ANALYSIS OF BREAKUP EVENTS

V. Braun(1)**, S. Lemmens**(2)**, B. Reihs**(2)**, H. Krag**(2)**, and A. Horstmann**(3)

(1)*IMS Space Consultancy at Space Debris Office, ESA/ESOC, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany,*
Email: vitali.braun@esa.int
(2)*Space Debris Office, ESA/ESOC, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany*
(3)*Institute of Space Systems, TU Braunschweig, Hermann-Blenk-Str. 23, 38108 Braunschweig, Germany*

ABSTRACT

The dominating source of space debris are breakup events, mainly due to on-orbit explosions and collisions. Some of the events resulted in only few objects which might even be short-lived. For the others, on-orbit fragments contribute to the collision risk satellites are facing during their operational life. In addition, analyses of the long-term evolution of the space debris environment rely on statistics derived from debris-generating events in the past. In this paper, the European Space Agency's (ESA) approach to analyse breakup events is presented. In the recent past the Database Information System Characterising Objects in Space (DISCOS) was updated and an automated breakup event monitoring tool established. Among others, DISCOS information is used to update ESA's Meteoroid and Space Debris Terrestrial Environment Reference model (MASTER), which then provides population inputs to long-term environment evolution analyses. Recent upgrades and current approaches shall be highlighted and discussed.

Keywords: Space debris; breakup; fragmentation; DISCOS; MASTER.

1. INTRODUCTION

The breakup of the NOAA 16 satellite in November 2015, at a mean altitude of about 850 km, resulted in more than 450 fragments[1] that are currently being tracked by the U.S. Space Surveillance Network (SSN). Shortly after the event, ESA's Space Debris Office (SDO) started to evaluate the risk increase for the currently operated missions by ESA. With some of the Sentinel spacecraft being operated close to an altitude of 800 km, the mission operators were interested in an estimate of the additional risk due to that breakup and thus the expected increase in the number of collision avoidance manoeuvres for the entire mission span.

There are several tools the SDO applies to perform such analyses. The Database Information System Characterising Objects in Space (DISCOS) is the core element which provides the necessary information on the objects in the space debris environment. DISCOS information and additional data gathered during dedicated survey campaigns are used to validate ESA's Meteoroid and Space Debris Terrestrial Environment Reference model (MASTER). It allows to assess the debris and meteoroid flux for any mission on an Earth orbit. A new tool called BreakUp Simulation Tool and Estimation of Risk (BUSTER) has been developed for the dedicated analysis of breakup events. It automatically extracts information from DISCOS and the reference population in order to come up with the estimates the mission operators ask for.

Those tools will be described in Section 2, highlighting the recent upgrades and discussing the current challenges in modelling debris generating events but also in the estimation of risk. After this, results from BUSTER for recent breakup events are presented in Section 3 along with a first attempt to validate risk estimates via a Conjunction Data Message (CDM) analysis.

Besides operational aspects for current missions, an increase in the knowledge on breakups in Earth orbits benefits assessments of the long-term evolution of the space debris environment. Many of today's state-of-the-art models rely on assumptions for the traffic model that are derived from the past. Examples include the yearly launch rate, disposal rates but also explosion rates. For the latter, many past studies assumed an optimistic scenario where passivation would effectively lead to no explosions in the future. Looking at the past few years in Section 4 the question is whether applying a zero explosion rate can be really justified from the data at hand.

2. SPACE DEBRIS TOOLS

2.1. DISCOS

Information on launches and launch vehicles, spacecraft properties and much more is provided by DISCOS for all trackable, unclassified objects. DISCOS plays a cru-

[1] `https://www.space-track.org`, as of April 7, 2017

Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office
Ed. T. Flohrer & F. Schmitz, (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

cial role in daily activities at the SDO, as it is used in the routine collision avoidance, for re-entry analyses and contingency support. Moreover, it is currently accessed by more than 130 users via the DISCOSweb platform[2] with information being exploited in various activities and scientific studies.

The currently ongoing transition to DISCOS 3 includes long awaited upgrades: for example, an object path history that can reflect objects being released from other objects, or the association of debris objects to specific events in space. For breakup events the approach so far was rather static, meaning that a table provided information on individual events and was updated whenever a new event was confirmed. However, there was no process to keep monitoring past events for updates. With the introduction of BUSTER (Section 3) all events are now being monitored for newly added fragments to the tracked population and the database is updated accordingly. Moreover, the entire event database has been revised and more than 150 missing events (most of them classified as *anomalous* or yet unconfirmed) were added. This included a revision of the event cause classification. The main motivation here is that the modelling of breakup events (Section 2.2.1) clearly benefits from more detailed assessments of the breakup cause. In Figure 1 the status of DISCOS 2 is shown according to the former classification.

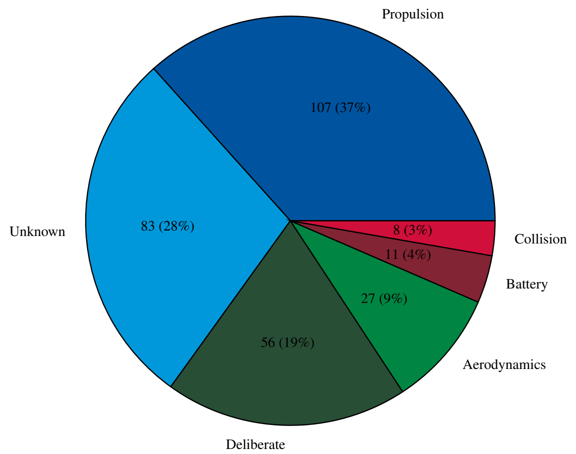

Figure 1. Assessed event cause for the fragmentation event database in DISCOS 2. Event counts and percentages (in parantheses) are given.

The new classification scheme is the following:

Propulsion: Stored energy for non-passivated propulsion-related subsystems might lead to an explosion, for example due to thermal stress. Several sub-classes are defined for rocket stages that showed repeated breakup events:

[2] `https://discosweb.esoc.esa.int`

Delta upper stage There were several events for the Delta second stage due to residual propellants until depletion burns were introduced in 1981 [6].

SL-12 ullage motor The Blok D/DM upper stages of the Proton rocket used two ullage motors to support the main engine. They were released as the main engine performed its final burn.

Titan Transtage The upper stage of the Titan 3A rocket used a hypergolic fuel oxidizer combination.

Briz-M The fourth stage of the Proton launcher is used to insert satellites into higher orbits.

Ariane upper stage Breakups for the H8 and H10 cryogenic stages were observed, most likely due to overpressure and subsequent bulkhead rupture. Passivation was introduced in 1990 [1].

Tsyklon upper stage The third stage of the Tsyklon-3 launcher used a hypergolic fuel oxidizer combination.

Zenit-2 upper stage The second stage of the Zenit 2 launcher used an RP-1/Liquid oxygen propellant.

Electrical Most of the events in this category happened due to an overcharging and subsequent explosion of the batteries. A special class has been defined for the Defense Meteorological Satellite Program (DMSP) and the National Oceanic and Atmospheric Administration (NOAA) satellites:

DMSP/NOAA class Based on the Television and InfraRed Observation Satellite (TIROS-N) satellite bus, some of the satellites in this series suffered from battery explosions.

Accidental For subsystems that showed design flaws ultimately leading to breakups in some cases. This includes, for example, the breakup of Hitomi (Astro-H) in 2016 or the sub-class of Oko satellites:

Cosmos 862 class The Oko missile early warning satellites were launched into Molniya orbits. Each satellite carried an explosive charge in order to destroy it in case of a malfunction. Reportedly, control of this mechanism was unreliable resulting in an explosion for many of the satellites [2].

Aerodynamics A breakup most often caused by an overpressure due to atmospheric drag.

Collision There have been several collisions observed between catalogued objects. In the case of the Cosmos 2251 and Iridium 33 event in 2009, two large fragment clouds were created. A sub-class are small (and thus uncatalogued) impactors:

Small impactor Also a collision, but there is no explicit evidence for an impactor. Changes in the angular momentum, attitude and subsystem failures are, however, indirect indications of an impact. In the case of Sentinel 1A in August 2016, the impact feature in the solar array wing could even be captured in a photograph via the camera used to verify solar panel deployment after launch.

Deliberate: all intentional breakup events. There might be several reasons to destroy spacecraft deliberately, including the testing of weaponry and avoiding design features to be disclosed by inspection.

ASAT Anti-satellite tests.

Payload recovery failure some satellites were designed such that they exploded as soon as a non-nominal re-entry was detected.

Cosmos 2031 class The Orlets reconnaissance satellites were introduced in 1989 and employed detonation as a standard procedure after the nominal mission [6].

Assumed Introduced for the MASTER model. Currently the only assumed events are in the GEO region, backed by information obtained during survey campaigns.

Anomalous Defined similarly to [6] as "the unplanned separation, usually at low velocity, of one or more detectable objects from a satellite that remains essentially intact." This may include debris shedding due to material deterioration, which includes insulation material or solar panels all of which have been observed from ground in the past. The difference to the definition in [6] is that events with sufficient evidence for an impact of debris or micrometeroids are classified under Small Impactor. Sub-classes for anomalous events are defined, as soon as events occur multiple times for the same spacecraft or bus type. Currently, the following sub-classes are defined:

Transit class satellites of the U.S. Navy's first satellite navigation system operational between 1964 and 1996.

Scout class refers to the Altair upper stage of the Scout rocket family.

Meteor class Russian meteorological satellite family in LEO.

Vostok class refers to the upper stage of the Vostok rocket (Blok E)

ERS/SPOT class both the ERS-1 and -2 satellites, as well as the SPOT-4 satellite had confirmed anomalies and fragments were catalogued. They are based on the same satellite bus.

Unconfirmed A provisional status until an event is confirmed and classified accordingly.

Unknown Is assigned whenever there is lacking evidence to support a more specific classification.

Cosmos 699 class For many of the ELINT Ocean Reconnaissance Satellites (EORSAT) a breakup was observed during the orbital decay. Explanations for the event cause include deliberate, residual propellants and batteries - but no cause was ever confirmed [2, 11].

Delta 4 class events with several catalogued objects for the Delta Cryogenic Second Stages (DCSS).

L-14B class The third stage of the Long March 4B (CZ-4B) launcher used a hypergolic propellant.

H-IIA class The second stage of the H-IIA launcher used a cryogenic propellant.

In total, DISCOS now lists 504 events, with a detailed breakdown of the classification given in Table 1.

Table 1. Event counts for the new event cause classification in DISCOS 3. Grouping of sub-classifications indicated by horizontal lines.

Classification	**Event count**
Propulsion	28
Delta upper stage	12
SL-12 ullage motor	51
Titan Transtage	3
Briz-M	7
Ariane upper stage	27
Tsyklon upper stage	5
Zenit-2 upper stage	9
Electrical	7
DMSP/NOAA class	17
Accidental	3
Cosmos 862 class	22
Aerodynamics	31
Collision	5
Small impactor	11
Deliberate	9
ASAT	14
Payload recovery failure	10
Cosmos 2031 class	7
Assumed	8
Anomalous	60
Transit class	23
Scout class	4
Meteor class	12
Vostok class	7
ERS/SPOT class	3
Unconfirmed	16
Unknown	34
Cosmos 699 class	28
Delta 4 class	5
L-14B class	19
H-IIA class	7

Table 2. Current list (Ten top-listed events as of April 3, 2017, `https://www.space-track.org`) of breakup events by total number of catalogued fragments. The number of catalogued on-orbit fragments is also given.

	Parent object		Total	Orb.
1	Fengyun 1C	1999-025A	3430	2846
2	Cosmos 2251	1993-036A	1668	1100
3	Pegasus HAPS	1994-029B	754	83
4	Iridium 33	1997-051C	628	344
5	Cosmos 2421	2006-026A	509	0
6	Ariane 1 (H8)	1986-019C	498	32
7	Cosmos 1275	1981-053A	480	423
8	Titan Transtage	1965-082B	473	33
9	NOAA 16	2000-055A	457	457
10	Thorad Agena D	1970-025C	376	235

The ten breakup events with the highest number of catalogued fragments are listed in Table 2. The total number of fragments is an important quantity used in the modelling, as will be outlined in Section 2.2.1. However, it is less predictive for other applications like the long-term evolution of the environment. This can already be seen from the difference between the Fengyun 1C and Cosmos 2421 events: the former happened at an altitude of about 850 km whereas the latter saw a fragmentation at about 420 km. All of the 509 fragments for Cosmos 2421 re-entered Earth's atmosphere within a few years whereas a high share of the Fengyun 1C fragments will remain on orbit for many more years. Section 4 shall highlight a possible way of extracting breakup statistics relevant for long-term analyses.

2.2. MASTER

The general approach in MASTER is to model all historic debris generation events covering a size regime between $1\,\mu\mathrm{m}$ to $100\,\mathrm{m}$. It allows to use the knowledge on orbit and debris object properties to obtain flux estimates and assess impact risks for any satellite mission in Earth's orbit. The latest version is MASTER-2009[3] with an upgrade activity currently on-going.

2.2.1. Event modelling

The core element of MASTER is the Program for Orbital Debris Environment Modeling (POEM). It simulates individual events from a database of 265 fragmentations (including assumed events, see Section 2.2.2), 2437 solid rocket motor firings and 16 reactor core ejections from Soviet Radar Ocean Reconnaissance Satellites (RORSAT). Moreover, single release events like the two Westford experiments from the 1960s and leakage of sodium-potassium (NaK) droplets from two Topaz reactors are considered.[4] Surface degradation models account for the release of paint flakes and Multi-Layer Insulation (MLI) objects from spacecraft surfaces as well as ejecta from debris and meteoroid impacts. Debris objects generated from the models for all the events are propagated and provided as population snapshots by POEM.

The National Aeronautics and Space Administration (NASA) breakup model EVOLVE 4.0 [7, 9] was adapted for POEM to generate fragment clouds. The size distribution function for explosions follows a power law [7]:

$$N\left(L_c\right) = 6 \cdot s \cdot L_c^{-1.6}, \qquad (1)$$

where N is the number of objects larger than the *characteristic length* L_c, the latter being defined as the geometrical average of three orthogonal axes of the spacecraft body: the first axis coincides with the largest dimension, the second coincides the largest dimension in a plane orthogonal to the first one and the third one is normal to the first and second axes. It is a reasonable choice to have the characteristic length as the independent variable of the model as this quantity can be easier extracted from fragment measurements for both on-orbit events and laboratory experiments as, for example, the mass.

The unitless parameter s was introduced to scale the original power law valid for upper stages with a mass between $600\,\mathrm{kg}$ to $1000\,\mathrm{kg}$ ($s = 1$) to apply it to other types of explosion events [7].

For collisions, the power law is given as [7, 9]:

$$N\left(L_c\right) = 0.1 \cdot M^{0.75} \cdot L_c^{-1.71} \qquad (2)$$

where $M = m_1 + m_2$ is the sum of the mass of the two colliding objects in case of a catastrophic collision, whereas for a non-catastrophic event $M = m_i \cdot v_r^2$ results as the product of the impactor mass m_i and the relative impact velocity v_r. An event is considered as catastrophic if the ratio between the kinetic energy of the impactor (or smaller object) and the mass of the impacted (or larger) object is equal to or larger than $40\,\mathrm{J\,g^{-1}}$.

From the observation of the orbit evolution for fragmentation objects one can derive the area-to-mass ratio A/m. It is then possible to have a relationship between L_c and A/m using a χ^2-distribution [7]. Using a simple geometrical relationship for the cross-section A from L_c, one obtains the fragment mass dividing A by A/m.

The velocity distribution of the event can be observed from the orbit evolution of the fragments as well. A log-normal distribution for the absolute value of the additional velocity, Δv, as a function of the A/m is applied with a uniform distribution of the velocity direction.

Implementing the model as described in [7] since MASTER-2001, several modifications have been introduced in POEM:

[3] access via `https://sdup.esoc.esa.int`

[4] Note that the provided numbers may be subject to change during the ongoing population validation for the upgraded MASTER version.

Small fragments The power law for NASA's breakup model was validated for a size range between $1\,\mathrm{mm}$ and $1\,\mathrm{m}$ via observational data from on-orbit explosions, the Solwind ASAT and the ground-based Satellite Orbital Debris Characterization Impact Test (SOCIT) series [7, 8]. An extrapolation to smaller sizes resulted in fragments with unrealistic densities. The A/m distribution has therefore been modified in order to constrain the density to values corresponding to Titanium spheres for very small objects.

Large objects For objects $>1\,\mathrm{m}$, adding randomly two to eight objects larger than $1\,\mathrm{m}$ for mass conservation was recommended in [9]. In POEM, one to eight objects are randomly drawn as a function of the parameter s.

Additional velocity The Δv distribution for small objects was adapted to better match measurement data [4].

Fragment material In the SOCIT experiments [8] it was observed that different materials are not equally distributed as a function of fragment size. The A/m distribution for objects $< 1\,\mathrm{mm}$ was adapted to meet the higher share of plastics for small fragments from spacecraft.

For explosion events, the parameter s in Equation 1 was derived for different event types as shown in Table 3 [4]. The new classification scheme for DISCOS, as outlined in Section 2.1, reflects the different event types in POEM and thus harmonises the interaction between the data from DISCOS and the model in POEM.

Table 3. Applied explosion model parameter s for event types in POEM.

Event type	s
SL-12 ullage motor	0.1
Cosmos 699 class	0.6
Cosmos 862 class	0.1
All Soviet/Russian battery-related events	0.5
All Soviet/Russian ASAT	0.3
Other satellites/rocket bodies	1.0

However, a pre-defined scaling factor for certain object types does not always reproduce the number of observed fragments. A *dynamic scaling* approach from the Battelle model [5] is thus applied using a reported number of observed fragments (or number of catalogued fragments) multiplied with an altitude dependent catalogue incompleteness (so-called *Henize*) factor to scale the power law distribution in a way that observations can be reproduced in a certain size region. The number of objects N_t larger than the minimum *trackable* size $L_{c,t}$ can be obtained via Equation 1:

$$N_t = 6 \cdot s \cdot L_{c,t}^{-1.6}. \tag{3}$$

The Henize factor f_H is computed via:

$$f_H = \begin{cases} \sqrt{10^{\exp\left(-\left(\frac{\log L_{c,t} - 0.78}{0.637}\right)^2\right)}}, & L_{c,t} > L_c^*, \\ \sqrt{10}, & L_{c,t} \leq L_c^*, \end{cases} \tag{4}$$

where $L_{c,t}$ is provided in centimetres and $L_c^* = 10^{0.78} \approx$ 6 cm. The minimum trackable size can be obtained as a function of the orbit altitude, see [4] for more details. It is now possible to compute the scaling parameter s given a number of actually tracked fragments N_t^* using Equation 3 and Equation 4:

$$s = \frac{f_H \cdot N_t^*}{6 \cdot L_{c,t}^{-1.6}}. \tag{5}$$

In an analogous way, the parameter M for collision events can be obtained for the dynamic scaling approach:

$$M = \left(\frac{f_H \cdot N_t^*}{0.1 \cdot L_{c,t}^{-1.71}}\right)^{\frac{4}{3}} \tag{6}$$

It is important to note at this point that both the altitude dependency of the trackable diameter and the catalogue incompleteness are models that deviate from reality as assessing the properties of a network of observational sites is arduous, including generally classified information on sensor sensitivity but also observability constraints resulting from the relative geometry between the observation network and the fragments' orbits. This implies that N_t^* does not necessarily correspond to the actual number of reported or tracked fragments, it merely represent a first order estimate which is further refined in the validation process explained in the following.

2.2.2. Validation of MASTER

Several data sources are used in the validation process of the MASTER reference population. The small particle population is validated with in-situ measurements and returned surfaces, including

- the Long Duration Exposure Facility (LDEF),
- solar array wings of the Hubble Space Telescope returned during the SM1 and SM3B Shuttle missions and
- the European Retrievable Carrier (EuReCa).

For the large object population, ground-based observations from the

- ESA Space Debris Telescope / Optical Ground Station (OGS),
- the Tracking and Imaging Radar (TIRA), often used in so-called Beam Park Experiments (BPE) with the radio antenna in Effelsberg and

- for the first time during the MASTER-2009 upgrade, the European Incoherent Scatter radar network (EISCAT) in Scandinavia

are used as the primary data sources. Using the Program for Radar and Optical Observation Forecasting (PROOF) to translate the orbit and object properties of the population snapshots into simulated measurements, one can directly compare the to the real observations. This allows to iteratively adjust the scaling parameter s for the individual breakup events.

The validation process for MASTER-2009 started shortly after the three major breakups of Fengyun 1C, Cosmos 2251 and Iridium 33 occurred in 2007 and 2009, respectively. Fragments from those clouds were detected during the dedicated campaigns by TIRA and EISCAT. It was then the task of the analysts to assess those events and find an appropriate value for N_t^* (or M). The selected N_t^* for the reference epoch May 1, 2009 is given in Table 4 and compared to the number of catalogued fragments today. The differences are remarkable. The Fengyun 1C event was highly underestimated. One reason for this is the *cataloguing latency* inherent to a sensor network, which is depicted in Figure 2 for the age of the first Two-line Element (TLE) of the Fengyun 1C fragments. Although more than 2000 fragments were already catalogued within the first year after the event, the next five to six years saw several batches of tens to hundreds of fragments added to the TLE catalogue. The number of detected objects as a function of object size obtained on February 10, 2008 with the EISCAT network is shown in Figure 3. Even though [10] reported on the SSN tracking more than 2200 objects $> 5\,\mathrm{cm}$ by the end of June 2007 and the detections by EISCAT indicated an under-prediction of the model, the estimate of N_t^* for the Fengyun 1C event remained at $N_t^* = 1000$. As mentioned in the previous section, the difficulty here was to assess the observation network properties for the tracking of Fengyun 1C fragments: the figure of 2200 fragments was based on objects $> 5\,\mathrm{cm}$, which is smaller than the minimum trackable diameter in the model. It was a very surprising result to see such a good match when the MASTER population validation in 2016 started within the upgrade activity and the green curve in Figure 3 was obtained. The latter was based on 3425 modelled fragments. So even with 2200 fragments back then one would have had difficulties in matching the observations by EISCAT.

Table 4. Number of catalogued fragments (N_t^*) used for the MASTER-2009 reference epoch compared to the current number for the event clouds from Fengyun 1C, Cosmos 2251 and Iridium 33.

Parent object	M-2009	Current[1]	Deviation
Fengyun 1C	1000	3430	+243 %
Cosmos 2251	1050	1668	+59 %
Iridium 33	467	628	+34 %

[1] `space-track.org`, April 3, 2017.

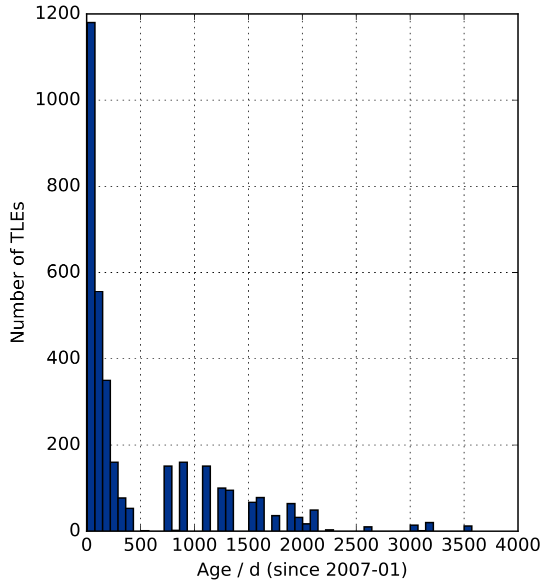

Figure 2. The age of the first TLE of each catalogued fragment of the Fengyun 1C event relative to the event epoch in January 2007.

For the GEO region, different dedicated observation campaigns with the OGS have revealed that besides the two known fragmentation events of a Titan Transtage (1968-081E) in February 1992 and the Ekran 2 (1977-092A) satellite in June 1978 there is a larger population of objects with unknown origin. A third event very close to the GEO region was confirmed by the SSN in January 2016 for a Briz-M upper stage (2015-075B) with ten associated pieces of debris, six thereof catalogued at the moment[5]

The observation results from the OGS in the past were showing objects clustering in typical inclination vs. right ascension of ascending node (RAAN) plots, indicating potential new breakups. As the MASTER population is event-based, a missing event means missing debris flux so that some of the observed patterns were impossible to reproduce by just calibrating the models in POEM. For the GEO region, a number of additional *assumed* breakup events were introduced to match those patterns. As those events are unconfirmed, the usually causal link between object flux as a result from MASTER and underlying event is frail, but it is still necessary to reproduce the observed object numbers.

In Figure 4 all currently modelled fragmentations in MASTER in or near the GEO region are shown, a list recently revised in [3]. With the Vimpel catalogue[6], a new source of orbit information found its way into the analyses of SDO in 2016. It combines results from observations by the International Space Observation Network (ISON) and their partners. The Vimpel data is shown in Figure 4 for January 2017. An interesting feature is the slight offset of the confirmed Titan Transtage event

[5] `https://www.space-track.org`, April 7, 2017.
[6] `http://spacedata.vimpel.ru/`

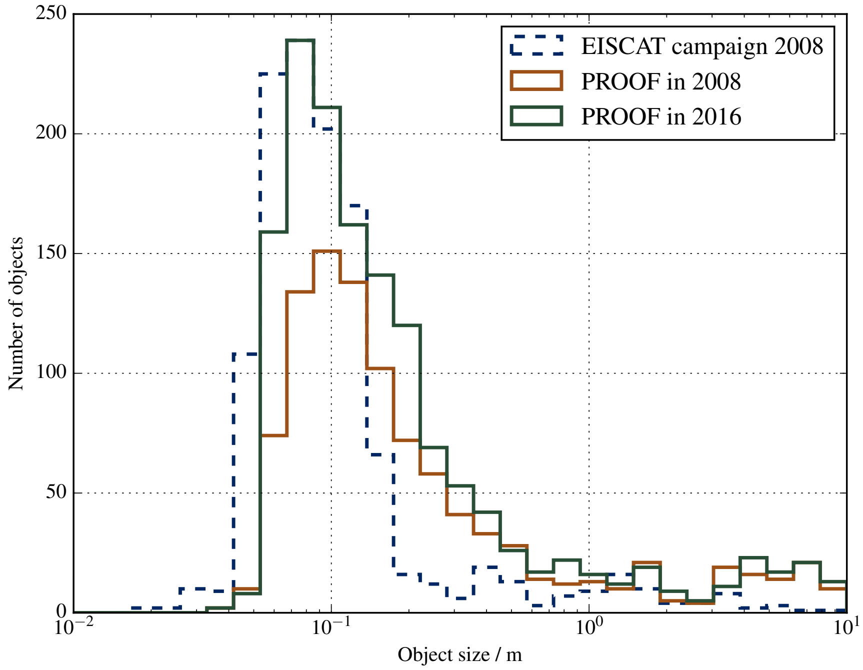

Figure 3. Detections of the EISCAT network on February 10, 2008. Also shown are the simulated detections with PROOF for the MASTER-2009 population and the currently ongoing validation for the upgraded MASTER in 2017.

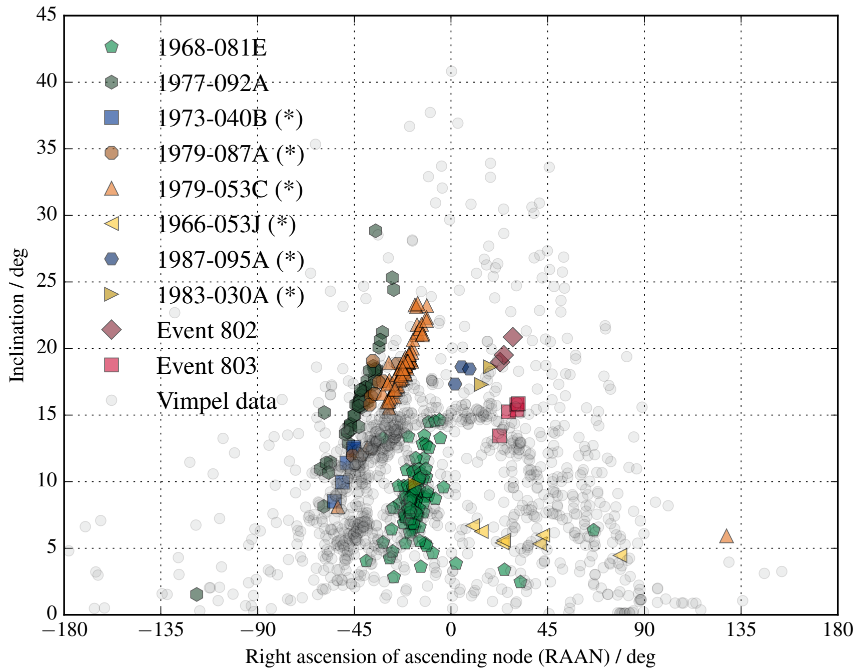

Figure 4. Currently modelled fragmentation events in or near the GEO region in MASTER. Only objects with $d > 30$ cm shown. Events with asterisk indicate assumed events associated with a parent, while Event 802 and 803 are not associated with any satellite. Overlay of objects from the Vimpel catalogue for January 2017.

(1968-081E) in the plot which from visual inspection would make a better fit if it would be shifted in RAAN. With the current validation process on-going, which includes the evaluation of recent OGS campaigns, it remains to be seen if this requires an update in the initial conditions of the breakup or the assumptions in the propagation of the cloud. In any case, the Vimpel information presents a complementary source which will be considered in future analyses.

A first step to filter known objects from other catalogues was made by applying a simple correlation algorithm that matches objects from the SSN TLE catalogue with Vimpel orbits. This allows to identify deficiencies in object number counts for the unknown objects and potentially unconfirmed events. An example for Vimpel objects correlated with TLE objects is shown in Figure 5 for three known events. It also shows two recent Briz-M events with two and four objects, respectively, that were positively correlated between TLE and Vimpel catalogues and seem to match well with the MASTER fragment clouds. On the other hand, the Titan Transtage event shows again an offset compared to the correlated objects.

2.2.3. From population snapshots to spatial density

The population snapshots generated by POEM contain discrete objects even though the underlying models to generate those objects are generally stochastic. In order to reflect this, the tool Probability Density (ProbDens) was introduced to convert population files into multi-dimensional probability densities that can be readily translated to flux values again by the MASTER flux browser [4, 12]. One property of the probability density tables of MASTER is that the orbital elements RAAN and the fast variable (true anomaly) are uniformly distributed, which means that the representation of fresh fragmentation is rather inaccurate unless one uses the special *cloud* population files with an additional dimension for RAAN.

2.3. BUSTER

The work on the BreakUp Simulation Tool with Estimation of Risk (BUSTER) software started around the time of the NOAA 16 event with the main objective being to regularly screen recent the TLE catalogue for new objects for known fragmentation events and analyse the relative risk increase due to single breakup events. The obtained results allow to provide a figure on the expected number of additional collision avoidance manoeuvres for the ESA missions. Moreover, using a breakup model not only allows to extract manoeuvre statistics but also the increased risk of impacts for untracked objects and thus a potential subsystem or even mission failure. BUSTER works in four steps:

1. Run POEM to generate a fragment cloud and propagate it across the time span of interest (Section 2.2.1).
2. Convert the population snapshots to spatial density (Section 2.2.3).
3. Run the MASTER flux browser to obtain the spatial density for the reference population.
4. Divide the spatial density for the fragment cloud by the one from the reference population to obtain the relative risk increase.

BUSTER was soon identified as the core element for ESA's Fragmentation Frontend[7], which is aiming at providing relevant statistics to ESA missions but also operators, researchers and engineers around the world for all fragmentation events. Moreover, in the course of the development of BUSTER, many automated tasks have been introduced, which will be beneficial in the population generation process for the MASTER model and the derivation of future breakup statistics for debris environment evolution models (Section 4).

3. BREAKUP ANALYSIS WITH BUSTER

A typical analysis result from BUSTER is shown in Figure 6. It shows the risk increase relative to the MASTER reference population from May 1, 2009 for all breakup events since that epoch. The two most notable events are the NOAA 16 (2000-055A) and DMSP F13 (1995-015A) breakups from November and February 2015, respectively. The additional risk is given as a function of the altitude and can be quickly assessed for different ESA missions in LEO. For example, the Sentinel 2 (A and B) and Sentinel 3A satellites would experience an additional risk of objects greater than 10 cm of about 20% to 40%, respectively, for all events combined.

An attempt to verify such estimates is to analyse the history of actual high risk events for those satellites. The received Conjunction Data Messages (CDM) for a subset of ESA satellites the SDO provides collision avoidance support for were analysed for a time period between November 2015 and April 2017. The results are shown in Table 5 for the Top 6 events, counting the number of individual identified risk events where chaser objects originated from the same breakup event. A notable first result is that two events, the Fengyun 1C breakup in 2007 and the collision between Cosmos 2251 and Iridium 33 in 2009, contribute to about half the number of events for all the satellites in this analysis. A surprising result is to see the international designator 2005-043 appearing in the statistics for the Sentinel 1 satellites. In October 2005, a Cosmos-3M launcher put eight small satellites into orbit at an altitude which is similar to the one of the Sentinels, which were not there back then, of course. One of the objects was ESA's educational mission SSETI Express

[7] https://fragmentation.esoc.esa.int

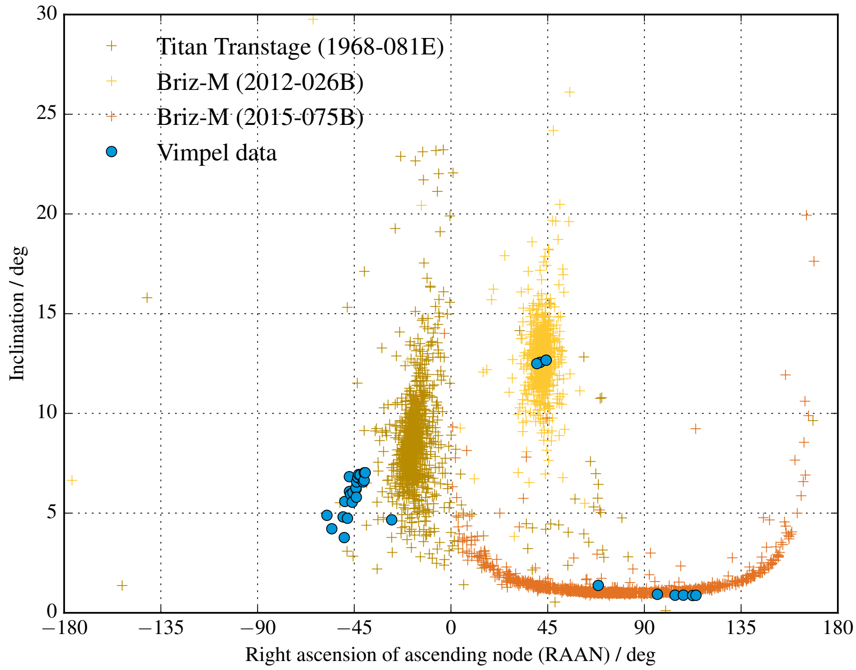

Figure 5. Comparison of two Briz-M and a Titan Transtage event to Vimpel orbits that were positively correlated with objects from the TLE catalogue for those events in January 2017. POEM event clouds are shown for objects larger than 1 cm.

which itself deployed three of the seven other satellites from this launch.

In Table 5 also the statistics for the NOAA 16 and DMSP F13 events are provided. For Sentinel 3A, the count of the NOAA 16 event is ranked on fifth position. However, the relative number of events for all the ESA satellites in Table 5 is lower than the estimates provided by BUSTER for objects larger than 10 cm in Figure 6. As an example, the estimated risk increase for Sentinel 2A due to the NOAA 16 (2000-055A) event is given by BUSTER between 5% and 10% in Figure 6, while the actual statistics from the CDMs show a share of 1.4% in the total number of events with known chaser objects. There are many possible error sources contributing to the observed deviation:

- The BUSTER risk increase is computed relative to the MASTER reference epoch from May 1, 2009. Although one could compute it relative to the actual epoch, this would introduce uncertainty as well due to the environment evolution prediction from 2009 to 2017.
- Risk increase is currently evaluated as the ratio between two spatial density values in a 1-dimensional distribution. Only the altitude is considered. Moreover, binning (in this example with 20 km bins) might be an issue.
- The MASTER reference population from May 1, 2009 underestimated the catalogued fragments for all the major contributing events for Sentinel 2A, as shown in Table 4. Correcting those figures with the actual number of catalogued fragments (Table 2) would result in an update for NOAA 16 to about 1.8% of all events for Sentinel 2A.
- CDM statistics may suffer from several systematic errors, including unnoticed changes in the screening volume, repeated conjunctions with the same chaser objects and alike.
- The estimated statistics from BUSTER are based on objects larger than 10 cm. In reality, the comparison is difficult as the chaser objects might be even smaller. For example, extracting the Radar Cross Section (RCS) for all Fengyun 1C fragments from the CDM data gives about 20% of the chasers with a size smaller than 10 cm. The actual sensor sensitivity and cataloguing properties for the SSN are difficult to assess.
- The NOAA 16 and DMSP events are both battery-related. The experience from Soviet/Russian battery-related events led to defining the scaling parameter as $s = 0.5$ (see Table 3), effectively reducing the number of generated fragments to 50 %. A comparable analysis for the TIROS-N/NOAA/DMSP event class is still to come.

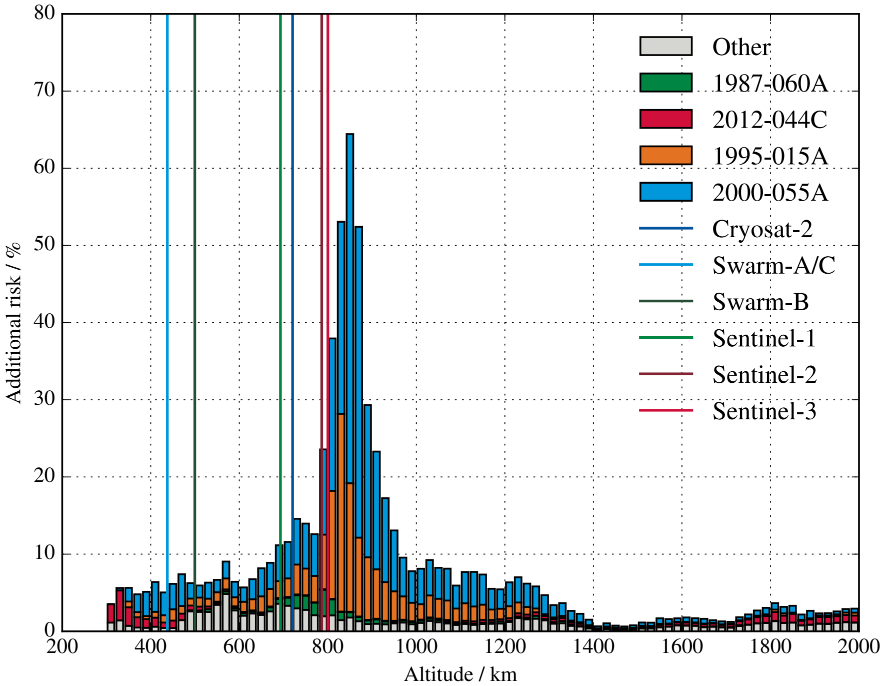

Figure 6. Risk increase relative to the MASTER reference population from May 1, 2009 for all events from May 2009 through December 2016 for object greater than 10 cm. The mean altitude of some ESA missions in LEO are indicated by vertical lines.

Table 5. Number of events from CDMs received for different ESA satellites since November 2015. The shares are computed for the set of known chaser objects, whereas the number of unknown chaser objects is given for information only and not taken into account.

Parent name	COSPAR	Sentinel 1A	Sentinel 1B	Sentinel 2A	Sentinel 3A	Cryosat 2
Fengyun 1C	1999-025	18.4%	14.9%	20.3%	28.0%	18.9%
Cosmos 2251	1993-036	28.7%	25.3%	17.1%	12.7%	23.2%
Iridium 33	1997-051	8.4%	12.4%	5.4%	2.3%	14.7%
CZ-4 (L-14)	1999-057	3.6%	3.9%	2.1%		4.7%
SL-16 second stage	1992-093	2.5%		2.9%	3.8%	
Meteor 2-6	1980-073				3.3%	
Delta 2910 second stage	1978-026			2.3%		
Cosmos 1275	1981-053					1.4%
SL-8 second stage	1982-051					1.4%
Thorad Agena D	1969-082		2.6%			
Cubesat launch	2005-043	3.5%	3.0%			
NOAA 16	2000-055	0.1%	0.3%	1.4%	2.5%	0.6%
DMSP 5D-2 F13	1995-015	0.4%	0.4%	1.1%	1.4%	1.0%
Events with *known* chaser objects		6152	2000[1]	8176	1475[2]	6934
Events with *unknown* chaser objects		1263	481[1]	1768	260[2]	1503

[1] since April 25, 2016 (launch date)

[2] since February 16, 2016 (launch date)

4. BREAKUP STATISTICS AND ENVIRONMENT EVOLUTION

The knowledge on breakups and associated statistics is crucial when it comes to modelling the future evolution of the debris environment. Fragments from explosion and collision events are by far the dominating source of objects for the tracked population but also in the small particle size regimes down to $1\,\mathrm{mm}$ for those regions where most of today's satellites are operated.

It is thus essential to strive for the highest possible accuracy in modelling past events, as those make up the initial population going into the environment evolution models. But breakup models are then also used in those tools to generate fragment clouds for future events. The outcome of any activity on the future debris environment evolution is thus very sensitive to the assumptions made in the used breakup model.

An important assumption is the expected annual explosion rate in the traffic scenario. For MASTER-2009, there were three different future scenarios defined which were then applied in ESA's Debris Environment Long-Term Analysis (DELTA) software to forecast the environment until 2055. The annual explosion rate $\dot{e}$ was defined as $\dot{e} = 5.6 \pm 0.4$ for a business-as-usual scenario. For the two mitigation scenarios it was assumed to start with a rate of $\dot{e} = 1.0 \pm 0.2$ and decrease to 5 % of that value until 2020. The main question is how to come up with those numbers. Figure 7 shows the yearly event count and, as an example, for each year the average of the preceding 10 years. The result for 2009 would be about 8.3 events per year for this methodology. But this is a worst case as it includes atmospheric breakups and anomalous events which on the one side do not produce long-living fragments or, on the other hand, only very few fragments which might be also less relevant for the long-term evolution. In a second example, shown in Figure 8, only those events were counted where at least 50 % of the generated fragments have (or had) a lifetime larger than 20 years. Although the numbers are arbitrarily chosen, this is the kind of analysis one would do to get an estimate for the annual explosion rate, which, in this case corresponds to 3.4 events per year. As an example, being more strict and selecting only those events where 90 % of the generated fragments have at least 10 years and 25 years of remaining lifetime results in an estimate of 3.2 and 2.8 annual events, respectively.

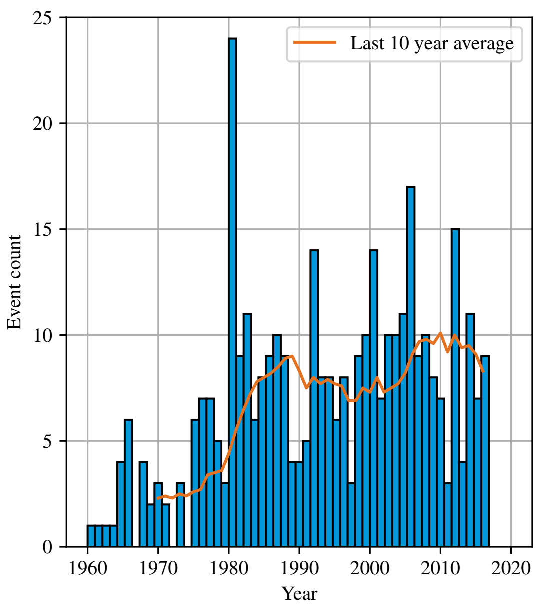

Figure 7. Number of events per year extracted from DISCOS. Also shown for each year is the average of the preceding 10 years.

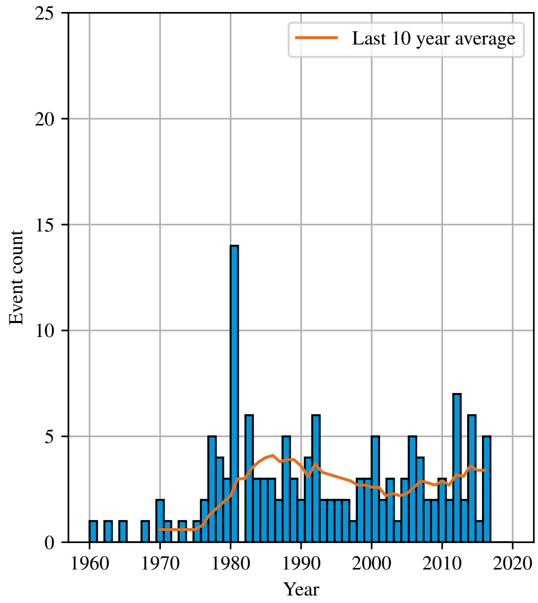

Figure 8. Number of events per year counting only those where 50% of the fragments had a lifetime larger than 20 years. Also shown for each year is the average of the preceding 10 years.

Going further, one could even think of refining it by looking at different event classes and counting how many objects of the same type are still on orbit or even being launched today, etc. But even without this additional step, Figure 8 shows two important features: first, the number of *environmentally relevant* breakups is significantly lower for the 10-year-average than the one defined for MASTER-2009 in the business-as-usual scenario. However, and second, from this analysis there is no evidence of a declining rate in the explosion events. The current value from Figure 8 is at $\dot{e} \approx 2.2$ for 2017 and even when going back until 2000 there would always be a justification for 1.5 to 2.0 events per year.

5. CONCLUSION

The current approach of ESA's Space Debris Office in modelling breakup events was outlined. Some of the major tools relevant for debris risk analyses are currently being upgraded. In DISCOS, the event database saw a major review introducing more event type classes which in turn allows for higher fidelity in modelling breakup events. The MASTER model will soon be upgraded as well with the validation of the population currently on-going. The general validation approach and some first-look results were presented, also introducing first attempts in exploiting information from the Vimpel catalogue. With BUSTER, a new tool has been developed to monitor and analyse breakup events. It is used to estimate the increased risk after a fragmentation event based on a reference population. ESA's database of CDM messages received from JSpOC was analysed to see how well BUSTER risk estimates match with real high risk events. Various error sources have been discussed that possibly lead to the observed deviation with BUSTER's estimate being conservative (5% to 10% vs. about 1.4% from CDMs for Sentinel 2A). A more detailed investigation is required to properly assess the errors. Besides the use case of breakup statistics for the operational missions, it was also discussed that those statistics are very relevant for any debris evolution model. Taking only those events into account that produce fragments with longer lifetimes, one may arrive at an average of about 3 explosions per year, which is less than what is currently used in the business-as-usual scenario in MASTER, but also clearly higher than what was assumed for the mitigation scenarios.

Future work will focus on expanding the event type classes in DISCOS to discriminate, for example, between reliability issues for a spacecraft and environmentally induced breakups. Moreover, with the anticipated upgrade of the breakup model, e.g. via NASA's DebriSat activity, there are many challenging investigations ahead to improve the current knowledge on breakup events and use it for the benefit of long-term evolution analyses.

REFERENCES

1. Bonnal, C., Sanchez, M., and Naumann, W. (1997). Ariane Debris Mitigation Measures. *Second European Conference on Space Debris*. Vol. 393. ESA Special Publication, p. 681.
2. Clark, P. S. (1994). Space debris incidents involving Soviet/Russian launches. *Journal of the British Interplanetary Society* **47**, 379–389.
3. Flegel, S. K. (2013). *Multi-layer Insulation as Contribution to Orbital Debris*. Dissertation, Technische Universität Braunschweig.
4. Flegel, S., Gelhaus, J., and Möckel, M. (2011). Maintenance of the ESA MASTER model. *Final Report, ESA contract 21705/08/D/HK*.
5. Fucke, W and Sdunnus, H (1993). Population model of small size space debris. *ESA contract 9266/90/D/MD*.
6. Johnson, N. L. (2008). History of on-orbit satellite fragmentations, 14th Edition.
7. Johnson, N. (2001). NASA's new breakup model of EVOLVE 4.0. *Advances in Space Research* **28**.9, 1377 –1384.
8. Krisko, P. H., Horstman, M, and Fudge, M. L. (2008). SOCIT4 collisional-breakup test data analysis: With shape and materials characterization. *Advances in Space Research* **41**.7, 1138–1146.
9. Krisko, P. (October 2011). Proper Implementation of the 1998 NASA Breakup Model. *Orbital Debris Quarterly News* **15**.4.
10. ODPO (July 2007). Detection of Debris from Chinese ASAT Test Increases. *Orbital Debris Quarterly News* **11**.3.
11. Pardini, C. (2005). Survey of past on-orbit fragmentation events. *Acta Astronautica* **56**.3, 379 –389.
12. Wegener, P (2004). *Modelling and Validation of the Space Debris Flux onto Satellites*. Dissertation, Technische Universität Braunschweig.