OBSERVING THE UNSEEN: SUB-CM SPACE DEBRIS INSIGHTS FROM EUROPEAN SPACE AGENCY'S PAST AND ONGOING MISSIONS

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ABSTRACT

This study presents the findings from a comprehensive processing and analysis of the available DEBIE-1 in-situ impact dataset (2002–2024), including measurements from both Sensor Units. The resulting flux measurements are compared with both previous and newly released MASTER-8 population files from January 2025, highlighting differences between the model's predicted flux for various artificial and natural sources. Despite challenges such as detector size and noise sensitivity, the processed dataset provides valuable insights into the sub-millimetre object regime in space, serving as an independent source for validating very small space debris and meteoroid populations. The study also highlights ongoing efforts at the European Space Agency to enhance sub-centimetre debris monitoring, including design and development activities as well as early-phase missions currently underway.

1 INTRODUCTION

The rapid expansion of space activities and the continuous development of space infrastructure are inherently tied to the evolving space debris environment. Accurately modelling this environment remains a complex challenge, tackled by tools such as the European Space Agency's (ESA) Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) and the National Aeronautics and Space Administration (NASA)'s Orbital Debris Engineering Model (ORDEM). These models provide validated debris flux estimates crucial for risk assessment across different orbital regimes. Given the dynamic nature of space debris, frequent model updates are necessary, relying on both remote sensing and in-situ observations for validation.

Large debris populations are well-documented through ground-based tracking systems, with radar and telescopes cataloguing objects over 10 cm in the Low Earth Orbit (LEO) and 30–40 cm in the Geostationary Orbit (GEO). Technological advancements now allow for the detection of even smaller LEO objects, which are expected to be incorporated into catalogues in the near future. However, debris in the centimetre to sub-centimetre range remains largely uncharted, relying on statistical sampling via remote sensing, in-situ detectors, and analysis of retrieved space-exposed hardware. As these methods only provide population snapshots for objects up to a few millimetres, bridging the observational gap requires two key strategies: enhancing the processing of existing in-situ datasets and advancing new technologies to improve statistical models and reduce uncertainties in small debris population estimates.

1.1 ESA's MASTER model

ESA's MASTER is a semi-deterministic model designed to simulate the state of the space debris population for a historical reference and multiple decades into the future. It achieves this by incorporating various sub-models that account for predefined debris sources. Individual debris-generating events are modelled, with the resulting object clouds propagated forward in time. The current version, MASTER v8.0.3, includes the following sources [1]:

- Launch and Mission-Related Objects (LMRO) from the past launch traffic,
- Explosions and collisions, modelled with a modified version of NASA's Standard Breakup Model,
- Solid Rocket Motor (SRM) Firings, generated with empirical models for SRM Slag and Dust,

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- Sodium-potassium alloy (NaK) droplets, generated with dedicated release and leakage models,
- Paint Flakes, generated with a surface degradation model,
- Ejecta, generated by an Ejecta Model developed under an ESA contract,
- Multi-layer insulation (MLI), generated by an event-based MLI model,
- Background Meteoroid Sources, which are described by either a) the Divine-Staubach model or b) the Gruen Model.

Once historical population snapshots are generated up to a reference epoch, MASTER undergoes calibration using real measurement data. This process involves converting the model's flux output into a measurable quantity, allowing for direct comparison with observational data. For larger debris in LEO and GEO, sources such as TLEs from the Combined Space Operations Center (CSpOC) are commonly utilized. Smaller debris can be evaluated through in-situ detectors or by analysing surfaces retrieved from space missions. The small particle validation of the MASTER model has been performed using measurement data from the Long Duration Exposure Facility (LDEF), the returned solar arrays of the Hubble Space Telescope and the European Retrievable Carrier (EuReCa) [1]. The reference epoch of the current version of the model is Aug 2024 [2], with both the population files and the MASTER model being available for download from the Space Debris User Portal [3].

MASTER-8 forecasts 54000 space debris objects greater than 10 cm (9300 of those being considered active), 1.2 million space debris objects from greater than 1 cm to 10 cm and 140 million space debris objects from greater than 1 mm to 1 cm to be in orbit in 2025 [4].

1.2 Small space debris observations

The idea of in-situ impact detection stems from studies on the meteoroid environment and its effects on spacecraft and space hardware in orbit. Since the 1960s, assessing the flux capable of penetrating a spacecraft has been crucial for developing effective shielding, particularly for crewed missions. One of NASA's earliest initiatives to examine the frequency of small meteoroid impacts was the Pegasus Project, launched in 1965. Over time, space-exposed hardware and surfaces returned to Earth—such as the Long Duration Exposure Facility (LDEF)) [5] [6] [7], Space Flyer Unit (SFU), European Retrievable Carrier (EuReCa) [8], components from the Solar Maximum Mission (SMM), as well as the solar panels and camera of the Hubble Space Telescope (HST)—have provided valuable data on meteoroid and space debris impact flux.

Over the past three decades, several in-situ detectors have provided time-stamped measurements. In LEO, examples include the DEBris In-orbit Evaluator (DEBIE-1) on PROBA-1, DEBIE-2, and the Space Debris Sensor (SDS)-DRAGONS [9] on the Columbus module of the International Space Station (ISS). Other examples include the Système Opérationnel de Détection Active de Débris (SODAD) on SAC-D (Aquarius) and the ISS, the Micrometeoroid/Space Debris Detector (MDD) on a COSMOS 3M upper stage, the Munich Dust Counter (MDC) on BREM-SAT, the Solar Panel-based Space Debris Impact Detector (SOLID) on TechnoSat, the Austrian Particle Impact Detector (APID) on ADLER-1 as well as various detectors and experiments on the Mir Space Station [10] [11] [12]. In GEO, the Geostationary Orbit Impact Detector (GORID) [13] plasma detector collected measurements of small space debris and meteoroids from 1996 to 2002.

Remote sensing techniques have been widely used to observe and track space objects through ground-based instruments. The primary source of Two-Line Element (TLE) data is the Combined Space Operations Center (CSpOC) database, which monitors more than 39,000 space objects using the United States Space Surveillance Network (SSN) [4]. This space object catalogue is primarily maintained through ground-based radar for tracking objects in low Earth orbit (LEO), while large optical telescopes are utilized for monitoring higher-altitude regions like geostationary orbit (GEO). Additionally, specialized radar and optical telescopes are employed in sporadic beam-park campaigns to gather statistical data, detecting objects as small as approximately 2 mm in LEO and 8 cm in GEO. However, objects below these size limits remain undetectable by ground-based sensors.

To tackle the challenge of detecting small space debris, various space-based optical sensing systems have been explored both theoretically and experimentally. Passive optical detection methods, which typically involve cameras and telescopes, have been tested in space through photographic surveys conducted on the International Space Station (ISS) [14] and the Mir space station [15] [16]. Space-based telescopes and onboard cameras can utilize streak detection techniques, allowing for the observation of much smaller objects than those detectable from the ground. Beyond passive methods, active in-orbit sensing technologies, such as radar and LIDAR scanning systems, have also been investigated, with some concepts successfully demonstrated in space.

1.3 The Debris In-Orbit Evaluator

The Debris In-Orbit Evaluator (DEBIE) detector was conceived in 1996 as a low cost and resource dust sensor that could be used as secondary payload on spacecraft [17]. The very first DEBIE sensor system (also referred to as DEBIE-0) was flown on STRV-1c in a Geostationary Transfer Orbit (GTO) in November 2000. Unfortunately, two weeks after launch, a technical problem resulted in the receivers being shut down, allowing no telemetry commands to be sent to the spacecraft [18]. The successor of the first demonstration attempt was DEBIE-1. The detector flies onboard ESA's PROBA-1 satellite which was successfully launched in a polar LEO on October 22, 2001. DEBIE-1 completed its commissioning phase in July 2002 and has been collecting measurements ever since. The last sensor system flown was DEBIE-2, launched in February 2008 as part of the European Technology Exposure Facility (EuTEF) on the exterior of Columbus on the ISS. The detector was retrieved and returned to Earth in September 2009, after about 18 months of operations [18].

The DEBIE system is designed to detect particle impacts using multiple components, enabling the determination of a particle's mass and velocity. The sensor's front target consists of a 6 µm aluminium foil mounted on an aluminium mesh, with the foil maintained at 0 V for grounding. Sensors positioned both in front of and behind the foil collect impact plasma, while those mounted on the mesh measure impact momentum. Each sensor is connected to a charge-sensitive amplifier, assigned to a dedicated channel. More specifically, plasma grid wires located in front of the foil are charged at ±50 V to measure the charge generated when electrons (PL1e channel) and ions (PL1i channel) accelerate toward them. Behind the mesh, two piezoelectric crystals (PZT1 and PZT2) detect impact signals that are approximately proportional to mv, where m is the particle mass and v is the particle speed, at low to moderate velocities. At higher velocities, additional momentum from impact ejecta recoil introduces an enhancement factor. Foil penetration is identified through a signal in the rear plasma channel (PL2e), with the number of penetrations determining flux for a given density of Fmax (6 µm) [18] [19] [20].

The DEBIE sensor units underwent two calibration campaigns at the Max-Planck Institute for Nuclear Physics (MPI-K) in Heidelberg, Germany, using the MPI-K Van de Graaff dust accelerator. Calibration of the PZT sensors was conducted alongside the plasma sensor calibration for the DEBIE Flight Models. The first campaign, held in December 1999, focused on calibrating the two PROBA-1 DEBIE-1 Sensor Units: SU1 (ram-facing) and SU2 (starboard-facing), each with a detection area of 10×10 cm^2. Due to inconclusive results, a data reanalysis was undertaken, and a second campaign took place in June 2003, which validated the findings of the reanalysis. The detector response equations have been detailed in [18] and were used to derive the PZT and PL sensor curves, which define the instrument's detection limits, including the minimum detectable signal and saturation levels. For an ideal measurement, a signal must fall between the instrument's minimum and maximum thresholds for both PZT and PL sensors, ensuring a unique mass-velocity solution. To enable comparisons with models such as MASTER, [18] utilized the calibration equations and the PL1i channel response to determine the lower detection threshold for each sensor unit. For SU1, the minimum detectable mass is 4.68×10^{-15} kg, assuming a particle impact speed of 15.0±2.8 km/s, corresponding to a diameter of 1.52 µm (assuming a density of ~2500 kg/m^3). For SU2, the lower threshold is 3.65×10^{-14} kg at an impact speed of 7.5 km/s, corresponding to a particle diameter of 3.03 µm. The upper detection threshold considered in this paper, aligns with the saturation limit of the PZT channel, estimated at 3.5×10^{-10} kg or ~65 µm in diameter [20] [18].

2 PROCESSING OF A HISTORIC IN-SITU DATA SET

The small particle validation of the current MASTER population has been conducted using measurement data from four sources: the solar arrays retrieved from the Hubble Space Telescope during its first and third servicing missions (HST-SM1 and HST-SM3B), the European Retrievable Carrier (EuReCa), and the Long Duration Exposure Facility (LDEF) [1]. However, the validation is subject to limitations introduced by having real data that represent only specific size ranges, altitudes, and time periods. In more detail, the dataset used for the current validation covers low LEO altitudes between 475 km and 614 km, with the most recent being the HST-SM3B solar array, retrieved in 2002.

To expand the validation process, one of the Debris Mitigation Facility (DMF) activities (Small Flux Updates from Impact Detectors), conducted in 2021 under an ESA contract (Nr. 4000135757/C77-059), assessed 22 historic space debris and meteoroid impact databases for potential integration into future MASTER updates. Due to constraints related to data availability, sharing policies, and quality, only five datasets were successfully acquired and processed. These included unfiltered impact measurements from DEBIE-1, DEBIE-2, and GORID (sourced from the European Detector Impact Database [21]), alongside particle flux data from the SODAD instruments onboard the SAC-D satellite and the International Space Station (ISS), obtained from literature sources and direct communication [22] [23].

As part of the DMF activity, a processing tool was developed for the DEBIE and GORID instruments, featuring dedicated noise filters and the capability to estimate flux, mass distributions, and uncertainties under specific assumptions [24]. However, due to the short timeframe of the DMF activity and challenges in processing post-2016 DEBIE-1 impact data, only a portion of the dataset was analysed. The subsequent *Impact Risk Stochastics* project, whose results are published in [20] and [25], aimed to retrieve, process, and statistically analyse a more complete DEBIE-1 dataset, building upon the DMF in-situ impact detector efforts.

This work builds on the analyses performed in the frame of the *Impact Risk Stochastics* project and compliments it by a) processing the entirety of the DEBIE-1 dataset, including both Sensor Units, up to the latest known data retrieval in 2024, and b) utilising the latest published MASTER population released in 2025, with a reference epoch in August 1st 2024; an epoch that coincides almost perfectly with the most recently available DEBIE-1 measurements.

2.1 Raw Data Retrieval

The DEBIE-1 raw data have been retrieved from the European Detector Impact Database (EDID) [21].

In this work, we consider July 2002 as the official start of operations. During that time, the sensor's onboard thresholds were adjusted in an on-orbit calibration to reduce excessive false triggers caused by noise. As reported in [18], this adjustment resolved the issue of thousands of false detections in the first months of operation. At the time of writing, the last available sensor registration from EDID's latest data ingestion is 3 Nov 2024. The raw data consists of all data sets from both Sensor Units (SU1 and SU2). Figure 1 illustrates the EDID user interface for retrieving raw DEBIE-1 data. No filtering has been applied for the retrieval, as the Real Impact indicators currently available through the Portal are only representative for data before mid-2005 [20]. The total size of the raw data is approximately 1.7 GB, with more than 4 million sensor registrations. Approximately 80% of the raw data are registrations from SU2.

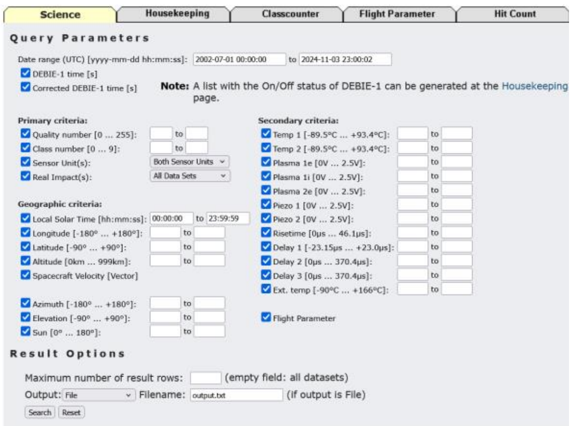

Figure 1: EDID user interface for the retrieval of the raw DEBIE-1 data.

The orbital and attitude files of PROBA-1, as well as the Sensor Status (On/Off) indicators were obtained directly from the satellite's housekeeping database.

2.2 Raw Data Handling

The preliminary processing has been performed using a python processing pipeline developed in the frame of the DMF-04 activity [24] in 2021. The pipeline can be used to process datasets from three in-situ detectors: DEBIE-1, DEBIE-2 and GORID and consists of a noise filtering module, a parameter conversion and uncertainty calculation module and a MASTER comparison module. For the purpose of this work, the pipeline has been utilised for the noise filtering of the raw DEBIE-1 set of SUs.

The filtering of the false events is based on the instrument-specific parameters determined during the instrument calibration and early data analyses, as reported in [18]. In more detail, the processing included: a) filtering out all noise events by considering the individual instruments channel thresholds and delays, b) filtering out noise events due to thermal cracking and/or battery and charging effects when crossing the terminator and c) filtering out of periodic cluster events during passings above the Kamchatka peninsula where a radar operates. An additional deduplication filter has been included, which ensures that multiple number of registrations with identical or near identical parameters within 3 seconds after each other are removed [26]. It should be noted that due to updates in the EDID data ingestion code, all data have been additionally converted back to the previous format to maintain compatibility with DMF-04 pipeline.

As reported in [24] and [20], SU1 showed an erratic behaviour during certain months between 2016-2018 and 2023, with very frequent triggering that could not be attributed to any known noise sources or spacecraft attitude changes. A similar behaviour is observed for SU2, starting approximately in 2018. The reduction of altitude which could be linked to atmospheric disturbances has been hypothesised [20]; however, no conclusive explanation could be drawn. These registrations, all exceeding the 93% quantile of monthly impacts, were classified as outliers.

The data reduction percentages following the application of each filter are included in Table 1. The filtered database includes a total of 714 registrations from SU1 and 151 registrations from SU2.

Table 1: Data reduction percentages for the two Sensor Units of the DEBIE-1 sensor following the application of four dedicated filters

Filter	Data reduction percentages	
	SU1	SU2
Channel Thresholds/Delays	99.42%	99.95%
Terminator	0.19%	0.02%
Kamchatka	0%	1.03%
Deduplication	0.03%	0.001%
Outlier detection	3.59%	7.63%

2.3 MASTER Simulation Setup

The comparison of the DEBIE-1 flux against the predictions of the semi-deterministic MASTER model offers an insight in the significance of the collected and processed data as well as in the accuracy with which the model can represent the sub-mm space debris and meteoroid environment in LEO.

For the purpose of this comparison, the position, velocity, and spacecraft attitude retrieved from PROBA's telemetry data have been utilized. The CState tool has been used to convert the state vectors in Keplerian elements for the MASTER runs. A total of 276 monthly runs were conducted for the period 2002-2024, well covering the known operation duration of the DEBIE sensor. The latest month considered for the comparison is August 2024, which coincides with the current Reference Population as, at the time of writing, the future population is not yet released. The individual sources have been used as input while the software version is MASTER v8.0.3. For comparison with the previous population files (Reference Epoch November 2016), the simulations performed in [20] and [25] have been repeated and included in the analyses.

Similar to the assessment performed in [20], the detector surfaces are modelled in MASTER as orbiting targets. Following an analysis of the attitude of PROBA-1 and the computation of the azimuth and elevation of the detectors in the orbital frame until August 2024, the basis that the SU1 is facing on average the flight direction and SU2 the starboard side is presumed. The assumption is backed up by MASTER's internal flux averaging per orbital revolution which accounts for slight changes in attitude accordingly [20].

The output of MASTER includes monthly fluxes (impacts/m^2/year) of the individual debris and meteoroid sources as described in 1.1. The flux has been scaled down to match the detector size and was normalised with respect to the time periods during which the detector was switched off. In order to compare the sensor's measurements with MASTER, the SU1 and SU2 impact data have been grouped in months and converted to flux.

3 RESULTS AND DISCUSSION

Figure 2 and Figure 3 illustrate the flux comparison between the measurements from SU1 and SU2 respectively, in comparison to the predictions of the MASTER model using a) the 2016 reference population files and b) the latest 2024 reference population files. The periods when the sensor was off, as well as the periods during which erratic behaviours were recorded are flagged and excluded from the Figure. In both cases, the average monthly flux measured by the SUs is in the same order of magnitude with MASTER's predictions, taking however relatively higher values. Given the limited data set for SU2, particularly after grouping the data monthly, many months contain only a single impact, which results in certain recurring flux values observed in Figure 3.

Figure 4 and Figure 6 illustrate the comparison between the cumulative number of impacts measured by SU1 and SU2 respectively, and to the MASTER-predicted number of impacts on an equivalently sized and orbiting surface. The differences between the predictions using the previous reference population and the new one are highlighted. On average, the newly forecasted small space debris population has been reduced, showing however a fast-increasing trend is observed, starting from the second half of 2023. As no meteoroid modelling updates are part of the new population, the meteoroid background annual flux remains unchanged.

Figure 5 and Figure 7 show the differences between the corresponding MASTER-predicted fluxes for all sources considered by the model. In both cases, the flux represents the two SU (ram-facing and starboard-facing) surfaces, accounting for their sizes and sensitivity. The following observed differences are of particular interest:

- A decrease of the collision fragments in 2007, likely attributed to the re-calibration and/or downscaling of fragmentation events [2].
- Differences in certain SRM events, attributed to revised event parameters of firing events as reported in the DISCOS [27] database.
- A substantial increase of the Paint Flakes flux starting around the beginning of 2023. The increase is likely attributed to the increase of LMROs, specifically the Starlink constellation objects, in PROBA-1's orbit, considering loss of altitude (approximately 580 km in the beginning of 2023) [2].
- A substantial increase in the Ejecta flux starting around the beginning of 2023, also attributed to the increase of objects in PROBA-1's orbit [2].

Overall, the findings show a reasonable compatibility between the post-processed measurements recorded by SU1 and the predictions of MASTER. With the exception of the 2023 steep increase showed by the 2024 Reference Population, both DEBIE and MASTER's fluxes show similar trends throughout the years. Increases in number of impacts following certain fragmentation events in the vicinity of the sensor have been studied in [20], with no direct correlation established, suggesting that DEBIE did indeed detect ejecta, SRM dust, paint flakes and meteoroids primarily.

As highlighted in [20], a significant challenge encountered during the processing of the DEBIE-1 data was the treatment of the periods in which false impacts were obviously still present in the dataset. Taking into consideration the significant reduction rates following post-processing, the importance of on-ground and on-orbit calibration and processing of sensor systems that are inherently susceptible to environmental noise is emphasized. A collection of lessons learned presented in [25] summarises considerations for future use of in-situ detectors and are therefore still relevant and in-line with the results presented in this study.

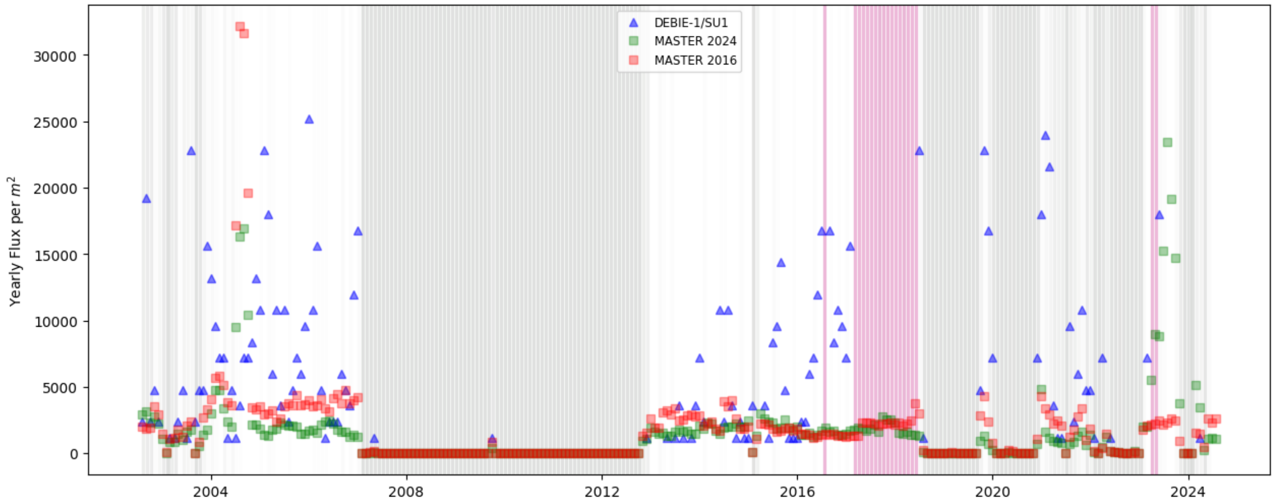

Figure 2: Space debris and meteoroid flux measured by DEBIE-1's SU1 compared to MASTER's predictions. In green markers, the flux simulated monthly with MASTER using the latest 2024 population. In red markers, the flux simulated monthly with MASTER using the previous 2016 population. In blue markers, the flux detected in a month by DEBIE-1/SU1. The status of the sensor is given in the background: grey when the sensor was off most of the month, purple when the data was erratic. All monthly MASTER fluxes have been normalised for the sensor's status. Similar to the periods when the sensor was off, the erratic sensor fluxes are not included in the plot.

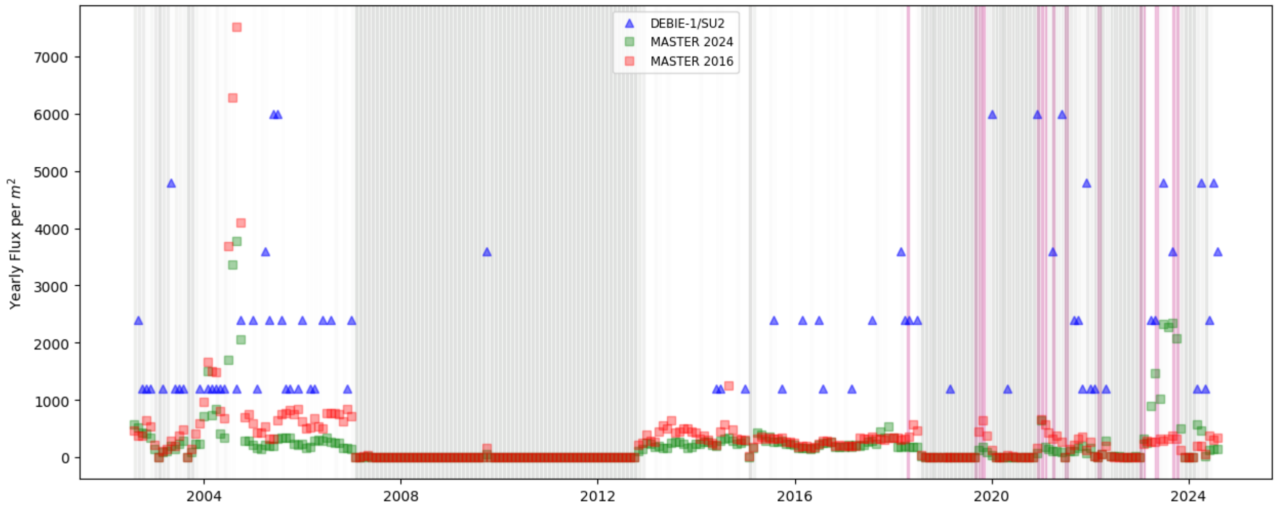

Figure 3: Space debris and meteoroid flux measured by DEBIE-1's SU2 compared to MASTER's predictions. In green markers, the flux simulated monthly with MASTER using the latest 2024 population. In red markers, the flux simulated monthly with MASTER using the previous 2016 population. In blue markers, the flux detected in a month by DEBIE-1/SU2. The status of the sensor is given in the background: grey when the sensor was off most of the month, purple when the data was erratic. All monthly MASTER fluxes have been normalised for the sensor's status. Similar to the periods when the sensor was off, the erratic sensor fluxes are not included in the plot.

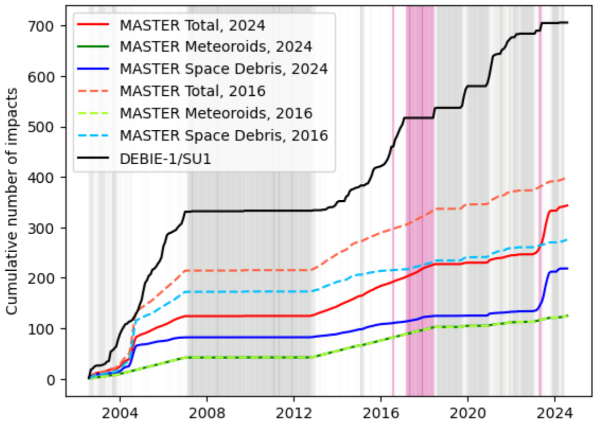

Figure 4: Cumulative number of space debris and meteoroid impacts from DEBIE-1/SU1 with respect to MASTER's flux using a) the 2016 reference population and b) the 2024 reference population. The status of the sensor is given in the background: grey when the sensor was off most of the month, purple the data was erratic.

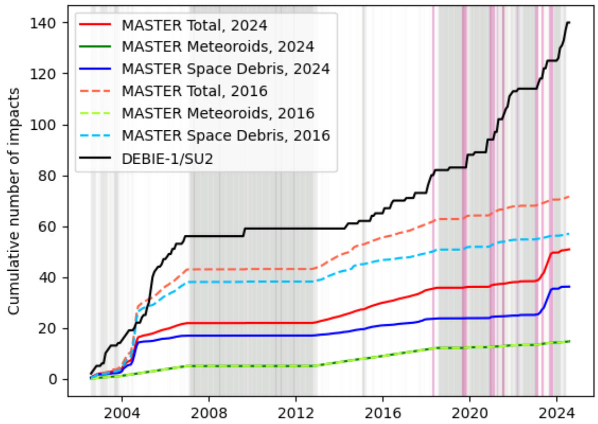

Figure 6: Cumulative number of space debris and meteoroid impacts from DEBIE-1/SU2 with respect to MASTER's flux using a) the 2016 reference population and b) the 2024 reference population. The status of the sensor is given in the background: grey when the sensor was off most of the month, purple the data was erratic.

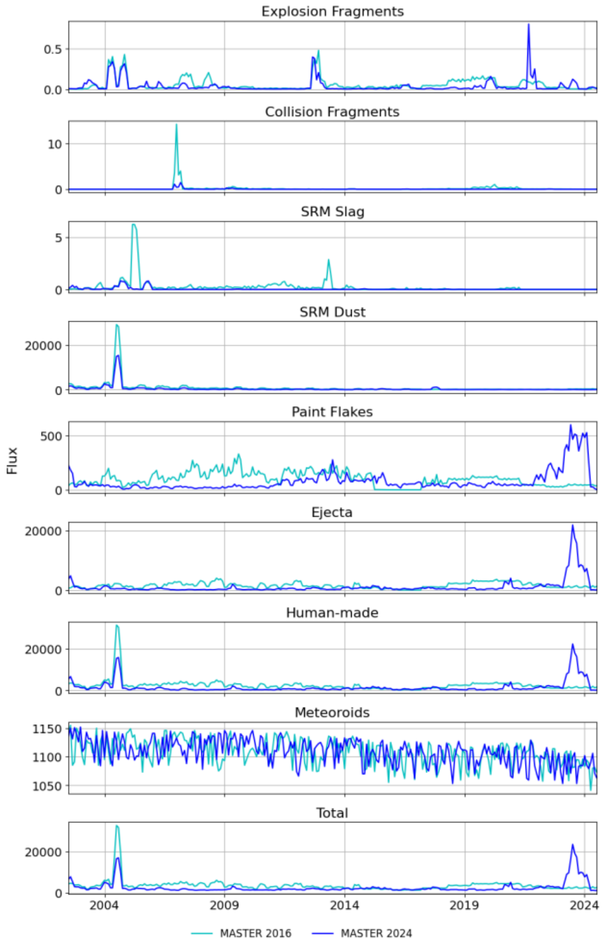

Figure 5: Individual source comparison between the 2016 and 2024 MASTER reference population for a DEBIE-1/SU1-equivalent orbiting surface. The diameters represent objects with sizes between 1-65 μm.

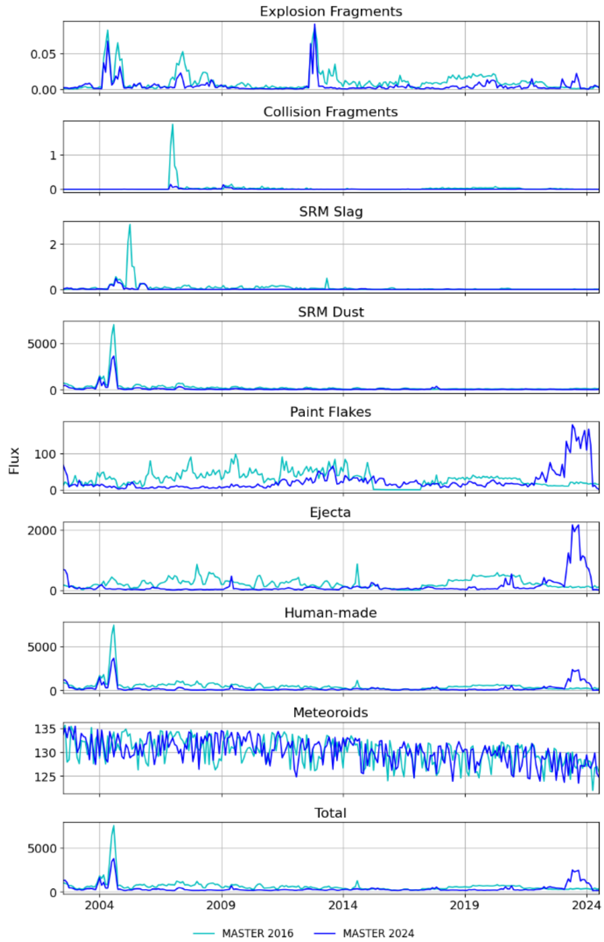

Figure 7: Individual source comparison between the 2016 and 2024 MASTER reference population for a DEBIE-1/SU2-equivalent orbiting surface. The diameters represent objects with sizes between 3-65 μm.

4 ON-GOING AND FUTURE ACTIVITIES

4.1 Sail Array for Impact Logging in Orbit

The small size of existing detectors and retrieved surfaces limits their ability to provide statistically significant impact counts for sub-centimetre particles. To address this, the proposed Sail Array for Impact Logging in Orbit (SAILOR) mission aims to deploy a large-area collector capable of capturing enough impacts for meaningful statistical analysis. This mission could serve as a foundation for sampling across various orbits and potentially be utilized by multiple missions. By measuring impact diameter, flux density, and velocity vectors of objects as small as 0.1 mm, SAILOR is expected to enhance and validate space environment models, focusing on critical orbital regions and particle sizes.

The mission concept involves large-area thin foils exposed to the microparticle environment for several years. A camera system will inspect and document impacts in situ, with images transmitted to Earth, providing an alternative to sample return missions and electronic impact detectors. The observation system will be supported by active in-situ detectors placed on the sails for cross-validation and efficient scanning.

A pre-phase A study conducted in 2022 confirmed the feasibility of the deployable sail concept [28]. The ongoing Phase A/B1 includes a critical review of this study, functional analysis, and mission trade-offs to establish a proposed baseline. Phase A focuses on identifying key technologies, defining preliminary system requirements, and outlining a system verification plan. Phase B1 will refine satellite requirements using Model-Based Systems Engineering (MBSE), define the system and sub-systems, and release technical specifications. Pre-development and testing of critical instruments will also take place, alongside risk management, integration planning, and cost estimation for the space segment, ground segment, and flight operations.

The project has completed the Mission Baseline Review (MBR), with the Preliminary Requirements Review (PRR) as the next major milestone, marking the conclusion of Phase A. The mission aims for launch readiness by 2029, a space segment mass under 100 kg, and reliance on high Technology Readiness Level (TRL) components for both platform and payload.

4.2 In-Orbit Coincident Laser Sheet Particle Monitor

The Coincident Lasersheet Particle Monitor (COLA) activity, completed in June 2023 under ESA Contract 4000133569/21/NL/CRS [29] [30], explored a laser sheet-based in-situ detection system for tracking space debris and meteoroids. Expanding on earlier research [31] [32], the proposed system uses a double laser sheet with optical detectors to capture time-tagged measurements. When debris or meteoroids pass through the laser sheet, they scatter, reflect, absorb, or transmit light, with a portion of the scattered light captured by a camera. By analysing scattering angles, the intersection point can be determined, while the size and shape of the scattering pattern provide insights into the particle's characteristics. A second laser sheet at a different axial position enables tracking at two points along its trajectory, aiding in orbit reconstruction.

Two detection concepts were developed and simulated using an Event Simulator (EvS). The first concept uses two continuous wave (CW) lasers combined with photodetectors to determine the particle's position and time-tagging. The second concept is based on a flash LiDAR system that uses pulsed laser sheets, where the backscattered light is collected by a single LiDAR, providing all necessary information to determine the object's trajectory and velocity. For each concept, the detection system consists of a light source to generate the laser sheet, an optical system for light transmission, laser sheet generation optics, collection optics, and a photodetector for capturing data.

As part of the EvS, an improved optical database was created, including 12 particle models with 11 different sizes and 6 orientations. Measurements were performed on sample types representing ejecta from carbon fiber-reinforced plastic (CFRP) targets at wavelengths of 500 nm, 700 nm, and 1100 nm to evaluate whether phase function variations across different wavelengths could help identify debris material properties. The particle database allows updates and modifications by users and is initially generated from the MASTER database based on mission parameters such as LEO, MEO, and specific orbital characteristics.

As part of the feasibility study, a Flight Model Development Plan (FMDP) was developed for the instrument, which remains applicable to any concept considered for further implementation.

4.3 Space Debris Optical Telescope

The concept of a space-based optical telescope for detecting small space debris in orbit has been one of the most enduring ideas explored for space debris observation missions. An envisaged mission, currently explored in the frame of the Space Based Observations Mission (SBOM) and Verification of In-Situ Debris Optical Monitoring from Space (VISDOMS) projects, aims to demonstrate and evaluate the potential of space-based optical telescopes for space debris monitoring using a small satellite platform [33]. Its primary goal is to enable statistical observations of sub-catalogue-sized objects in LEO and beyond, providing an initial assessment of the population density of debris in the millimetre to centimetre range from space. Additionally, the mission will explore the feasibility of tracking objects smaller than 1 meter at greater distances, such as those in GEO. The instrument is expected to feature a sufficiently large aperture to detect object streaks and accurately characterize debris. The mission is planned to operate in a dawn-dusk sun-synchronous LEO at an altitude between 600 km and 900 km, with a projected launch not earlier than 2029 [34].

5 CONCLUSIONS AND OUTLOOK

Building on the DMF activity, which identified and developed tools for processing space debris and meteoroid impact databases, and the Impact Risk Stochastics Research Project, under which two decades of DEBIE-1/SU1 data were processed and analysed, this study presents the findings from a comprehensive processing and analysis of the entire available DEBIE-1 dataset. This includes data from both sensor units and comparisons with the newly available MASTER 2024 Reference Population.

The processed datasets, which currently provide flux measurements along with mass estimates and uncertainties, show compatibility with MASTER's flux predictions and may be considered candidates for integration into the MASTER model validation process.

The processing effort and assumptions required to handle raw DEBIE data highlight significant challenges posed by historical in-situ datasets from active sensors. The size of the retrieved database underscores the importance of efficient noise handling and filtering, both on the ground and onboard. Additionally, the small size of a detector, combined with its placement and orientation, may further limit the usefulness of even long-duration datasets.

With the growing demand for improved space environment modelling and frequent population updates, various ESA studies and initiatives are addressing the challenge of closing the sub-centimetre gap in MASTER. To overcome the size limitations of historical detectors, the SAILOR mission proposes deploying large area sails capable of capturing sufficient impacts for statistical analysis without requiring an extended mission duration. The COLA project has explored advanced technologies, including laser sheets and LiDAR, which could not only determine object size but also infer shape and potential material composition. Meanwhile, the concept of an optical telescope in orbit, materializing through the SBOM and VISDOMS activities, focuses on capturing debris and meteoroid streaks in images, enabling object characterization through space-based observations.

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