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On-orbit breakup forensics: analysis of measurement data to reconstruct fragmentation events in space

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Abstract

The status of the space debris environment is strongly affected by the possible occurrence of fragmentation events. In orbit break-up events can occur due to collisions with other satellites or debris, as well as due to internal explosions within a satellite. Knowledge for characterising such events for both, inclusion in space debris environment models and for timely ad hoc analyses for operational needs, is based on distributed, heterogeneous, and in general very diverse sources. It is then important to understand the dynamics and consequences of these events, and to develop methods to reconstruct and characterise them based on real data from historical break-up events.

This work focuses on On-Orbit Break-up Forensics to provide innovative methodologies for the analysis and characterisation of space fragmentation events. The aim of the work is to develop a new tool to reverse engineer a fragmentation starting from observed fragments. Moreover, new metrics are defined to characterise the dynamics and density distribution of a cloud of debris, to better define pruning and filtering criteria for the reverse engineering on the cloud and optimise the tasking of sensors for dedicated observation campaigns. The activity is financed through ESA's Technology Development Element and aligned to contribute to the technology objectives from ESA's Space Safety Programme, focusing on the improvement of the technologies for effective risk evaluation, by establishing a theoretical formulation for the estimation of the space debris density within days after a break-up event in orbit.

Keywords: In-orbit breakup; Fragmentations; Collision risk; on-orbit forensics.

Acronyms/Abbreviations

BC	Ballistic Coefficient
CoM	Centre of Mass
EI	Environmental Impact
FEI	Fragmentation Environmental Index
FoR	Field of Regard
FoV	Field of View
FRED	FRagmentation Epoch Detector
IOD	Initial Orbt Determination
LEO	Low Earth Orbit
LMO	LEO – MEO crossing orbit
MEO	Medium Earth Orbit
MOID	Minimum Orbital Intersection Distance
OFELIA	Orbital Fragmentation rEconstruction moduLe for forensIcs Analysis
OM	Observability Metric
PDF	Probability Density Function
RAAN	Right Ascension of the Ascending Node
SNR	Signal to Noise Ratio
SOFT	Simulation of On-Orbit Fragmentation Tool
SST	Space Surveillance and Tracking
TLE	Two Line Elements

1. Introduction

The status of the space debris environment is strongly affected by the possible occurrence of fragmentation events. In orbit break-up events can occur due to collisions with other satellites or debris, as well as due to internal explosions within a satellite. The increment in the total number of fragments present in space also increases the risk of collision for other satellites. In addition, even smaller fragmentations can affect operational satellites; in fact, collision avoidance manoeuvres may be required to avoid the most dangerous fragments. Knowledge for characterising such events for both, inclusion in space debris environment models and for timely ad hoc analyses for operational needs, is based on distributed, heterogeneous, and in general very diverse sources. It is then important to understand the dynamics and consequences of these events, and to develop methods to reconstruct and characterise them based on real data from historical break-up events.

This paper describes the research performed within the ESA-funded project "T711-802SD – On-Orbit Breakup Forensics" by the consortium led by Politecnico di Milano, with the participation of GMV, Istituto di Fisica Applicata "Nello Carrara", Consiglio Nazionale delle Ricerche and SpaceDyS. The activity is financed through ESA's Technology Development Element and aligned to contribute to the technology objectives from ESA's Space Safety Programme, focusing on the improvement of the technologies for effective risk evaluation, by establishing a theoretical formulation for the estimation of the space debris density within days after a break-up event in orbit.

The aim of this project is to provide innovative methodologies for the analysis and characterisation of space fragmentation events. The work leverages the state-of-the-art debris modelling and observation capabilities to improve the estimates of the spatial and temporal distribution of debris fragments after a break-up in orbit. The aim of the work is to develop a new tool to reverse engineer a fragmentation starting from observed fragments. Moreover, two metrics are being defined to characterise the dynamics and density distribution of a cloud of debris, to better define pruning and filtering criteria for the reverse engineering on the cloud and optimise the tasking of sensors for dedicated observation campaigns. This activity will contribute to the development of a digital twin of the space debris environment after a fragmentation, which will support forensics in space and the risk assessment for space missions in their design phases.

In this paper, a literature review is performed on the modelling approaches for fragment modelling and reconstructions and fragment characterisation (Section 2). Past fragmentation events are then analysed to define some reference scenarios and better define the requirements of the tool (Section 3). Two metrics are proposed for describing the fragment dispersion in the cloud resulting from an explosion or a collision in space and to assess the observability of fragments from a network of sensors. The two metrics are to be validated through a sensitivity analysis considering synthetic and real events (Section 4 and Section 5). Then the overall architecture of the OFELIA (Orbital Fragmentation rEconstruction moduLe for forensIcs Analysis) tool is described in Section 6 with a description for the functionality of each module.

2. Revision of modelling approaches for fragment cloud reconstruction

Past works focused on the detection of a fragmentation event, exploiting different features of the orbital motion of the fragments. Andrisan et al. [1] developed the Simulation of On-Orbit Fragmentation Tool (SOFT), to determine the epoch and the objects involved in a breakup. The type of fragmentation is assessed through an analysis of the orbital elements and of the distribution of the detected fragments. For event identification, the average distance among the fragments in the cloud is studied. The true objects involved in the event are determined by comparing the computed orbit with a background catalogue.

Dimare et al. [2] characterised a fragmentation by defining an orbital similarity function between the orbital elements of the detected fragments with the DEBORB software. The time of the breakup corresponds to the time of the minimum of the mutual distances among the known fragments. Similarly, the parent is chosen as the known satellite with the minimum distance from the fragments at the time of the fragmentation event. Several orbital similarity functions have been evaluated to correlate fragments with known orbits to parent(s), like it is usually done for asteroid families. The D-criterion from Southworth and Hawkins [3] and the one of Jopek [4] resulted to be the most suitable definitions for this formulation.

Frey et al. [5][6] developed a method to search for a fragmentation event in the long term, i.e. in the order of years, exploiting a continuum approach for fragmentation modelling in Low Earth Orbit (LEO), based on the density of objects. The method uses the PlanODyn [7] semi-analytical propagator to backpropagate the Keplerian elements of individual fragments. The detected peaks in the spatial density indicate the epoch and location of a breakup. The estimation of the epoch of the breakup is refined by looking for the convergence of objects in inclination and Right Ascension of the Ascending Node (RAAN), which have been considered as robust features in LEO.

Tetrault et al. [8] devised a tool for fragmentation reconstruction focusing on the importance of the ballistic coefficient estimation from the B^* value of the Two-Line-Element (TLEs), mostly for objects with high area-to-mass ratio *A/M*. The tool calculates the time and location of the event and identifies the true, pre-fragmentation objects involved in the event, with variable ballistic coefficient computations. The method backpropagates the objects within the fragmentation cloud and computes at each step the Centre of Mass (CoM), velocity and average distance from the CoM. The fragmentation event is considered to occur when the average distance is at minimum, then the CoM becomes the event location, and the epoch is computed. The parent satellite is identified by comparing the computed initial orbit to a catalogue.

The PUZZLE algorithm aims at detecting occurred breakups (epoch estimation and parent(s) identification) and at characterising the events in terms of energy, mass, and orbital elements [9]. Rather than assuming that a fragmentation has occurred a priori, the tool analyses the TLE data of unclassified objects to detect possible fragmentations occurred in the recent past. The algorithm exploits a backwards propagation of the objects to search for possible close encounters and for a common origin in space and in time by means of pruning and clustering algorithms. Then the filtered objects are matched with known objects possibly involved in the event. The NASA standard breakup model [10] is used to simulate the detected fragmentation event and to reconstruct the distribution of the generated fragments. A first version of the PUZZLE software focused on short-term investigations (i.e., order of days) [11], while a later version allowed to include long-term analyses (i.e., order of months up to years) as well [12]. The two routines have the same objectives, yet they employ different methodologies for the search of fragmentations. The most significant difference is the type of orbital elements used in the two versions to obtain the history of generic objects. The short-term investigation makes use of osculating orbital elements, exploiting the Standard General Perturbations 4 (SGP4) propagator [13], while the long-term investigation is performed using mean Keplerian orbital elements coupled with the PlanODyn propagator [7]. The mean Keplerian elements and the long-term propagation used in the second version of PUZZLE introduce significant uncertainties, making it more difficult to define clusters (or families) of objects exploiting the relative position as in the previous version. In addition to this, another difference is introduced due to the use of PlanODyn, which requires the Ballistic Coefficient (BC) of each object. The BC must be estimated, as it is not included in the TLE data, introducing a further source of uncertainty. The PUZZLE software takes as input a set of TLEs, which are pre-processed to remove from the set the erroneous ones, taken as statistical outliers. Outlying TLEs may be due to modelling simplifications, failures in automated TLE generation process or human errors, pre-filtering is done for each set of TLEs corresponding to the same Satellite Catalogue Number according to the filtering algorithm proposed in [14]. This is a multi-step process, which filters out TLEs according to too large or too short update times, inconsistent mean motion, eccentricity, inclination and negative B^*. The fragments are generated by different events and belong to different clusters of objects; hence a set of pruning and clustering methods is implemented in the PUZZLE routine, coupled with the backward propagation. The short and long-term versions of the PUZZLE software work only in the LEO region, since they exploit the features of LEO orbiting objects to detect and reconstruct fragmentations. Several pruning and clustering methods are employed for fragmentation reconstruction:

- A triple loop filter, proposed by Hoots et al. [15];
- An orbit inclination filter;
- An orbit RAAN filter;
- A Hierarchical Clustering Method as in Zappala et al. [16].

The FRagmentation Epoch Detector (FRED) algorithm [17] deals with the fragmentation identification problem through a stochastic approach and starting from a single fragment orbital state (expressed through mean state and covariance) and the last available ephemeris of the parent object (assumed as deterministic). The process populates the fragment orbital state with a multivariate normal distribution and, for each couple sample-parent, the epochs of parent transit through the Minimum Orbital Intersection Distance (MOID) [18] are first computed on a time window and then clustered in time, returning fragmentation epoch candidates. For each cluster, both the three-dimensional MOID and the three-dimensional relative distance distributions are derived. Given that, at the actual fragmentation epoch, the MOID and relative distance were equal, the fragmentation epoch candidates are ranked according to the stochastic matching between the two distributions. The candidate featuring the best matching is returned, in terms of mean and standard deviation.

To determine the statistical matching, three metrics are investigated: the Mahalanobis distance, a tailored procedure based on the quantiles coupled with a principal component analysis and the Earth mover’s distance. From the results, the latter is deemed as the most performing and suitable for the problem, given the non-Gaussian distributions involved. FRED performance is assessed through a numerical analysis. For this purpose, the data set to test the algorithm is generated by simulating the detected fragmentation event through the NASA standard breakup model [10], and deriving afterwards synthetic results of an orbit determination process [19][20]. Numerical simulations have revealed that the algorithm reliability diminishes when the observed fragment orbital period or plane is close to the one of the parent object. Moreover, a sensitivity analysis showed that the algorithm performance is not significantly affected by the number of samples used to represent the fragment orbital state. Incorporating perturbations and orbit determination errors worsens performance, but the algorithm remains capable of correctly identifying the fragmentation epoch among candidate options. Moreover, the algorithm consistently outperforms an alternative deterministic metric based on the minimum relative distance between the parent ephemeris and the mean state of the fragment propagated over the analysis time window.

In this work, the DEBORB, PUZZLE and FRED code were applied to past fragmentation to define the requirements of a new tool OFELIA, which integrate the advantages of all past methods while trying to overcome their limitations.

3. Breakup event analysis

To define the requirements of the tool and select fragmentation scenarios, past fragmentation events were analysed and collected considering several sources for data [21]-[25]. At the time of the analysis (04/01/2024) the DISCOS database contained 656 events. We filtered the database keeping only events that happened in the last 20 years (after 01/01/2004) and removing those events whose origin was uncertain or anomalous and those with zero catalogued fragments. After filtering we obtained a database of 80 events. Fig. 1 shows the distribution of the filtered database events as a function of their event type.

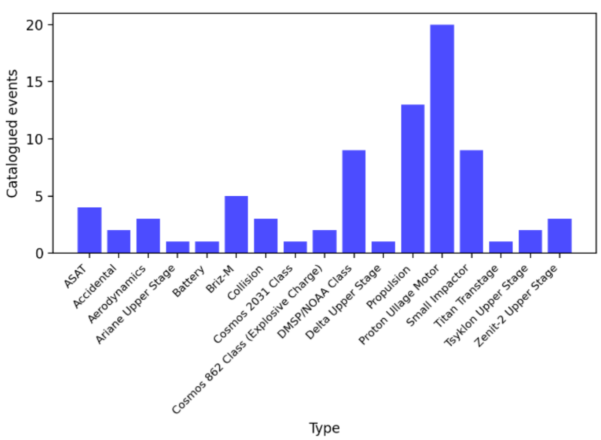


Fig. 1. Types of catalogued event.

Among them, the highest number of catalogued fragments were:

- Fengyun 1C, ASAT event, 3521 catalogued fragments, (2007-01-11)
- Cosmos-2251, Collision event, 2368 catalogued fragments, (2009-02-10)
- Cosmos-1408, ASAT event, 1775 catalogued fragments, (2021-11-15)
- Centaur-5 SEC (Atlas V 551), Propulsion event, 1226 catalogued fragments, (2019-04-06)
- Centaur-5 SEC (Atlas V 401), Propulsion event, 667 catalogued fragments, (2019-03-25)
- Centaur-5 SEC (Atlas V 401), Propulsion event, 623 catalogued fragments, (2018-08-30)
- L-15 (YF115) (Long March (CZ) 6A), Propulsion event, 532 catalogued fragments, (2022-11-12)
- NOAA 16, DMSP/NOAA Class event, 457 catalogued fragments, (2015-11-25)
- Fregat operational debris (SBB), Propulsion event, 339 catalogued fragments, (2020-05-08)
- DMSP Block 5D-2 F13, DMSP/NOAA Class event, 237 catalogued fragments, (2015-02-03)

A simple metric was used to measure the Environmental Impact (EI) of a fragmentation, equal to the product of the number of produced fragments times the average on-orbit time of the fragments:

$$EI = \sum_{i=1}^{N_b} (n_i \, \tau_i) \tag{1}$$

where N_b is the number of 1-day bins, n_i is number of fragments with on-orbit time τ_i measured in days, with τ_i going from one to the time difference between the download time and the fragmentation epoch.

The environmental impact values shown in Table 1 are relative to the Fengyun-1C fragmentation, the event with the highest metric, which has therefore a value of 1 in these units.

Table 1. Highest Environmental Impact fragmentation events.

Event	Date	Current number of catalogued fragments on DISCOS	Event type	Environmental impact
Fengyun-1C	11-01-2007	3521	ASAT	100.00%
Iridium 33 – Cosmos 2251	10-02-2009	2368 (1712 from Cosmos 2251 and 656 from Iridium 33)	Collision	48.30%
NOAA-16	25-11-2015	457	DMSP/NOAA Class	7.02%
DMSP Block 5D-2 F13	03-02-2015	237	DMSP/NOAA Class	3.70%
Briz-M	19-02-2007	106	Briz-M	3.12%
Briz-M	13-10-2010	122	Briz-M	3.05%

DMSP Block 5D-2 F11	15-04-2004	84	Propulsion	2.53%
Cosmos-1408	15-11-2021	1793	ASAT	2.47%
Fregat-SB	08-05-2020	340	Propulsion	2.07%
Proton-K/DM-2 ullage motor (SOZ)	10-06-2006	119	Proton Ullage Motor	1.54%
Long March CZ-3C	26-02-2012	41	Propulsion	0.92%
Tsyklon-3-3	12-02-2020	111	Tsyklon Upper Stage	0.78%
Long March CZ-3B/E	12-08-2012	31	Propulsion	0.67%
Briz-M	16-10-2012	116	Briz-M	0.62%
NOAA-17	10-03-2021	114	Battery	0.60%
Proton-K/DM-2 ullage motor (SOZ)	13-08-2014	25	Proton Ullage Motor	0.42%
Cosmos-1030	15-08-2004	12	Aerodynamics	0.34%
FW-4D (Delta E)	13-05-2006	10	Delta Upper Stage	0.34%
Proton-K/DM-2 ullage motor (SOZ)	08-03-2009	33	Proton Ullage Motor	0.32%
H-IIA 202 lower payload fairing half (4/4D-LC)	12-07-2020	117	Small Impactor	0.25%

Among them a final, more limited list of events was selected for further analyses, including both the most popular events, i.e. Fengyn-1C, Iridium 33 - Cosmos 2251, and Sentinel-1A. Moreover, for objects experiencing more than one break-up (as for Centaur-5 or Proton-K/DM-2 ullage motor events) only one representative were considered in the list, chosen either for the availability of data/literature or for the largest number of catalogued fragments generated by the event. A graphical representation collecting different information about the chosen cases is provided in Fig. 2.

For some selected fragmentation events the distribution of the orbital coordinates of catalogued fragments downloaded from Space-Track and their evolution over time was analysed. The initial set of fragments is the one used as input for the tests with DEBORB [2] in Section 3.1 and it corresponds to the situation one month after the breakup. To obtain the evolution over time, new sets are downloaded from Space-Track for different epochs. Epochs are selected at intervals of one month, starting 1 month after the breakup until 1 year after the breakup. Fig. 3 shows the analysis for the Fengyun-1C fragments cloud in term of (a) the classical Gabbard diagram reporting the apogee and perigee of fragments, often adopted in the Orbital Debris Quarterly News [23]; (b) a histogram of the fragments' dispersion in terms of the argument of perigee; (c) the inclination versus the right ascension of the ascending node, i.e. the direction of the orbital plane; (d) the right ascension of the ascending node versus the argument of the perigee. The fragments orbital elements (depicted in Fig. 3a and Fig. 3b) are propagated with SGP4 [13] at a common epoch displayed in the title, roughly 30 days after the fragmentation event, while parent elements are taken around 7 days before the event.

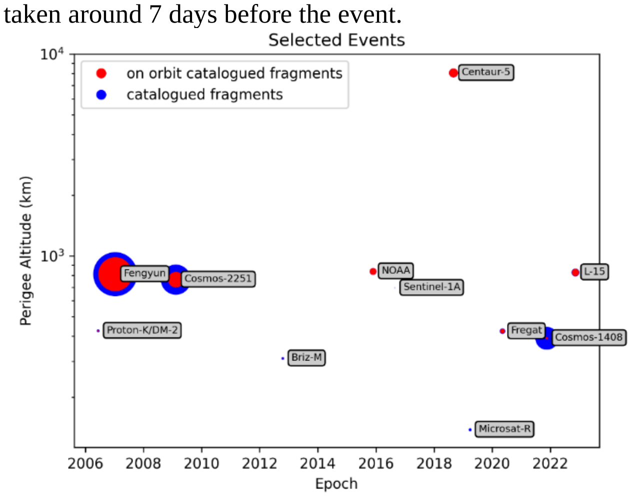
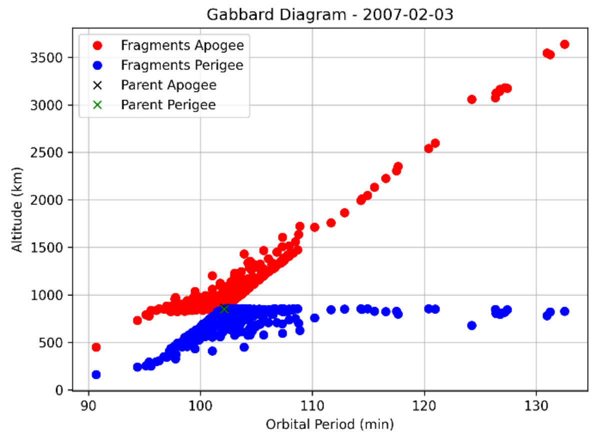
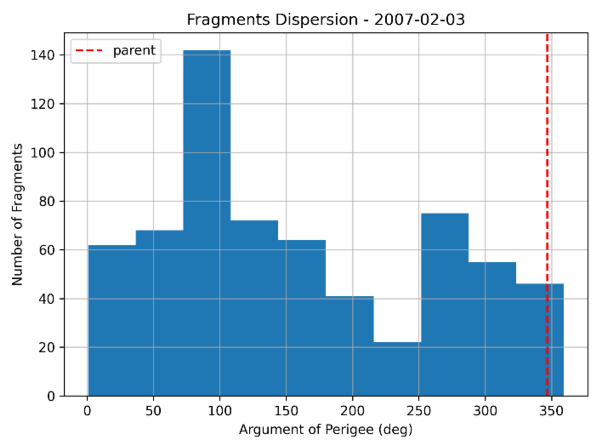


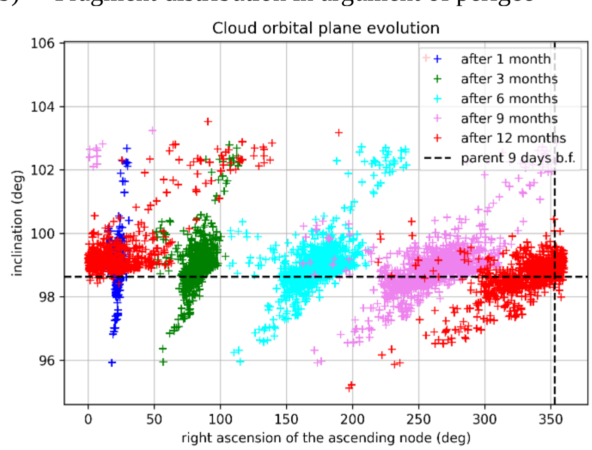
Fig. 2. Summary information on selected events (updated to 01/2024).



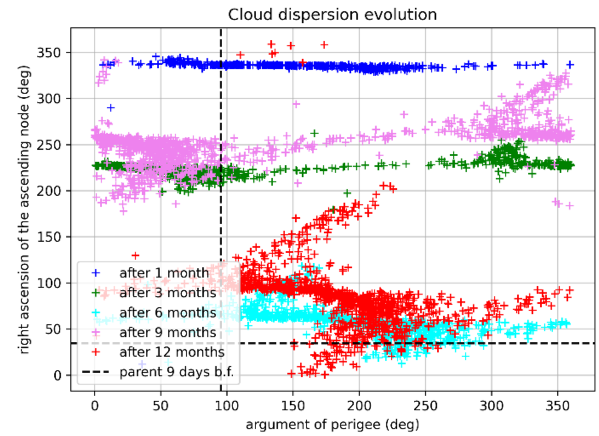
a) Gabbard diagram



b) Fragment distribution in argument of perigee



c) Evolution of the cloud orbital planes



d) Evolution of the cloud dispersion in argument of perigee.

Fig. 3. Fengyun-1C identified fragments cloud.

3.1 Analyses of the selected events with DEBORB

The algorithm for parent body identification implemented in DEBORB software [2] assumes that the input fragments belong to a unique cloud, i.e., that the initial set of objects does not contain debris originated by different parent bodies. The elimination of outliers can be obtained by using simple filters that limit the spread in semi-major axis, eccentricity and inclination of the fragments: this can be easily added in DEBORB as a preliminary step. The algorithm uses a numerical propagator, which is not optimal from the point of view of performance but is convenient when accurate propagation is required. DEBORB is general and can be used for different classes of orbits, provided that the dynamical model adopted for propagation accounts for all relevant perturbations. The method is applicable both if a short time has passed from the instant of breakup and if a long time (months) has already elapsed. Possible limitations may arise for long propagations if some relevant perturbations cannot be considered with the needed accuracy. This happens, for example, for very low objects, because the drag effect can strongly perturb the orbit even after few days. For these cases the applicability of the method is limited by the poor accuracy of propagation, and it can be used only if a short time has elapsed from breakup. The method currently implemented does not consider the orbital uncertainty of the catalogued fragments.

The tests reported in [2] revealed that sometimes, when using the distance D_{SH} defined by the equality:

$$D_{SH}^2 = (e_B - e_A)^2 + \frac{(q_B - q_A)^2}{R_{Earth}^2} + \left(2\sin\left(\frac{I_{BA}}{2}\right)\right)^2 + \left(\frac{e_B + e_A}{2}\right)^2 \left(2\sin\left(\frac{\pi_{BA}}{2}\right)\right)^2, \quad (2)$$

the breakup time might not be determined with high accuracy. However, the tests showed that a possible poor determination of the epoch does not necessarily prevent the correct individuation of the parent body. This is especially true when the object which fragmented has an "unusual" orbit (i.e. it is highly eccentric and does not lie in the most populated area), see the example of Proton-K/DM-2. We also have to underline that, unlike for the results in [2] which were obtained mostly with simulated scenarios, in the tests performed for this activity we are using only real data, and for example for the event epoch we are comparing with the time reported on Space-Track [22], which is itself an estimation in most cases and in any case provided only at a day-level accuracy

3.2 Analyses of the selected events with PUZZLE

The analyses done with PUZZLE are limited with respect to the analyses of DEBORB because of the use of the SGP4 propagator [13], which loses accuracy after about 14 days. Therefore, the analyses of break-up events whose fragments are catalogued months after the event are impossible. Indeed, the Centaur-5 and the Transtage 5 (Titan IIIC) break-ups have not been analysed as the fragments began appearing in the catalogue months after the event. The same issues concern the cases of Proton-K, Fregat-SB, Sentinel-1A, Cosmos-1408 and Long March CZ-6A, which do not provide a useful number of fragments within two weeks from the fragmentation. For this reason, the analysed events are the ones of Fengyun 1C, Iridium 33 and Cosmos 2251, NOAA16, Microsat-R and Briz-M.

To run the simulations with PUZZLE, the fragmentation search was set to at most 14 days before the TLEs epoch and the TLEs given as input to the software have been taken 10 days after the breakup. Two types of analyses have been carried out. In the first analysis, only the catalogue with the fragments (and the addition of the correct parent) was considered as input, to assess whether PUZZLE can correctly detect the fragmentation event. In the second analysis, instead, a single catalogue containing the fragments, and the candidate parents is given as input. The results for the first set of analyses are successful in most cases, both in terms of fragmentation epoch and parent identification. The fragmentation reconstruction failed for Briz-M, however it was expected as the break-up occurred in LMO, which is beyond the current capabilities of PUZZLE. Nonetheless, the routine was able to correctly identify the epoch of the fragmentation. The Microsat-R case also failed, yet further tests have shown that by increasing the tolerances of the algorithm the break-up is reconstructed correctly. As for the second set of analyses, the only successful reconstruction occurs for Iridium 33 and Cosmos 2251. This is due to the initial set of TLEs which has a very high ratio of parent candidates to fragments, with the parent candidates set containing debris on top of satellites. This makes it difficult for PUZZLE to discern the fragments belonging to the fragmentation event under analysis.

The analyses have highlighted some limitations of PUZZLE to be tackled for OFELIA. To improve the analyses with high ratio of parent candidates to fragments, a filtering of the candidates set should be carried out to retain only the satellites and possibly improve the detection of the fragmentation event. Moreover, the routine should be extended beyond LEO to account for fragmentations in higher orbital regions. The routine will also have to be extended to long-term analyses following the approach in [9].

3.3 Analyses of the selected events with FRED

The FRED algorithm allows to characterise the fragmentation event as soon as the orbital state at a certain epoch is available for the analysed fragment, either from an orbit determination result or catalogue. For this reason, the analyses done with FRED differ from the previous ones as the last TLE of the known parent object available before the event is given as input. Moreover, the very first TLE available on Space-Track for each fragment was used as input, together with five TLEs each to associate an uncertainty in the form of a 6x6 covariance matrix. The Earth mover’s distance was employed as metric to rank the match between MOID and relative distance distributions. The break-up events analysed with the FRED approach are Fengyun 1C, Cosmos 1408 [26], NOAA-16, Fregat SB, Iridium 33 and Cosmos 2251. The analysis focuses on the detection of the correct fragmentation epoch, defining the time error with respect to a reference epoch, when available, and providing the percentage of fragments returning an estimated epoch inside a reference time window when a single reference epoch is not available.

The results obtained with FRED algorithm show that for most of the analysed test cases the knowledge of a single fragment orbital state and associated covariance matrix allows to closely detect the epoch of the fragmentation event. Only for the Fregat SB case none of the solutions of the run is correct. This result can be attributed to the unavailability of TLEs in a close time span (limited to two weeks) with respect to the true event epoch. This obliges to use as input for the fragment mean state the orbit position derived from a first available TLE which is known weeks or months after the event, increasing the backward propagation time window and degrading the epoch detection accuracy. This constitutes one of the main limitations of FRED method, which on the other hand is advantageous when a prompt characterisation of the event is required.

4. Definition of metric for cloud expansion and multiple clouds

Two parallel formulations are developed for the cloud expansion metric, which aim to achieve different objectives:

- Gaussian Mixture Model (GMM) approach: it aims to provide inputs for the application of pruning filters in the fragmentation reconstruction analysis.
- Metric approach: it aims to provide a direct understanding of the phase of the cloud evolution at a given epoch, as well as of the type of occurred fragmentation event.

4.1 Gaussian Mixture Model approach

This formulation consists in reducing the multi-dimensional cloud dynamics to a set of one-dimensional GMM in each slow-varying orbital element (semi-major axis, eccentricity, inclination, right ascension of the ascending node and argument of perigee), at defined epochs. The metric is composed, for each orbital element, by the $(K+1)\times3$ time-varying parameters of the GMM, with K number of considered Kernels (i.e., number of Gaussian distributions). Given the fragments distribution, the parameters are computed, for each element, according to the following steps:

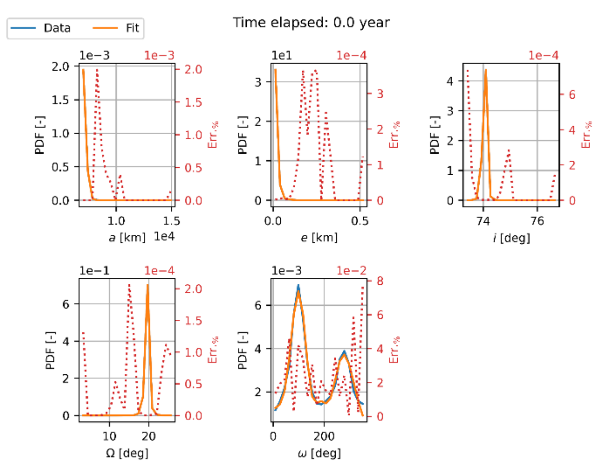
1. Computation of the discretised Probability Density Function (PDF) through samples' binning.
2. Computation of the continuous PDF (GMM) through least squares fitting.
3. Evaluation of the maximum error between the two profiles. If the error is higher than a given threshold, the number of kernels K is increased by 1 and the GMM is re-computed (as long as K stays lower than the maximum number of kernels allowed K_{max}). Otherwise, the parameters are stored.

The proposed metric is applied to one fragmentation in LEO. The parent orbit Keplerian elements for the two breakup scenarios are reported in Table 2.

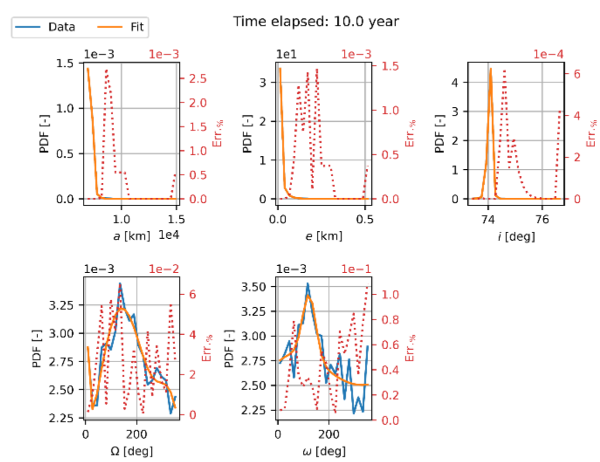
Table 2. Parent orbit Keplerian elements for a LEO breakup.

a **[km]**	***e*** **[-]**	***i*** **[deg]**	**Ω [deg]**	***ω*** **[deg]**	***f*** **[deg]**
7166	0.006	74.0	19.5	98.7	358.6

Fig. 4 depicts the comparison between the discretised (blue line) and continuous (orange line) distributions at fragmentation epoch and 10 years after breakup. The absolute percentage error between the two profiles is also shown (red dashed line). For the results of Fig. 4, a fixed number of Kernels (3) was considered for all the orbital elements. As it can be observed, a very accurate fit is obtained in semi-major axis, eccentricity and inclination at both epochs. For the cases of right ascension of the ascending node and argument of perigee, accuracy degradation can be noticed once the fragments get more randomised in the two variables, as the GMM cannot grasp the oscillations in the profiles, unless the number of kernels is increased. Nevertheless, it is still possible to infer the general behaviour of the fragments' cloud.



a) Fragmentation epoch



b) 10 years after fragmentation

Fig. 4. Comparison between discretised and continuous (GMM) PDFs - Fragmentation in LEO.

4.2 Metric formulation

This second formulation consists in reducing the multi-dimensional cloud dynamics to a single time-varying number, representing the spatial separation of the evolving fragments. As for the GMM approach, the metric requires as input the fragments distribution at specified epochs. At each epoch, the distance between all fragments and a reference object is evaluated. Different possibilities can be investigated for the definition of the reference object, e.g.:

- States of the parent object, assuming it had not undergone fragmentation. If this is the case, the parent orbit has to be propagated along with the fragments' cloud.
- Mean of the multi-dimensional fragments' distribution.

Note that, unless the time discretisation is very refined, the fragment-reference object distance shall stand for the average distance between the two objects considering all geometric relative positions, i.e., the fragment-reference object distance is averaged over one synodic period.

The metric at a given time is defined as the mean fragment-reference object separation.

5. Definition of observability metric and optimisation of sensor tasking

To effectively track the evolution of a cloud of fragments, it is essential to appropriately task ground-based sensors. To achieve this, specific metrics must be established to determine which sensors are optimized for observing the cloud and to assess how each sensor can contribute to its monitoring.

For this reason, two fundamental tools are employed. First, the Fragmentation Environmental Index (FEI) is applied to identify which sensors, from a predefined set, are most likely to detect the highest number of fragments. Following this preliminary analysis, the Observability Metric (OM) is used to quantify and classify the observational performance of the selected sensors. This approach allows for a preliminary selection of sensors using the FEI, which can then undergo a more detailed and computationally intensive analysis with the OM.

5.1 Fragmentation environmental index approach

The first tool employed in the development of the metric is the new FEI, an index developed by Gisolfi et al. [27] to quantify and visualize the medium-term effects on the environment of a fragmentation in LEO.

The FEI was developed to account for the impact on a space surveillance network of an event generating many fragments. Most of these fragments fall below the detection threshold of Space Surveillance and Tracking (SST) sensors, making millimetre and centimetre-sized objects particularly dangerous as they cannot be tracked or avoided by active spacecraft. To address this, a multiplicative weight ω_{tr} was introduced in the previous version of the metric [28] to enhance the significance of non-trackable objects (e.g., smaller than 10 cm, with this threshold being an input to the model) in its computation. The new form of the FEI is presented in Eq. (3):

$$\varXi = \frac{M}{M_0}\frac{A}{A_0}\frac{D(h)}{D_0}\frac{L(h)}{L(h_0)} f(i)\,\omega_{tr} \tag{3}$$

where M, A, L are the mass, area and lifetime of the considered object, while $D(h)$ is the spatial density. However, the most relevant aspect for monitoring a fragments cloud is the newly introduced weight ω_{tr}, which accounts for the importance of non-trackable objects. This weight can be defined for both optical and radar [29]-[35] sensors and is used to preliminarily assess whether a sensor is optimized to observe a given event. Therefore, only this component of the FEI metric is exploited for this preliminary analysis, defining which sensors are most likely to track clouds of fragments.

As regards the ω_{tr} related to optical sensors, its definition is strictly linked to the irradiance of the observed object with respect to the station and to the angular velocity of the object itself. In the radar case, however, ω_{tr} is linked with the Signal to Noise Ratio (SNR) of the fragment, dependent on its altitude and size.

The final ranking of a sensor's preliminary performance (whether optical or radar) is determined by summing all the weights computed for each observed fragment. This allows for selecting a subset of sensors from a list, individuating the ones more suitable for monitoring the cloud. Subsequently, a more detailed analysis is conducted using the OM on this subset.

5.2 Observability metric approach

As introduced previously, the OM is defined and used to quantify and classify the observational performance of the sensors selected in the preliminary analysis with FEI. Let us consider a cloud of fragments whose evolution is modelled according to [36] (or a similar source), and assume that one of the sensors (optical or radar) selected from the preliminary analysis is available for tasking. At a given *k*-th epoch, a volume of the sky V_{TOT} is scanned by the sensor's Field of View (FoV), extendable to the entire Field of Regard (FoR), and N_S bins of the cloud model used for the cloud propagation [36] are selected, as illustrated in Fig. 5, with a differential volume $\Delta V = V_{TOT}/N_S$.

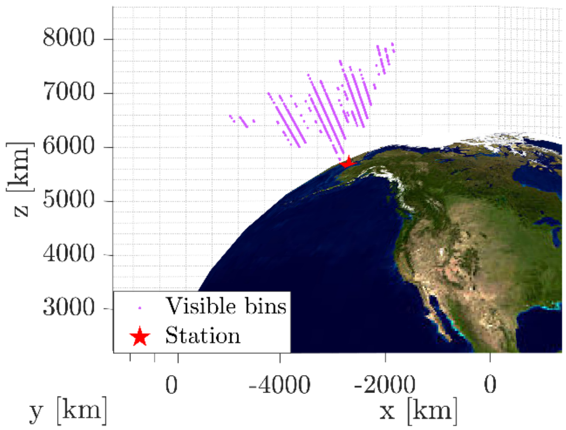


Fig. 5. Visible fragments bins [36] from a dummy station in an Earth centred inertial J2000 frame.

For each i-th position, the distribution of fragments density $\rho_{k,i}$ as a function of fragment size $\delta_{k,i}$ is computed, interpolating between the discrete values available in the i-th bin of spatial density and area to mass ratio. The minimum fragment size observable by the sensor at the i-th bin altitude is derived as well, depending on the sensor characteristics. The maximum fragment density for each i-th bin is then determined by examining the density corresponding to the minimum size. This value is then projected into the sensor's FoV reference frame, converting it from a 3D spatial density to a 2D density. This 2D density is then compared to the sensor's resolution limit, assigning a merit $\xi_{k,i}$ (resolution merit) of 1 if compliant, and 0 otherwise. . Next, the number of fragments detectable at the k-th observation epoch N_k^{fg} is computed, multiplying the detectable density with the ΔV found before.

The resulting number of fragments N_k^{fg} and resolution merit ξ_k represent the sensor performance metrics at the k-th observation epoch. Based on these numbers, it is possible to evaluate which sensors, from the preliminarily set selected through the FEI analysis, are most likely to detect the maximum number of objects.

6. OFELIA software architecture

The OFELIA forensics tool is conceived to integrate in a unique tool the different functionalities needed for on-orbit break-up reconstruction and characterisation. It is a modular tool, composed of independent modules which can be run independently or used together to complete a full cycle of operations, starting from the characterisation of the fragments from the processing of observations, going on with the break-up reconstruction, the simulation of the full cloud of fragments, the forward propagation of it, the characterisation of the cloud expansion and the optimisation of tasking observations for subsequent observations. The full cycle of operations can then be iterated to obtain more information and a better understanding of the break-up and its consequences at each step. To cover all the needed functionalities, interfaces with already existent ESA tools are implemented. The software tool is developed in Python, and it is intended to be used in a 64-bit Linux environment. The diagram in Fig. 6 shows the OFELIA forensics tool decomposition. The main components and the interfaces between them are represented, following the data flow of a complete cycle of operations for breakup reconstruction and characterisation.

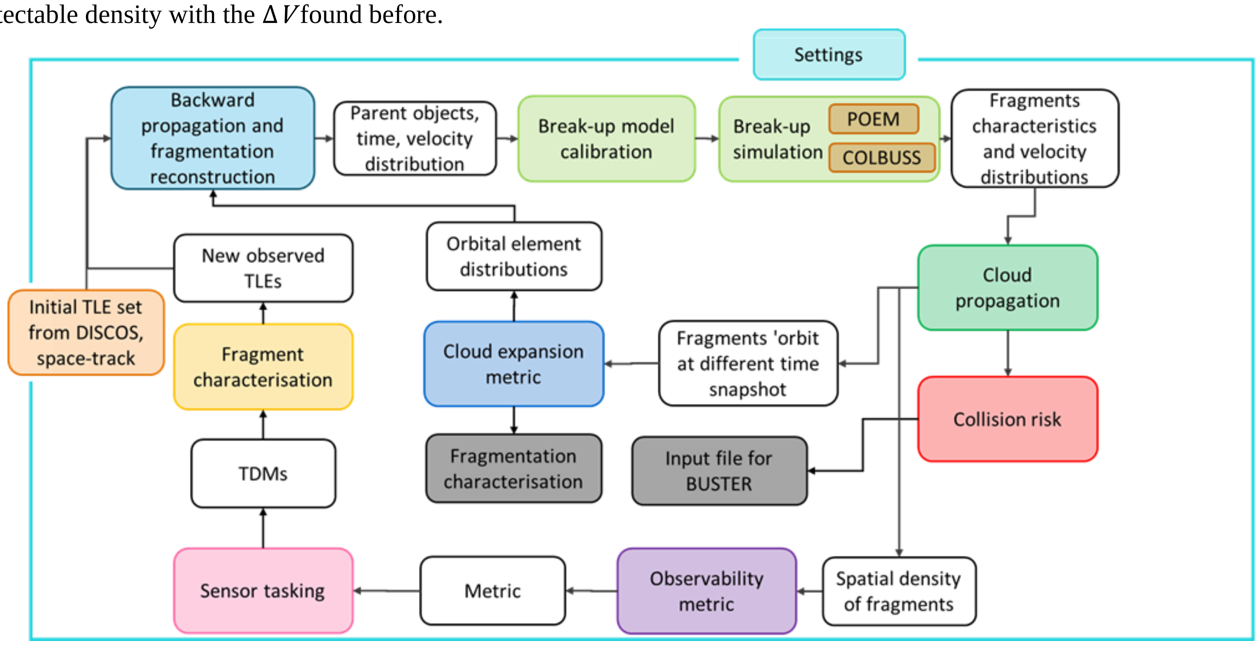


Fig. 6. OFELIA overall diagram.

The general interface inputs the settings of the processing, checks the existence of needed files, inputs observations, if available and the orbits of catalogued fragments. It also calls all the modules of the Forensics Tool to complete the full chain of operations. It outputs log messages and the results and data generated by the modules. The results are assembled in a HTML page with interactive graphs and tables.

The *fragmentation reconstruction module* works differently depending on two scenarios identified in the context of a fragmentation characterisation activity. In the first scenario, it is not known if a fragmentation event has occurred, and if it occurred, the involved objects and epoch/location of the event are not known a priori. An available or provided catalogue shall be taken as an input and screened [29] to look for the possible fragmentation. The module exploits the two approaches used for the analyses of fragmentation events in Sections 3.2 and 3.3, i.e. PUZZLE and FRED.

The results in the first scenario (Fig. 7) include the detection of the fragmentation event, the TLEs related to the involved parent and the produced fragments, and the estimated epoch of the event. The main limitation in this case could occur when an event is detected, but no TLEs related to the fragments are found in the analysis window. Therefore, the flow breaks due to scarcity of information. In the second scenario (Fig. 8), it is assumed that a fragmentation event has occurred, and its alert and information are available, provided by an external source. The TLEs related to the involved parent object(s) and produced fragments are accessible and used as input to the module. The latter exploits the same two approaches (PUZZLE and FRED) mentioned before. However, in this case the results of the module include only the missing information on the epoch of the event.

The *break-up model module* (Fig. 9) is made of two components: the POEM Model and the COLBUSS Model. The POEM Model component oversees calibrating and running the POEM break-up model, using the settings and data provided in input. The COLBUSS Model component performs the same functions for the COLBUSS break-up model.

The *cloud propagation module* (Fig. 10) is generally used to propagate an orbital state, either forward or backward in time, with a flexible interface regarding input orbit types, propagation methods, and output data. Typically, the input consists in several orbital states, corresponding to a cloud of objects originating from a fragmentation event.

The *collision risk module* (Fig. 11) produces the input for the ESA tool BUSTER, with an interface with the Forensics Tool, with the cloud propagation module.

The *cloud expansion metric module* (Fig. 12) characterises the spatial distribution of the cloud.

The *observability metric module* (Fig. 13) is organised into two main blocks. First, a preliminary analysis is conducted using the Fragmentation Environmental Index (FEI) weight to identify and characterize an optimized subset of sensors for observing the fragmentation event. Subsequently, a more detailed analysis is performed on this selected subset of sensors using the Observability Metric (OM) tool. In the first block, the FEI weights are used to compare sensor performance, analysing a set of both optical and radar sensors to determine which ones are best suited for observing the fragments cloud. The computation of the FEI weight is tailored to each type of sensor: for optical systems, it is based on the optical magnitude and irradiance of the observed object, while for radar systems, it relies on the Signal to Noise Ratio (SNR). This approach allows for a preliminary performance comparison of the sensors, thereby narrowing down the pool for a more detailed analysis. The detailed analysis is performed in the Observability Metric block, on each sensor selected during the preliminary analysis. Considering the device's Field of View (FoV) and relative pointing, only the visible bins of the continuum propagation model of the fragmentation are analysed. For each visible bin, the maximum fragment density is retrieved to determine the cumulative number of fragments observable within the FoV, consistent with the sensor's resolution limit. The final performance assessment is defined by the maximum number of fragments statistically observable by the sensor and the resolution figure of merit computed in the process.

The *sensor tasking module* is a tool to provide, based on inputs from Observability metric module, catalogued fragments and sensor information observation requests. It will provide an optimal plan to optimize observations taking as main parameter the sum of the predicted observed arc. It will take also into consideration survey like planning to observe cloud instead of focusing on individual fragments. For that, information from Observability metrics will be necessary. This submodule provides orbital information from observed data about the fragments to users and other subsystems. It is composed of 4 main parts to:

- provide additional tracks about known objects, if IOD track to orbit correlation with known object is positive;
- provide new object to catalogue if object is unknown;
- determine size of object from Visual Magnitude of Radar Cross-Section;
- determine attitude of object if enough data is provided.

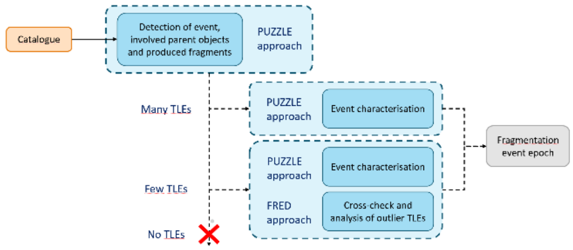


Fig. 7. Fragmentation reconstruction decomposition diagram (first scenario).

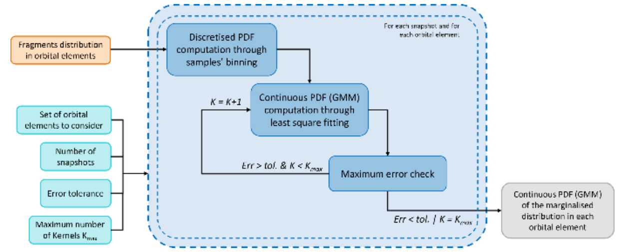


Fig. 12. Cloud expansion metric module decomposition diagram.

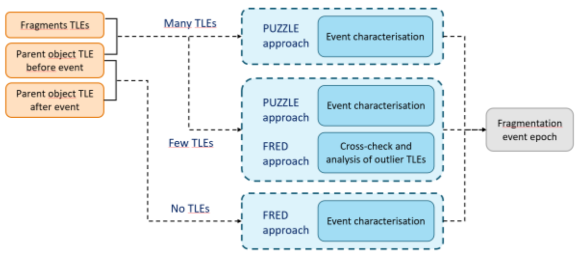


Fig. 8. Fragmentation reconstruction decomposition diagram (second scenario).

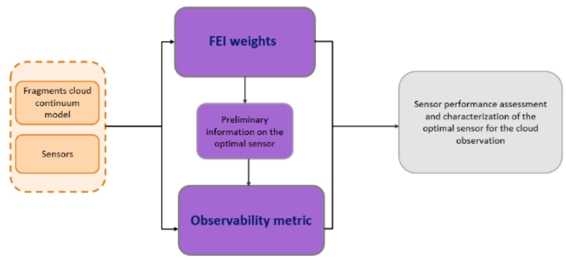


Fig. 13. Observability Metric module decomposition diagram.

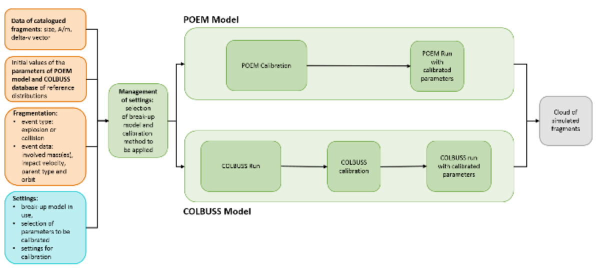


Fig. 9. Breakup model decomposition diagram.

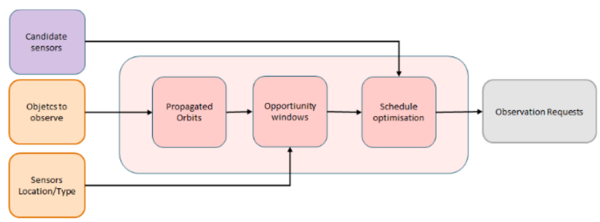


Fig. 14. Sensor tasking module decomposition diagram.

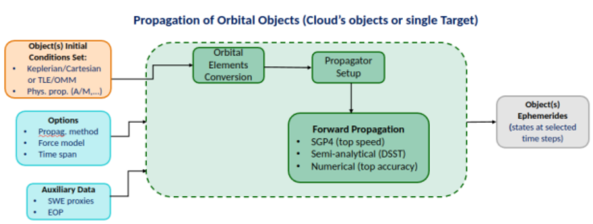


Fig. 10. Cloud propagation module decomposition diagram.

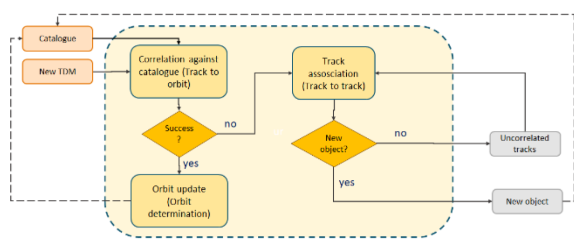


Fig. 15. Fragment characterisation module decomposition diagram.

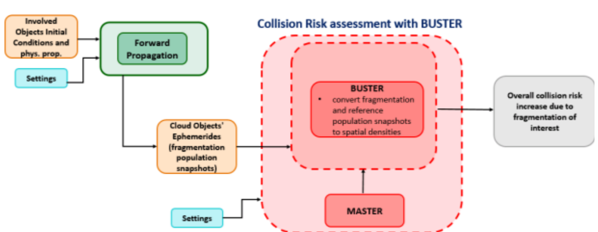


Fig. 11. Collision risk module decomposition diagram.

7. Conclusions

This paper presented the OFELIA (Orbital Fragmentation rEconstruction moduLe for forensIcs Analysis) tool.

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