Space Debris Risk Assessment and Mitigation Analysis Workshop

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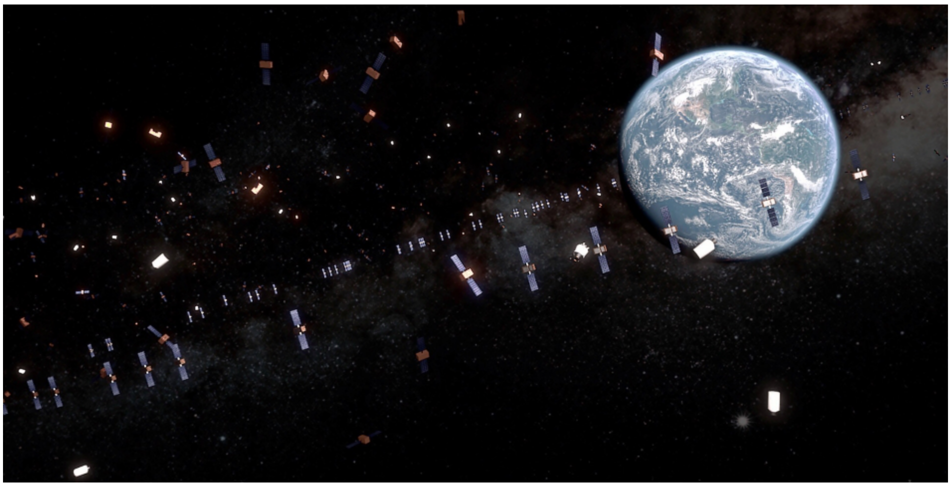
ESA/ESOC



Book of Abstracts

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Debris Mitigation Facility Small [< 5 mm] Flux Up-dates from Impact Detectors (DMF-04)

Author: Esfandiar Farahvashi[1]

Co-authors: Fabian Gabriel [2]; Erik Schulze [2]; Xanthi Oikonomidou [3]

[1] *etamax space GmbH*

[2] *etamax Space*

[3] *European Space Agency*

Corresponding Author: xanthi.oikonomidou@esa.int

Within a set of different activities, commonly referred to as the Debris Mitigation Facility (DMF), ESA aims to develop a unified set of software tools and procedures in view of the Agency's requirements and international regulation when it comes to space debris mitigation. One of the overarching user feedback that was received was the need to produce more regularly future debris environment forecasts. But forecasts require validation of the starting point, and as part of this activity, the objective is to validate and improve the MASTER environmental model in the small particle regimes (< 5 mm).
Consequently, in the framework of ESA's activity "DMF-04" (Small Flux Updates from Impact Detectors), available in-situ measurement data on impacts of small particles are being checked to see what their potential is for the validation of the MASTER environment model. Moreover, the lessons learned from the data collection and preparation shall help to compile guidelines for mission and instrument designers and operators addressing the preferred data format, quality and quantity of future in-situ measurement data sets. This shall allow future datasets to be compatible with MASTER and being easy to integrate in the processing chain.
The tasks performed in this activity can be summarised as follows:

1. Acquisition of applicable In-Situ databases
2. Processing of the databases
3. Comparison of the databases with MASTER 8
4. Establishing Lessons Learned for handling with In-Situ data

The in-situ databases *DEBIE1*, *DEBIE2*, *GORID*, *SODAD1* and *SODAD2* were used and analysed for this activity
To compare the databases with MASTER 8, it was desired to convert the events into flux vs fragment size distributions. For *SODAD1* and *SODAD2*, this information was already available and thus no further processing required.
For *DEBIE1*, *DEBIE2* and *GORID*, only the unprocessed databases were available. Each of the three databases lists more than 1 million entries with no reliable indication about whether an event should be considered as false or true impact event. Additionally, the particle size is only reflected in terms of detected sensor parameter for the impact. Therefore, available publications were reviewed and processing mechanisms developed to:

- filter out false impact events,
- convert measured impact data to fragment masses,
- generate flux vs. fragment size distributions.

As a consequence of the filtering, the databases were reduced significantly to contain only the potential true impacts. Hereby, the *GORID* database was reduced to 31%, *DEBIE1* to 0.02% and *DEBIE2* to 0.005% of their original size. The above processing steps were performed using a developed Python-based application.
The detected fluxes for each database were compared with the simulated fluxes using MASTER 8. Hereby, the orbit of the host spacecraft for each sensor operation epoch was analysed and expressed as mission phases in MASTER 8. The comparison showed that some of the databases provided a

good comparability to the simulated fluxes whilst other databases show a significant deviation. Finally, based on the activities performed, a list of best practices was established for in-situ detector developers to ensure that the resulting detected events can be used for a better validation of future meteoroids and space debris environment models. The list addresses considerations for the designing phase of a detector as well as for the processing and post-processing phase of the detected in-situ events. In general, the possible noise sources of the mission orbit and of the spacecraft components should be considered in the design and positioning of a detector to reduce false events and to provide valid measurement with high certainties to allow a good resolution of the impact velocities and masses. Furthermore, a centralised platform should be established for storing all relevant information about the detector (such as the database itself and the identified true impact events, related publications, find-ing and simulation file etc.) thus allowing an easy access for future studies.

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Characterisation of on-orbit fragmentation events based on TLE data

Author: Maximilian Pierzyna[None]

Co-author: Lorenz Böttcher [1]

[1] *TU Braunschweig*

Corresponding Author: m.pierzyna@tu-braunschweig.de

This study proposes a modelling methodology to characterise on-orbit fragmentation events by estimating the fragmentation epochs and parametrising the velocity perturbation distributions of the involved fragments. The methodology only utilises publically available two-line element (TLE) sets of the fragmented bodies and their debris objects which are propagated backwards in time using the analytical Simplified General Perturbations 4 (SGP4) propagator. That enables computationally efficient analysis of a large number of fragmentation events and makes the method available to the general public. A set of filters and weights is used to reflect and compensate for uncertainties throughout the procedure. The characterisation process is two-staged: First, the fragmentation epoch is estimated by propagation and geometrically refined as the point in time where all involved objects are closest on average. Second, probability density functions are fitted to the fragments' velocity perturbations at the estimated epoch and location to quantify and parametrise their magnitude and directionality distributions. The novelty is to fit a three-dimensional directional Kent distribution which captures the directionality information more accurately than a component-wise fit typically employed in such analyses. We successfully apply our methodology to a range of historic fragmentations covering different orbits (LEO, MTO, GTO, GEO) and fragmentation causes (explosions, collisions, anti-satellite tests). The estimated epochs are generally accurate within a few minutes of reference epochs from relevant literature, and our fitted parametrised velocity distributions agree well with reference distributions. The parameterised magnitude and directionality distributions enable an intuitive and objective comparison of different fragmentation events. Our approach is robust, accurate, efficient, and automatable and can also deal with more complex breakups such as sequential fragmentations, supporting its relevance for on-orbit breakup analysis. In the context of debris environment models, our approach can be employed to configure and verify the fragmentation models used to generate the MASTER populations.

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How the re-entry casualty risk could be impacted by future launch traffic?

Author: Carmen Pardini[1]

Co-author: Luciano Anselmo [1]

[1] *ISTI-CNR*

Corresponding Author: carmen.pardini@isti.cnr.it

Space activities are in the middle of an epochal transformation. The number of operational satellites in orbit could increase tenfold over the next decade due to the launch of mega-constellations. Concurrently, the application of mitigation measures, to avoid the accumulation of satellites in certain orbital regions for reducing the collision risk, will result in the end-of-life deorbiting of these satellites, thus raising the number of uncontrolled re-entries into the Earth's atmosphere. Furthermore, the increasing involvement in space activities of many emerging private companies will certainly has a far from negligible impact on the evolution of future launch traffic, and consequently on the potential growth of the re-entry casualty risk. Therefore, even if the risk related to uncontrolled re-entries is still relatively low compared to all other risks faced in everyday life, this risk could increase dramatically over the next few years.

To date the re-entry risk has been assessed and managed on an object-by-object basis, such as assessing whether or not a single event might exceed a certain casualty expectancy threshold, typically set equal to 1E-4. However, in view of future developments in space activities, characterized by the launch of numerous small satellites and mega-constellations, as well as the abandonment in low Earth orbit of large upper stages intended for an uncontrolled re-entry, it may be necessary to shift to a more holistic approach to the problem, at the very least more system-oriented than object-oriented. As a matter of fact, for instance, even if a single satellite re-entering from a mega-constellation has a casualty expectancy of the order of 1E-5, i.e. below the alert threshold of 1E-4, 100 of such satellites re-entering annually would have a casualty expectancy of about 1E-3, i.e. comparable to that of various past events which received great international attention. The same would also apply to the numerous upper stages re-entering in a given time frame. However, so far no collective risk limit has been established for satellite re-entries, and even managing that risk according to the US Range Commanders Council (RCC) recommendations, the proposed annual collective risk for the general public would be already marginally exceeded by the re-entry of the Starlink satellites, if no D4D was implemented. A priority action for the next few years will therefore be to at least establish a cumulative risk threshold on an annual basis, so that uncontrolled re-entries can be managed before their associated risk becomes too high to be controlled.

The aim of this presentation is first to introduce some metrics to characterize and classify the risk associated with uncontrolled re-entries, and thus to apply them to re-entering large intact objects (radar cross-section > 1 m^2), i.e. spacecraft and upper stages, whose uncontrolled re-entry could present a non-negligible risk. This analysis covers the transition phase between the so-called old and new space economy, or roughly the last decade, extending to possible launch traffic scenarios hypothesized for the near future. The intent is to assess how the re-entry casualty risk could increase in consequence of the foreseen evolution of space activities, and then to reflect on possible recommendations to limit and to control this risk.

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Deployable Surface-Based Debris Monitoring (DSBDM)

Authors: Xenia Lopez Corrales[1]; Charlotte Bewick[2]; Camilla Colombo[3]; Esfandiar Farahvashi[4]; Ernst Pfeiffer[1]; Marc Scheper[5]; Daniel Stelzl[None]

[1] *HPS GmbH*

[2] *OHB SE*

[3] *Politecnico di Milano*

[4] *etamax space GmbH*

[5] *OHB System - Bremen*

Corresponding Author: lopez-corrales@hps-gmbh.com

The New Space era has enabled the development speed of space technology as it has never seen before. However, this exponential increment in technological maturity is accompanied by an increase

in the generation of space debris, which poses a risk to the several satellites in orbit.
Space debris models allow us to simulate the space debris environment. They include more than 30,000 objects, with diameters above 5-10 cm, which can be tracked from ground and are maintained in catalogs by Space Surveillance Networks on Earth. For the millions of objects with lower diameters, which cannot be tracked using ground-based observations, statistical modeling is used. Space debris models rely on in-situ measurements in order to validate their estimations of the non-trackable debris populations.
The validation of the current models has been performed using measurement data from returned surfaces, like the returned solar arrays of the Hubble Space Telescope. However, the number of returned surfaces has been limited. Moreover, having a large catalog of impact events provides a high number of statistical data for model validation. This can be achieved by applying large detection surfaces to (a) observe a high rate of impact events and (b) to increase the possibility to observe impacts of larger particle sizes.
Therefore, addressing this situation, the ESA Activity "DSBDM" (Deployable Surface-Based Debris Monitoring) has the goal to study the feasibility of detecting the population of space debris in the submillimeter to 1-centimeter size region using a large deployable detection surface. . Impact information such as size, impact direction and impact velocity will be derived in order to validate and enhance space environment models and at the same time improve our knowledge and understanding of the space debris environment. This study is conducted by the consortium consisting of OHB Systems, etamax Space, HPS, and Politecnico di Milano University.

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Observing opportunities of space conjuncting objects in the orbits prior to the closest approach

Author: Giulio Campiti[1]

Co-authors: Giuseppe Brunetti [1]; Caterina Ciminelli [1]

[1] *Politecnico di Bari*

Corresponding Author: giulio.campiti@gmail.com

As space access becomes more affordable and several mega-constellations are deployed into orbit, the already congested space environment will increasingly force satellites to disrupt their activities to avoid catastrophic collisions. Besides various projects for actively removing space debris, new solutions are needed to more accurately estimate the collision probability between active satellites and other space objects, reducing both the rate of false alarms and the propellant required for manoeuvres. A little explored approach is to enable satellites to make autonomous observations of the objects at risk of collision with them, thus contributing with unique information to the tracking data, which are currently mostly produced by means of ground-based sensors. This can be achieved by exploiting the natural dynamics of conjuncting space objects, which typically make several close passes before the closest approach, whereby an at-risk satellite has multiple opportunities to observe a hazardous object before a risky close approach. In this study, such observing windows are investigated more in detail by reproducing and analyzing thousands of historical conjunction events. Two-Line Element (TLE) sets are extracted for each event from past reports of Celestrak's SOCRATES service and the trajectory evolution of each pair of objects in the days prior to the closest approach is simulated using a SGP4 orbital propagator. A statistical analysis is performed to determine how many opportunities a satellite generally has to observe a secondary object, how long they last on average and other relevant features, with a view to assess the practical feasibility of the proposed approach to collision avoidance.

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The impact of satellites on Hubble Space Telescope observations

Author: Ben Aussel[1]

[1] *Westfälische Wilhelms-Universität Münster*

Corresponding Author: baussel11@gmail.com

Being situated in low Earth orbit, the Hubble Space Telescope (HST) is susceptible to higher orbit artificial satellites crossing its field of view. In a dedicated summer student project, we studied the impact of artificial satellites on HST images, updating previous results based on the most recent HST observations. We used satellite classifications from the Hubble Asteroid Hunter (www.asteroidhunter.org) project to train two independent deep learning algorithms. For the composite images, we used an automated deep learning model built with Google Cloud AutoML Vision. For the individual images, we built our own binary image classification model. We observe that both models lead to consistent results. We applied the algorithms to the past 20 years of HST data, available in the ESA Hubble Space Telescope archives, and we measured, for the first time, the fraction of images impacted by artificial satellites. When normalized by exposure time, we observe an increase in the chance of HST observing a satellite, which is consistent in two different HST instruments. This increase is in line with the increasing number of satellites in orbit around the Earth. We discuss the impact of satellites on HST and on other observatories situated in low-Earth orbit, such as the ESA CHEOPS mission.

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Debris Mitigation Facility – Enabling Attitude Based Applications (DMF-03)

Author: Gennaro Principe[1]

[1] *Deimos Space*

Corresponding Author: gennaro.principe@deimos-space.com

Nowadays, commercial and scientific applications dominate in space flight. We have now become accustomed to many services provided from space in our daily lives: communications, weather forecasts, television, remote sensing of the environment and navigation. Since the era of space exploration started, the number of Earth-orbiting objects has on average grown due to high frequency of space activities, on-orbit fragmentation and collisions between existing space objects, resulting in many small fragments. The increase of space debris led to the creation of space debris reference models by different agencies, with the European reference being the Meteoroid And Space debris Terrestrial Environment Reference (MASTER) model.

This crowded space environment makes it necessary, when designing a mission, to take into account how the mission interacts with the environment as well as the impact on other missions. For this purpose, ESA Space Debris Mitigation Requirements were introduced, which describe current mitigation measures that represent best practice to preserve the orbital environment and protect current space assets. The above-mentioned space debris mitigation requirements turned into mission requirements, that have become applicable for any ESA mission since 2014. The Debris Risk Assessment and Mitigation Analysis (DRAMA) software tool is used to enable ESA programs to assess their compliance with the ESA's mitigation requirements.
Similar approaches have been also taken by many different countries that monitor and supervise outer space activities by entities under their jurisdiction. The regulatory regime in place, however, makes it necessary to align the current set of tools related to space debris mitigation in a way that accommodates state-of-the-art engineering techniques from the early design phases of a space mission onwards. For this purpose, the project DMF01 has been devised, aiming to develop a framework that combines existing space debris mitigation tools, such as DRAMA and MASTER, to support mission designers in the requirements verification.

In contrast, in the project DMF03 individual analysis modules that are being used in debris mitigation and risk analyses are updated and then integrated in the above-mentioned framework. Such

upgrades intend to analyse spacecraft attitude-related dynamics in the space debris mitigation context. Main goals of the activity are the following:
• Integration of a 6-Degree-of-Freedom (DOF) simulator that covers the main attitude motions in the foreseen context;
• Augment the model from DMF-01 to account for movable parts (like solar panels) and combine it with user-defined attitude laws.
• Augment existing analysis modules to enable the usage of attitude motion descriptions.
• Estimation of drag and solar radiation coefficients for a given object model and attitude law.
• Improve disposal analyses based on attitude modes for different disposal techniques and exploitation of force model resonance conditions.
• Improve environment awareness including the crossing of protected regions and operational altitudes of major satellite constellations.

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Risk assessment and mitigation activities at Politecnico di Milano

Authors: Camilla Colombo[1]; Andrea Muciaccia[1]; Mirko Trisolini[1]; Lorenzo Giudici[1]; Juan Luis Gonzalo[1]; Borja Del Campo[2]

[1] *Politecnico di Milano*

[2] *Deimos UK*

Corresponding Author: camilla.colombo@polimi.it

In this talk we will present the ongoing activities at Politecnico di Milano on space debris risk assessment and mitigation. A particular emphasis will be given on how we leverage, and exploit tools made available by ESA Space Debris Office such as MASTER, DRAMA and OSCAR.
The THEMIS software, developed by PoliMi and DEIMOS UK under an ESA funded study, will allow assessing the space debris index of a given mission that can be characterised in terms of trajectory evolution for the launch, operational and end-of-life phase, spacecraft mass, cross area and reflectivity and drag coefficients. The risk is evaluated as the collision probability during the mission times the fragmentation effects plus the explosion probability times the effect of the explosion on the same set of representative targets selected from DISCOS. The collision risk is assessed via MASTER population files and flux information, while the explosion probability is assessed though statistical analyses by using DISCOS data. For assessing the fragmentation effects, the collision probability is estimated through the STARLING 2.0 tool, developed at Politecnico di Milano, to characterise the time evolution of the distribution of space debris density in the phase space of the orbital elements. The space debris density and the characteristic lines, representing the fragments' orbit evolution, are computed with PlanODyn, a semi-analytical propagation tool which allows including all orbit perturbations and computing the Jacobian and Hessian of the dynamics. Explosion and collision effect maps are computed through extensive simulations and then stored for multiple index computations. The mission profile is propagated via OSCAR or can be inputted as OEM file by the s/c operator. In the following part of the THEMIS development, the index on multiple mission will be aggregated on all the space debris population to assess the overall space capacity and will be interfaced with the DELTA long-term evolution tool.
While THEMIS uses synthetic fragmentations for assessing the space debris index, the actual collision probability needs to be assessed also in the case of real in orbit collisions or explosions. To this aim, the PUZZLE tool was developed under an ASI funded project, to characterise the fragmentation event starting from the TLE of uncatalogued fragments. The fragments are backward propagated using SGP4 for short-time assessment or PlanODyn for medium to long-time assessment, the orbits are filtered through a sequence of pruning criteria on the MOID, the orbital elements families and the time at Close Approach (CA). In this way the fragments belonging to the event are identified together with the parent objects. Once the fragmentation is characterised, the STALING 2.0 tool can be used to assess the riskiest orbits and threatened missions. In case a possible CA is identified the MISS tool can be used for computing the required collision avoidance manoeuvre to maximise the MOID at CA or to minimise the collision probability. The manoeuvre can be modelled either as an impulsive effect or a low-thrust slow push or a perturbation enhanced orbit change when a solar or drag sail is considered.

Finally, maps of debris fluxes from MASTER are used in several mission design processes to statistically characterise orbital regions in terms of debris flux, debris particles and relative direction of the incoming velocity. These kind of analysis has been used, for example, for the definition of the requirements and operational phase of the ASI funded e.Cube mission project, which will validate in-orbit the sub-millimetre space debris population, and for the DSBDM project, funded by ESA.
In this directions, current activities at Politecnico di Milano are also focused on exploiting the continuum-based STARLING approach to derive a population evolution model for space debris long term simulations. Moreover, we are working on constructing an EOL planner based on the semi-average orbit evolution within the PlanOyn approach. Within these activities validation with real data is the next open challenge.

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Definitions, Terms and Semantic

Author: Valentin Eder[1]

[1] *Space Analyses GmbH*

Corresponding Author: valentin.eder@spaceanalyses.at

The goal of the session is to develop an common understanding of terms used in the context of space traffic and how the terms are used specific in the workshop.
It is planned to collect inputs from the participants as well as to give a guidance to topic of (lexical and situational) semantic rules in space situational awareness.
At the end it should be clear for the participants in what meaning the terms are used for the workshop.

Different terms and meanings of context, sustainability, risk (within different roles), resilience, scenarios, system and classifications are discussed in an interactive
way. The participants will work with and in different stakeholder roles and risk formulations to enable a broader understanding of this complex topic.

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How insurance companies address collision risk in space

Author: Chris Kunstadter[None]

Corresponding Author: chris.kunstadter@axaxl.com

Space insurance is a critical enabler of innovation and investment in space. With the growing population of active and derelict satellites, spent rocket bodies, fragmentation objects, and lethal non-trackable debris, insurers need to be able to determine and characterize the risk of collision, particularly in low earth orbit. Through collaboration with industry on analytical tools, active participation in industry organizations, and engagement with policymakers and regulators, AXA XL is leading the space insurance market in promoting space and responsible space activity. This session will explore the ways that space insurers assess collision risk in orbit and quantify the financial exposures – both insured and uninsured – that could be at risk from a collision in various orbital regimes.

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Satellite design under space debris risk: DRAMA and Master use in OHB

Authors: Bayrem Zitouni[1]; Sara De Masi[1]

[1] *OHB*

Corresponding Authors: prak.sara.de-masi@ohb.de, bayrem.zitouni@ohb.de

What are the concrete implications of the DRAMA and MASTER tools in a satellite design? This presentation is about OHB use of these tools in its satellite design. A MMOD case in Halo Orbit and re-entry requirements impacts on missions are presented as example