view of the past, current and planned traffic and followed mitigation practices. The MASTER software is being used to provide past, current and future flux estimates and related to the operational practices of space missions, including potential breakups and assessing their environmental consequences. This facilitates the current development of techniques to assess the sustainability of space missions, including the carrying capacity, environmental indices [22, 20], the Space Sustainability Rating (SSR) [21] or the recent evaluation of the environmental impact of the entire fleet of ESA satellites [19]. Such analyses are generally very sensitive to the model's future predictions. This not only involves the discussion on potential scenarios but also the model's structure as well, including the granularity provided in its parameters, including orbital regions, size regimes and snapshot epochs (see also Section 2.3).

2.2.3. Model uncertainties

The MASTER-8 model upgrade included establishing a first approach to provide flux uncertainties. Being based on the deviation of the model's provided flux to actual flux measurements and recognising that obtained measurements can be very different, especially when comparing the small to the large object validation, the object diameter spectrum was identified as the essential information common to all measurement types currently part of the MASTER validation process. The measurements from different survey campaigns obtained over the last decades (for the large object validation) and returned surfaces (for the small object validation) had to be reasonably combined to establish the flux uncertainties across the entire diameter spectrum. The many challenges besides the discretisation of the diameter spectrum involved aspects of inter- and intra-sensor weighting or information aging [8]. The latter relates to the fact that the latest returned surface used in the MASTER validation is the Hubble Space Telescope's solar panel recovered by the Space Shuttle (STS-109) in March 2002. How can environmental data from more than two decades ago inform on the current model's validity (i.e. with respect to the current environment)? A certain validity results from arguing that space debris source mechanisms, once reasonably understood, would provide the means to extrapolate: an SRM burn in the 1990s, given a similar design, may result in the same slag and dust characteristics when it is also being used in the 2020's. However, the latter example may also be flawed, especially in view of the sharp decline of SRM usage over the past few years.

The first advantage identified during the design and implementation of the flux uncertainty approach was its suitability in the validation process: as a general statement, if it is possible to improve the model, one could expect to achieve smaller uncertainty. It was further identified that the validation process could address the peculiarities of single (and major) events. For instance certain survey campaigns after 2009 obtained a large share of measurements coming from fragments of the Fengyun-1C Anti-Satellite Test (ASAT) and/or the Cosmos-Iridium collision event.

Options to further automate the validation were studied already during the upgrade of MASTER-8 and were also discussed at the workshop. Given the many heterogeneous data sources, machine learning techniques could prove useful to characterise those data sets, but it was also pointed out that a rather labour-intense aspect is the research and the forensics involved in establishing the event database.

The importance of flux uncertainties was emphasized, as it enables to apply less conservative margins in mission design.

2.3. A Future Scenario

The third and last day of the workshop was about looking ahead. In technical terms and from the modeller's perspective, it entailed questions related to the anticipation of space flight trends (in launch traffic, explosion rates, post-mission disposal behaviour) and what a useful and workable scenario would be for the broad use-cases of the model. Beyond this, talking about a future scenario also involves recognising the growing system dependency and risk as discussed earlier. Therefore, the third day was about identifying potentials for stronger and more comprehensive stakeholder participation to facilitate the ongoing dialogue on (societal) risk perception and mitigation which is necessarily connected to and thus shaped by the predictions made by the environment model.

2.3.1. Initial conditions

The MASTER reference population provides the initial conditions of the space debris environment in all major environment evolution studies, mainly coordinated over the past decades on IADC level. Assuming a further democratisation, which can be understood in this context as even more actors carrying out environmental impact and evolution assessments in a non-centralised way, it becomes more important to make transparent and broaden the discussion about model assumptions, initial conditions, derived metrics and objectives in such activities. This is necessary to guarantee comparability and improve understanding of the situation of space environment sustainability beyond the relatively small circles of space sector technical experts.

In several workshop presentations, the need to have more contextual information about the objects (such as the type, origin and public ID, if available) of the initial population was highlighted.

2.3.2. Modelling the future

The current approach in modelling the future evolution of the environment with MASTER is to identify trends in events generating debris (such as SRM firing or explosion rates), in disposal behaviour and in launch traffic. Based on those trends several assumptions are made on how the environment may evolve in the future (more details can be found in the MASTER-8 documentation [9]). As an example, the current 8-year launch traffic pattern of the years 2009–2016 is continued as a repeated cycle to cover the entire projection span. Given the recent sharp increase in launch rates, one may question this approach and consider additional input, for instance envisaged satellite constellation deployments, more general market forecasts (e.g. [30]) or, as also mentioned during the workshop, to link national budgets with launch activity. Moreover, one should be mindful of growing military activity (including ASATs) also signficantly contributing to launch activities and the debris population. Besides the launch traffic, the need to consider in more detail the compliance rates (including the uncertainty, such as the question which post-mission disposal rate to assume for emerging large constellations) and operational concepts (including potentially commercial active debris removal and on-orbit servicing) but also a revisit of the currently non-correlated explosion rates was highlighted.

During the discussions, it turned out that different groups may agree on a common baseline (initial conditions and modelling assumptions) but have different objectives when working with the projections. Mission designers may require a plausible scenario (e.g. by extrapolating current trends) paired with a more pessimistic (or worst-case) output to consider margins and have a span on the order of a few decades covered. Other groups may want to have those or even additional scenarios for much longer time periods on the order of centuries or even millennia. Longer spans, for instance, facilitate the dialogue on carrying capacity and associated indices to inform on the sustainability of the environment.

Given the fluctuations in launch rates mentioned earlier, the question was raised on how often population updates should occur in MASTER. A reasonable time span mentioned was on the order of 1 to 2 years, which is in line with the current idea to automate the MASTER population processing pipeline to facilitate those faster updates. This could be paired with an archive where besides the latest population files, older versions would also be made available to the users.

2.3.3. Stakeholders and engaging with society

In a dedicated session, we discussed additional direct or indirect stakeholders of the MASTER model. Different groups were identified, with many already represented at the workshop (as mentioned at the beginning): mission designers (including commercial operators and constellation designers), researchers, academia (including student groups designing and launching small satellites), insurers, software developers, engineers (including instrument developers), legislators, spacecraft operators (e.g. via anomaly/failure investigation), financing companies and other emerging stakeholders. An interesting example are the 30-35 world-wide direct space insurance companies, which use the model output combined with anomalies and claims made by their customers to derive the premiums they can offer, thereby acting as an enabler of innovation and investment towards a cleaner environment. The recent discussions about light pollution and the need for *dark skies* at UN level emphasized that models can inform astronomers and, even more general, humans and non-humans alike in what the night sky may look like in the future.

A dialogue on what we, as a society, value and expect from spaceflight activities, could pave the way towards value-based regulation, valuing orbits and applications and, on the other side, introduce the necessary restraints or bans to keep all the activities within limits. Here, new procedures which are designed to properly deliberate opportunities and risks of certain uses of the space environment were identified as critical. It was mentioned that the risk posed by space debris could eventually backfire and put the credibility of spaceflight activities and the institutions that govern and conduct them at risk.

We discussed stakeholder's potential motivations to contribute to the shaping of space debris futures. Are the motives for more participation financial? Are they personal? Or even more altruistic? They seem to range from attaining intellectual property rights to the creation of a common sense of belonging and a shared purpose by caring for the environment. Ways to get more people involved in contributing not only to MASTER but also to the broader governance of space debris were discussed and ESA's Ideas portal[3] was mentioned as an example to promote open innovation technologies relating to space debris.

Several potential improvements were discussed to facilitate the dialogue with stakeholders, including more passive ways like dedicated publications for the broader society or video tutorials but also rather active means through online/in-person trainings, participatory workshops and conferences, questionnaires and fora.

It was discussed how the MASTER model could be used to engage and consult people outside the space sector to understand and discuss the problem as well as collaborate in raising its agenda. The visualisations of the space debris population as a direct model output are already broadly used and help in public outreach activities triggering questions. The same is true for real pictures of the consequences of impact events (e.g. via the Space Debris Movie[4]). The recently and jointly released infographics and podcasts by the UN and ESA on the space debris problem are another example. It was mentioned that it might generally be difficult to get people rallied around an issue that seemingly does not affect them or their lives directly - and whether this means that only single catastrophic events may trigger a response or significant change. On the other hand, as became visible, there is a broad interest in space-related aspects in society at large which could be utilised to trigger a productive and timely public discourse on future space sustainability. Taking note of the rising general awareness of environmental sustainability issues, this may be used to finally include the near-Earth space environment to be part of and closely entangled with the system Earth.

3. DEBRIS MITIGATION FACILITY

Several years of active exchange and engagement in developing and establishing space debris mitigation practices collaboratively with agencies and groups worldwide, as well as ESA's policy to adopt the ISO 24113 standard and make space debris mitigation requirements applicable to all ESA projects, established the need to significantly extend the current compliance assessment capabilities. In 2020, the Debris Mitigation Facility (DMF) was initiated as a set of activities planned over a time frame of five years, with the objectives to

- integrate space debris mitigation related databases, tools and processes into a common framework;
- move towards digital engineering;
- improve and innovate existing analytical capabilities and
- enable an open source community approach.

The first industrial contract was awarded towards the end of 2020 (DMF-01), kicking off the development of the entire framework through the combination of existing functionalities from DRAMA and MASTER and combine them with compliance assessment procedures in a new Graphical User Interface (GUI). Following the model-based system engineering approach, the framework will be mission-centric, supporting several mission phases and multiple satellites. The next activities are about to start: while DMF-02 is an ESA-internal activity to improve the MASTER population processing, DMF-03 is in the tendering phase at the moment and will target improvements in the analysis modules. Further studies are currently being defined to be issued very soon.

3.1. User platform

With a community approach aiming to continue and improve the on-going interaction with users and stakeholders, the DMF-01 activity will provide a platform to facilitate such exchanges in a multilateral way, thereby reflecting on the mentioned ideas during the workshop of a common forum. The idea is to use this platform to resolve bugs and inform on known issues; to discuss feature requests and the interpretation of obtained results; but also to exchange mission or satellite models such as the 3D models exemplarily shown in Figure 5.

3.2. Python package

The release of an accompanying Python package with DRAMA 3.0 allowed to directly access the DRAMA analysis (command line) tools and enable an easy scripting for parametric studies. The user community quickly adapted to using those codes in their projects, which was reassuring and made the further development of those codes a priority also within DMF. The feedback received during the workshop but also in on-going activities (such as environmental impact assessment studies) is already part of the current roadmap for the Python package.

4. CONCLUSION AND OUTLOOK

Collaborative approaches have always been an integral part of ESA's efforts in space debris modelling and mitigation. The space debris environment today represents a major risk in view of the increasing space traffic and societal dependence on infrastructure in orbit.

The MASTER Modelling Workshop was initiated with the idea to bring current collaborative efforts to a new level and identify the potential of stakeholder involvement in the development of software, mitigation practices and improving the dialogue in the diverse community and society at large. The three-day workshop can be called a success given the very open and constructive discussions

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[3] https://ideas.esa.int

[4] https://www.youtube.com/watch?v=zT7typHkpVg

(a) Delta II second stage

(b) Mir

Figure 5: Examples for complex 3D models created with DRAMA.

about modelling and connected domains. The positive feedback received from the participants included the wish for a second edition and some new volunteers to moderate sessions if such a second edition occurred.

Based on the workshop results, the next steps include the establishment of a MASTER development roadmap which we would openly share and evolve with the community. The positive experience from involving external developers (and MASTER users) at an early stage in the testing of the upgrade towards MASTER-8 shall be continued.

To support the community collecting measurements of the environment, an openly accessible document on lessons learned and modelling practices appears to be a good idea to pursue.

Being aware that a community approach requires care, dedication and active agency of everyone involved, we can only reaffirm our motivation to continue on this path and are inviting everyone to join these efforts!

Time to act. Together.

ACKNOWLEDGEMENTS

The authors express their gratitude for all the support received from the volunteers in the preparation of the MASTER Modelling Workshop 2021 and making the moderated sessions possible: Nina Klimburg-Witjes, Francesca Letizia, Benjamin Bastida, Sven Flegel, Beatriz Jilete, Despoina Skoulidou, Quirin Funke and Tim Flohrer. We appreciate the various feedback and comments received before, during and after the workshop by many people. Finally, the workshop would not have been possible without the participants who were exchanging ideas during the presentations and even more actively engaging during the group sessions - making this first attempt an overall success!

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