DATA OF EUROPEAN IN-SITU IMPACT DETECTORS FOR ENVIRONMENT MODEL VALIDATION

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ABSTRACT

Space debris particles pose a significant threat to the safe operation of space systems. However, the fluxes of microparticles with sizes below 1 mm are not well known and thus, reliable data from in-situ microparticle detectors are required. This paper presents a summary of the microparticle sensor data included in the European Detector Impact Database (EDID). The focus is put on the DEBIE-1 dataset (DEBIE: Debris In-orbit Evaluator), which has been preliminarily analysed during the recent upgrade of the EDID. The analysis focussed on plausibility checks and a preliminary filtering of the large amount of noise events. Key findings of this analysis are presented by means of the evaluation of the latitude of events as function of time. The limitations of this analysis are addressed and their impact on the further use of the dataset is outlined. It is proposed to renew the efforts to process existing in-situ measurement data, to use the data to validate environment models, to develop new detectors and to plan and identify suitable flight opportunities for these instruments.

1 INTRODUCTION

Even very small space debris objects and micrometeoroid particles with sizes below 1 millimetre (collectively called microparticles) can pose a significant threat to the safe operations of satellites and other space systems or their instruments, respectively. Depending on the particle's size, speed, and impact angle, hypervelocity impacts can degrade surfaces, puncture sensitive structures, or damage internal components such as detectors of X-ray telescopes as happened during the XMM mission [8].

There are several means for the detection and analysis of microparticles such as the examination of scattering light on particle clouds (zodiacal light), inspection of surfaces retrieved from space (e.g. the Hubble space telescope solar generator) or spacecraft attitude disturbances (e.g. GAIA, LISA Pathfinder). However, these methods do not provide the required properties of a single particle (mass, velocity, directionality), as they integrate either over time or distance (or both).

Due to the named limitations, fluxes of microparticles are not well known. This leads to large flux uncertainties (up to a factor of 3, and in certain size ranges even larger) in space debris and meteoroid environment models (e.g. MASTER (Meteoroid And Space debris Terrestrial Environment Reference) or ORDEM (Orbital Debris Engineering Model) [9].

Therefore, it is of paramount importance to gather reliable data from in-situ microparticle detectors to validate and improve particle environment models. Furthermore, long-term measurements provide valuable information on the temporal evolution of the small-sized space debris population.

Several European in-situ microparticle detectors have flown or are still gathering data in Low-Earth Orbits (LEO) and Geostationary Earth Orbit (GEO), such as the Geostationary Orbit Impact Detector (GORID) or the Debris In-orbit Evaluators (DEBIE). The data of these sensors is stored, processed, and disseminated in the European Detector Impact Database (EDID).

This paper presents an overview of the microparticle detectors and the data collected so far, as well as some key findings based on preliminary processing and analysis of DEBIE-1 data. The recent upgrade of EDID will be presented. Furthermore, it underlines the importance of having continuous measurements of reliable microparticle fluxes in congested orbital regimes.

2 EUROPEAN IN-SITU MICROPARTICLE DETECTORS AND THE EDID DATABASE

The datasets in EDID consist of data gathered by different in-situ microparticle detectors operated by the European Space Agency (ESA) during different periods. GORID has been detecting impacts onboard the Russian Ekspress-2 geostationary satellite from 1997 to 2002. DEBIE-2 provided data from the International Space Station (ISS) and was mounted on the European

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Technology Exposure Facility (EuTEF) on the Columbus module from February to August 2008. Finally, DEBIE-1 onboard the PROBA (Project for On-Board Autonomy) spacecraft collects data from 2002 onwards and is still going strong despite almost 20 years of operation in a Sun-synchronous LEO.

2.1 The DEBIE Detectors

The concept of the DEBIE sensor was developed as a low cost and low resource dust sensor. It consists of several sensors to allow detections of impacting particles. Their signal could provide information on the particle's properties, such as speed, mass and (in some cases) density [1]. Several DEBIE sensor units (SUs) and their data processing unit are shown in Figure 1. The SUs make use of three plasma sensors, which measure the impact plasma produced, when the particle hits or penetrates a thin aluminium foil. Furthermore, two piezoelectric crystals (PZT) are located on the rear of the foil [1], which perform a kind of acoustic measurement of the impact and allow for so called coincident measurements in connection with the plasma sensor signals.

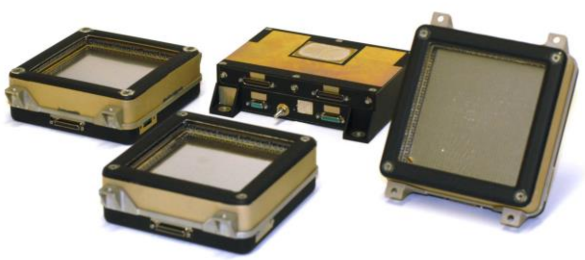

Figure 1. Models of DEBIE sensor units [2].

The DEBIE-1 system mounted on the PROBA-1 satellite consists of two SUs. The orbital configuration results in a fixed surface orientation with respect to the Earth [1]. This orientation is shown in Figure 2, with the first sensor unit (SU1) located in ram direction and the second sensor unit (SU2) to the right-side in-flight (starboard) direction in the nominal spacecraft orientation.

The plasma and PZT detectors are very sensitive and are triggered by several undesired effects such as for example thermal cracking, resulting in a high number of noise events in the measured impact data. Therefore, an extensive data analysis including the development of suitable filter algorithms became necessary.

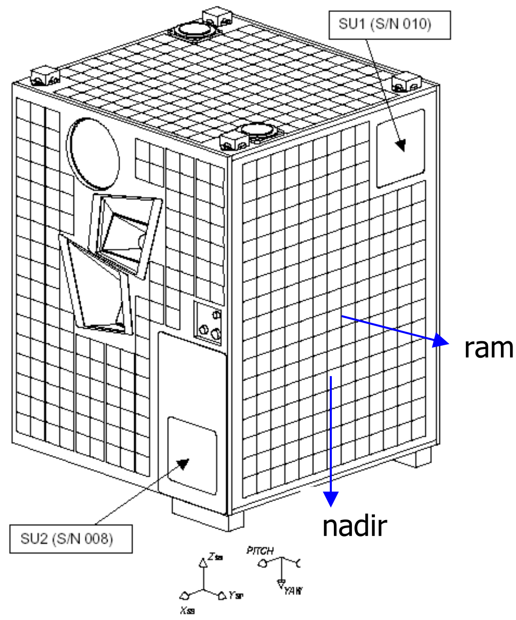

Figure 2. DEBIE-1 sensor unit orientation on Proba-1.

The DEBIE-2 system was mounted on EuTEF on the Columbus module of the ISS from February to August 2008. Its installation is shown in Figure 3. DEBIE-2 consists of three sensor units combined with one data processing unit. The SUs are oriented in the starboard (SU1), the Zenith (SU2) and the RAM (SU4) directions [2].

Figure 3. DEBIE-2 sensor units on ISS/Columbus/EuTEF [3].

2.2 The EDID Database

The EDID database is designed to provide an easy access to the impact data collected by the European impact detectors mentioned before. Historically, it was developed and operated by etamax space from 2002 to 2009. Afterwards, it was handed over to ESA's Space Situational Awareness (SSA)-Space Weather (SWE) service network in 2012.

Figure 4 shows the architecture of EDID. It extracts the necessary data from CCSDS (Consultative Committee for Space Data Systems) data packages and ASCII (American Standard Code for Information Interchange) files. After combining the sensors science and housekeeping data to calculate the position and attitude data of the satellite for each science/impact data set, they are inserted into the EDID database, which is based on PostgreSQL. User access to the data is provided via an Apache2 web server, which also allows for the generation of graphical representations of the retrieved data.

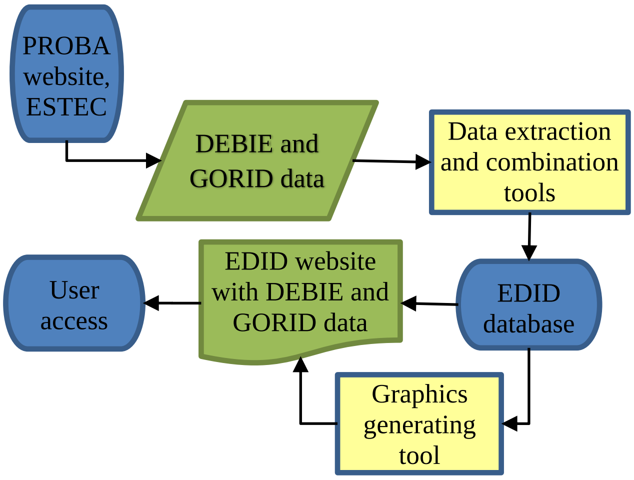

Figure 4. High-level architecture of EDID database.

The SWE instance of EDID contains all available GORID and DEBIE-2 data as well as DEBIE-1 data up to 2009 ("first flight period"). In the framework of the ESA study "Processing, Analysis and Interpretation of Data from Impact Detectors" (Contract 16272/01/NL/EC) DEBIE-1 data was thoroughly analysed up to September 2005 resulting in the identification of 216 real impact events on SU1 and 25 real impacts on SU2 amongst the large number of measured events [4]. The DEBIE-1 sensor was turned on for parts of the period after 2012 ("second flight period") until today and produced numerous data sets.

Recently, EDID was updated in an ESA activity to include the data acquired after 2012. This step included at first the setup of an independent instance of EDID using up-to-date software components. Afterwards, all available DEBIE-1 data until the end of 2019 was inserted into EDID and analysed by a preliminary software filter. The insertion of all available data resulted in 3,556,148 science data sets and 905,241 housekeeping data sets for the DEBIE-1 sensor units.

3 PRELIMINARY DEBIE-1 DATA ANALYSIS

To ensure the correct insertion of the DEBIE-1 data using up-to-date software several plausibility checks have been performed before beginning the implementation of an automatic data filter. The data filter resulted in a reduced number of potentially real impact events, but additional manual filtering and further investigations of known and potentially new noise sources have to be performed.

3.1 Plausibility Checks

The plausibility checks of selected samples focussed on two parts. Firstly, a comparison of the altitude of the events inserted into EDID to the one determined from an orbit simulation using STK (Systems Tool Kit) was conducted. Secondly, the SU orientation and the Local Solar Time (LST) calculated for the events in EDID were compared to the sensor temperature given through the PROBA-1 and DEBIE-1 housekeeping data packages.

In Figure 5 the altitude of the EDID events (blue dots) is compared to the PROBA-1 altitudes calculated by STK (green area) based on Two-Line Element (TLE) data. As can be seen in this sample from 01.02.2016 to 01.05.2016, most of the blue points from EDID are located within the green envelope given by the STK data. Furthermore, the data points are located at varying altitudes in all altitude regimes of the STK data, confirming their plausibility. The distribution of the data sets is not random for all data points, as it would be expected for a sample of debris impacts, but also shows a "wave"-like effect. This results from still present noise events in the data, which will be explained in detail in section 3.3. In the bottom right corner few points are outside the altitude envelope provided by STK. However, the deviation is small, and they do not undermine the overall plausibility of the altitude comparison. The reason might be the clock drift between the DEBIE-1 instrument and the PROBA on-board computer. This needs to be validated in a future data analysis.

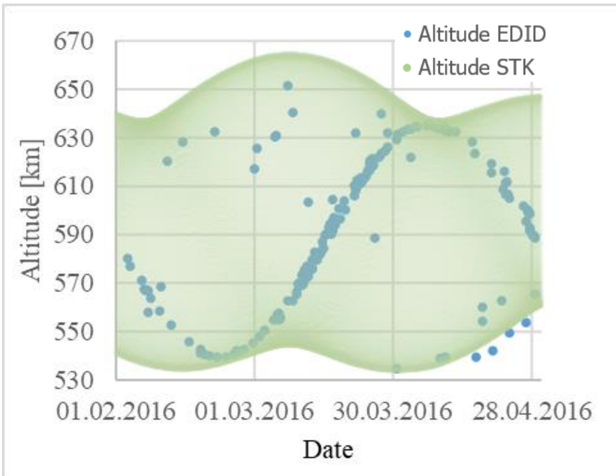

Figure 5. Altitude of EDID data compared to STK from 02.2016 to 05.2016.

To confirm the orientation of the SUs calculated in EDID, they were compared to the sensor temperatures in the given housekeeping data. This comparison showed a rise in the temperature of the sensor with sun angles close to 90 degree (perpendicular sunlight). Furthermore, the LST calculated for the event was compared to the temperature at this time. Here, a higher temperature could be observed for LSTs shortly after the highest sun intensity at midday. During the umbra periods with LSTs around midnight, the opposite effect was observed with decreasing temperatures. Both effects show a correct correlation of the calculated sensor position and orientation. A comparison to other data sources was not performed for this effect.

Both these checks showed plausible results, such that a correct processing of the downloaded telemetry data is given for the newly implemented instance of EDID. After this step, the preliminary data filter has been applied.

3.2 Automatic Filtering Approach

The preliminary data filter is based on the effects analysed by J. Schwanethal in [1]. These have only been applied to the data set until September 2005 so far [2] and were added manually to the dataset. It has not been implemented as an automatic filter into the database.

The automatic data filter mainly considers the delay timers on the DEBIE-1 SUs and the voltage thresholds on the plasma detectors, as described in [1]. The delay timers represent the time between the excitation of the two plasma channels on the one hand and the time between the excitation of the plasma channels and the piezoelectric sensors. This time is calibrated to the generation of valid delays. Furthermore, the events are compared to a fix voltage threshold and the ones below this threshold are basically cut off, as they are most probably noise events [1].

Applying this automated filter reduces the number of events drastically. Compared to the 3,556,148 events inserted into the database, only 8,370 potentially real events remain. This corresponds to a proportion of 0.24% potentially real events in the initially registered data sets. However, plotting the data sets on a latitude-time plot reveals that this analysis does not capture all the effects responsible for a false excitation of the SUs [1].

In these plots two effects become evident, which will be explained here and can be observed in the results of the preliminary data analysis presented in section 3.3. The first effect occurs during the crossing of the eclipse terminator (change from sunlight to eclipse), which can only occur on the northern part of the orbit (cp. Figure 6 for SU1). During this change of lighting conditions thermal spacecraft effects can occur, which cause the excitation of the sensors and result in a ‘real-looking’ event.
The second effect can be seen in the SU2 data by a bulk of ‘real-looking’ data sets at the same location (~ 55° latitude, ~ 170° longitude) over the earth at different times (cp. Figure 7). With this high correlation they are not expected to be actual dust impacts [1]. Indeed, it could be shown that the cause of these events is the excitation of the plasma channels of the detector due to a US radar facility on Shemya Island (Aleutians) [2].

3.3 Results of Preliminary Data Analysis

The results of the data analysis are considered within two representations. Firstly, the latitude-time plots mentioned in section 3.2 are shown for two exemplary time periods and both sensor units. Secondly, the impact fluxes are calculated from the results of the automatic filter and presented for each year included in the EDID database.

The first analysis period for the latitude-time plots is from 05.2002 to 02.2005. It corresponds to the one analysed in [2] and the results are mapped on top of each other. As can be seen in Figure 6 for the first DEBIE sensor unit, the preliminary filter presented by the blue data points produces more ‘real-looking’ events than events reported after the analysis in [2] with grey circles and crosses. Since the overlay was created by hand some inaccuracies result, but the events reported in [2] are mostly met by the events reported after the automatic filtering. However, the results still show the ‘real-looking’ events caused by crossing of the terminator line marked by the black line. An example of this behaviour can be seen at the beginning of the year 2003, as marked by the green ellipse in the data. Throughout the years this line with a +-5° uncertainty band accumulates events, and the total number of events would decrease significantly, if this effect would be considered.

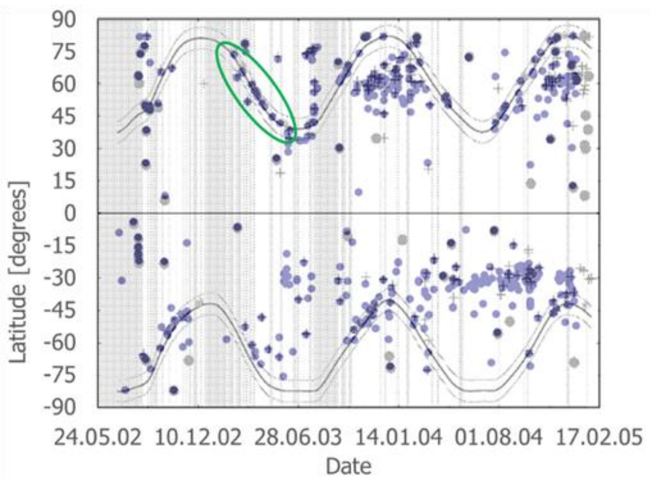

Figure 6. SU1 latitude of events as function of time from 05.2002 to 02.2005.

In Figure 7 the same comparison is performed for the second SU. Here, the observations considering the position of real events compared to the ones of the newly implemented filter and the noise effect of the terminator crossing are the same as for SU1. Here, the noise occurs mostly in the data of the southern hemisphere (related to terminator crossing from eclipse to sunlight), as exemplarily marked by the green circle at the beginning of 2004. Furthermore, the consideration of the second SU in addition shows the influence of the radar on Shemya Island. As marked by the green ellipse around August 2004, a considerable amount of 'real-looking' events results from this effect.

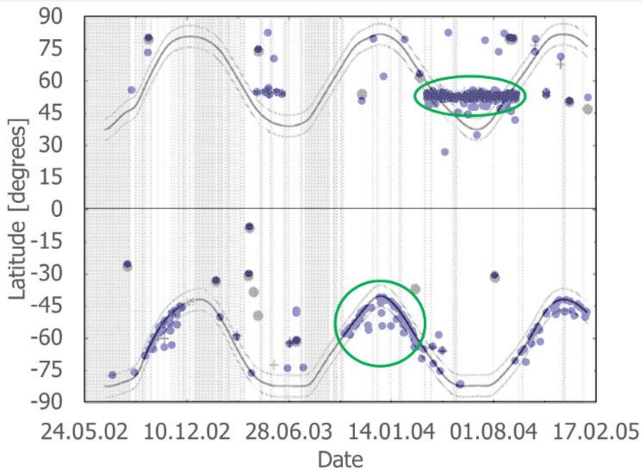

Figure 7. SU2 latitude of events as function of time from 05.2002 to 02.2005.

For the second period from 01.2016 to 07.2018 no extensive analysis has been performed beforehand. Therefore, no comparison to existing data was possible. However, these results show the same influence of the terminator crossing. As can be seen in Figure 8, the effect of a sinusoidal curve is present as well (for example marked in the green ellipse on the left). Comparing these events to the black terminator line determined using STK shows a deviation of more than 5° uncertainty considered before. Due to the almost identical course of the two lines, it can be concluded that the effect results from the terminator crossing and causes a higher number of noise events compared to the first period. The deviation leads to the conclusion of a systematic error, whose root cause could not have been found during the preliminary analysis. In contrast to the period analysed before, no events can be correlated to the terminator crossing in the southern hemisphere.

On SU1, two further effects can be seen (Figure 8), which could not be investigated. They are marked by the yellow ellipse and circle beginning around September 2017. For the ellipse on the northern part of the data, the number of reported 'potentially real' events is significantly higher than for all other periods of time. A reason for possible causes is not known, but this bulk represents an unusual behaviour due to the very high number of events and leads to the conclusion of an unknown noise source or the detection of a massive particle cloud possibly caused by a break-up event or a solid rocket motor firing. The same is assumed for the sinusoidal line taking place in the yellow circle located in the data of the southern hemisphere. Since it does not correspond to the terminator line, a different source is expected to be responsible for this effect. Due to the periodic course of the events, a noise effect is assumed, but a source could not be found in the preliminary analysis. However, both areas are not excluded from the automatic filter and have to be analysed before the data can be used for the validation of environment models.

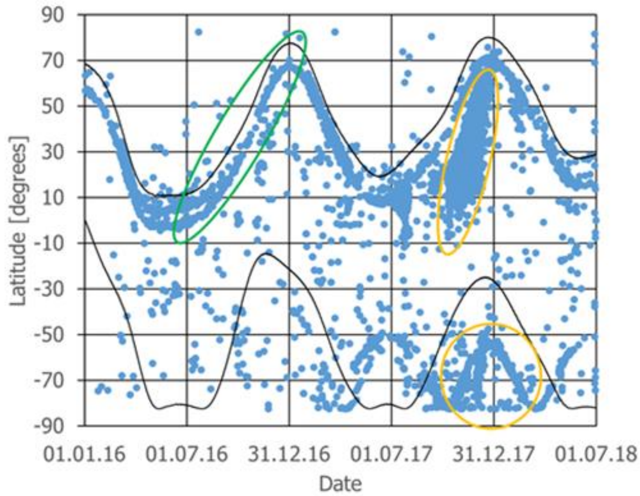

Figure 8. SU1 latitude of events as function of time from 01.2016 to 07.2018.

Considering the same period for the second SU returns significantly lower numbers of events, as shown in Figure 9. Still, the effect of the sensor excitation by the Shemya island radar station is visible, as exemplarily marked by the left ellipse. As for SU1, a sinusoidal course of 'real-looking' events is observed, but slightly deviates from the terminator line determined using STK. It is marked by the right green ellipse. In the bottom part several events are in the surrounding of the determined terminator line. However, a correlation between these two is not possible because of the expected systematic error between the terminator line and the 'real-looking' events at the other positions.

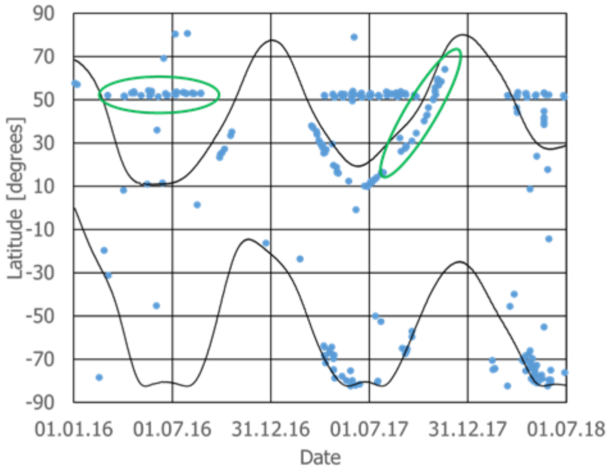

Figure 9. SU2 latitude of events as function of time from 01.2016 to 07.2018.

The impact flux f in impacts per square meter and year is calculated from the number of impacts N using Eq. 1. During the calculation, the detector area A and the on-time of DEBIE-1 t_{on} are considered.

$$f = \frac{\mathrm{N}}{t_{on} * A} \quad (1)$$

In Figure 10 the flux on both SUs and their on-time are shown for all years included in EDID. The on-time marked by the black line shows two major data acquisition periods for the DEBIE-1 sensor. The first one from 2002 to 2006 and the second one from 2013 to 2019. Towards the end of the considered period, the on-time decreases, but the sensor is still turned on regularly and the consideration of the on-time allows the calculation and comparison of the flux. The comparison of the two periods shows a few major findings. Firstly, the flux on SU1, as shown by the left pillar in blue, increases significantly in the second on-period compared to the first period. However, considering the results of the latitude-time plot in Figure 8 the numbers include the high number of 'real-looking' events potentially caused by the terminator crossing and unexplained effects beginning in 2017, which cause the outlier in the year 2017. Secondly, the flux on SU2 does not increase at the same rate, which results in a different flux ratio of SU1/SU2. A possible reason for this effect could be a different attitude of PROBA-1.

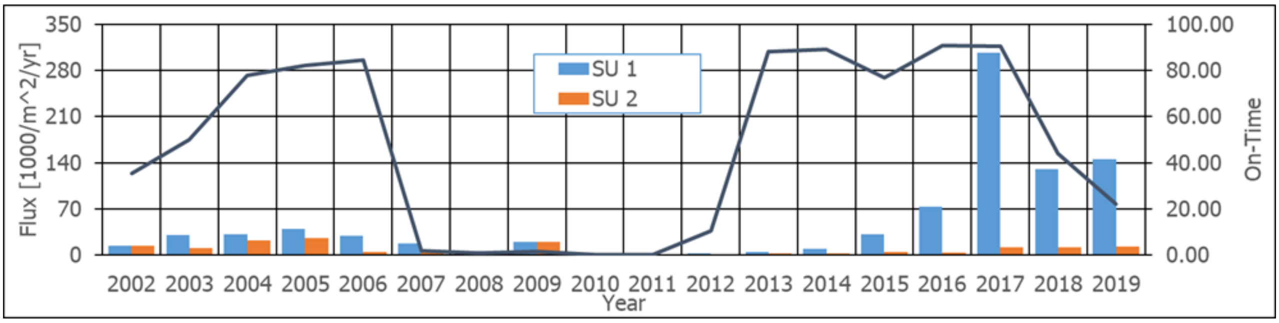

Figure 10. Impact flux and DEBIE-1 on-time from 2002 to 2019

4 DATA UTILITSATION

4.1 Summary

EDID is a valuable source of in-situ impact detector measurement data, which is available to the interested public and can be used for various scientific analyses.

Detailed analyses have been performed on the GORID data [5], [6], [7] and the DEBIE-1 data of the first measurement period [4].

A significant amount of data is available for further activities such as the calibration or validation of environment models, e.g. ESA's MASTER model.

Performing a preliminary analysis of the data is a first step in discriminating the real impact events from the large amount of noise generated by the DEBIE-1 sensor. These analyses also show the necessity of further work before the data can be used for a model calibration or validation. Figure 8 shows two possible further unknown sources of measured events, which could be either noise or impacts of debris cloud particles. These effects need to be investigated in detail before a reasonable comparison to environment models can be performed. Compared to the flux determined in an analysis using MASTER-8 for the debris environment and the Grün-Model for the meteoroid environment, the flux levels computed with DEBIE-1 data from EDID are by a factor of three to ten higher. This underlines the necessity of a detailed analysis of the measured data.

4.2 Data Gaps and Recommendations

The existing data in EDID results from three different sensors: GORID, DEBIE-1, DEBIE-2. To provide up-to-date access to measurement data of in-situ microparticle impact detectors, a continuous maintenance of EDID as a SWE software application is recommended.

Limited data analysis has been performed on the existing DEBIE-2 dataset [3]. Consequently, this dataset has not been used for any model validation purposes. With the Space Debris Sensor (SDS) operated by NASA, a different sensor is collecting data on the same orbit, which would allow for a comparison of the data and temporal evolution of the microparticle environment.

Additionally, the data leave various gaps due to restrictions in the operation time, altitude and orbit orientation of the different sensors and their detection range. For a validation of the environment models in a larger range, the insertion of further sensor datasets would be highly desirable. An additional possibility to close the gaps with more data sets would be the creation of a detector network using known sensor technology or new instrument concepts for in-situ microparticle detection.

5 CONCLUSION

Concluding, it can be said that EDID provides the necessary infrastructure for processing, storage, and validation of data from multiple in-situ impact detectors using up-to-date software solutions. For example, the largest dataset in EDID stemming from the DEBIE-1 sensor on PROBA-1 is still growing even after almost 20 years of operation. However, the current sensor data leave gaps due to altitude restrictions, on-times of the sensors and limitations in the identification of impactors.

For the DEBIE-1 dataset included in EDID a preliminary data analysis has been performed, which is a first step in identifying real impact events in the huge amount of data sets. As a result of this analysis 99.76% of the originally included events have been identified as noise events. However, further filtering is required, because known noise sources such as terminator crossings are still included in the dataset. This results from the signal characteristics of the sensors making the event look like a real impact. They can easily be separated from the randomly distributed events by means of a comparison to a simulated terminator line or the exclusion of data measured in latitude bands of known radar instruments, respectively. Furthermore, additional events were identified in the graphical representation of the dataset without a known reason. Due to the significant increase in events for a limited amount of time and an appearance in a sinusoidal form, a possible unknown source is expected. A use of these in-situ data as input to validation of microparticle environment models and temporal evolutions in coordination within the Space Safety (S2P) programme therefore requires further detailed measurement data analysis and interpretation.

To perform such activities, the maintenance of EDID as a S2P/SWE application, in addition to further research and development of the systematic data analysis, is required.

For a better coverage of the whole microparticle environment further sensor data would be necessary. Thus, we encourage the microparticle detector community to add further sensor data to the EDID database. This could also be coupled with the investigation of new instrument concepts for in-situ microparticle detection for a better characterisation of the environment.

6 ACKNOWLEDGEMENTS

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