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Robust short-term reconstruction of in-orbit fragmentation events

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Abstract

The growing amount of orbiting debris and the frequency of fragmentation events are threatening space operations and sustainability. This work proposes a novel method to reconstruct such events shortly after occurrence, addressing two scenarios: unknown and known fragmentations. The method combines filtering, clustering, and stochastic analysis of TLE data to identify fragments, parent objects, and the epoch of the break-up. Depending on data availability, the pipeline adapts to ensure robustness, leveraging two pre-validated methods. Implemented in the OFELIA tool, for an ESA-funded project, this module enables reliable reconstruction across various scenarios, outperforming existing tools in flexibility through a dual-method framework.

1. Introduction

As the number of objects in orbit increases, so does the risk of break-up events, which threatens the safety of operations in space and its sustainability. Indeed, fragmentation events are currently the dominant source of space congestion.[6] These have been occurring in orbit since 1961[3] due to catastrophic or non-catastrophic collisions between objects, explosions of inactive satellites and anti-satellite tests. Despite the implementation of collision avoidance manoeuvres, data from the past two decades indicate a persistent upward trend in the occurrence of break-ups. In particular, the collision between Cosmos 2251 and Iridium 33 occurred in 2009, and the Fengyun 1C missile explosion in 2007, are among the most catastrophic events ever recorded. These events resulted in the generation of the highest number of catalogued fragments, and consequently, they were responsible for the most significant environmental impacts to date[2,14] . For these reasons, it is of great importance to establish a tool that enables the reconstruction of break-up events following their occurrence. Indeed, once the break-up is characterized, models capable of forecasting the debris cloud evolution[7,10] can be leveraged, since the prediction of the trajectories of resulting fragments are fundamental to prevent further collision events. In addition, the earlier the reconstruction of the event takes place, the more accurate the outputs will be. Such outputs include the identification of the involved objects and the detection of the fragmentation epoch. If these information are retrieved early after the event, they are more precise, and the prediction of future debris evolution and the scheduling of subsequent re-observations for debris cataloguing is enhanced as well.

The tool employed for the reconstruction of these events then must be both accurate and robust when investigating the aforementioned aspects. Furthermore, it is essential that the tool can be applied in scenarios where a substantial amount of TLE data relating to the event is available, as well as in situations where only a limited amount is present. The latter case pertains to the capability for the immediate characterization of the event, in instances where the amount of information collected on the fragment objects is limited. These are the objectives of the work presented in the following paper, which describes a part of the research performed within the European Space Agency (ESA)-funded project ”T711-802SD - On-Orbit Breakup Forensics”. The project focuses on the development of a unique tool - OFELIA (Orbital Fragmentation rEconstruction tooL for forensIcs Analysis) - aimed at the detection, observation, characterization and reconstruction of debris and the event which generated them. This paper in particular presents the algorithm related to one of the modules of OFELIA tool: the fragmentation reconstruction (with the objectives mentioned above) through a backward propagation approach.

A variety of methods have been developed over the years to reconstruct break-up events. For example Dimare et al.[5] propose an approach using similarity distance functions applied to the orbital elements of fragments under investigation. Another relevant tool is the Simulation of On-Orbit Fragmentation Tool (SOFT)[1] , which determines the

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break-up epoch by identifying the point in time when the average distance among the fragments is minimized, and uses this to estimate both the time and the center of mass position. Celletti et al.[4] propose a different strategy, based on tracing debris back to their original objects by analyzing their proper elements and performing backward propagation. At Politecnico di Milano, two key methods have been developed to address this problem. The PUZZLE approach[13,15] combines backward orbital propagation with pruning and clustering algorithms to group fragments into families and associate them with parent bodies. In contrast, the FRagmentation Epoch Detector (FRED) method[12] adopts a stochastic framework, identifying potential break-up epochs through the evaluation of Minimum Orbital Intersection Distances (MOID) between the parent object and samples representative of the fragment(s).

The fragmentation reconstruction algorithm implemented in the OFELIA module builds upon the approaches presented by Romano et al.[15] and Montaruli et al.[12] , with the addition of some modifications, and integrating them into a unified framework designed to enhance reconstruction robustness. This methodology supports two operational scenarios: one in which the fragmentation event is known - meaning the parent and resulting fragments have been already identified and associated to the event - and another in which the event is unknown, with uncertainty surrounding both the parent body and the associated fragments. Based on the user's selection of the scenario, the algorithm follows a tailored procedure accordingly. Central to the method is the backward propagation of orbital elements using the SGP4 propagator[17] , whose accuracy constrains the analysis window to approximately two weeks post-event. Furthermore, as previously stated, the tool must be capable of managing the most critical scenario, i.e. when one seeks to characterize the event shortly after its occurrence and therefore possesses limited information about the objects involved. As a result, this approach is specifically suited for short-term break-up reconstruction.

The paper is organized as follows. Sec. 2 provides a comprehensive overview of the reconstruction module of the OFELIA tool. In particular it presents a detailed description of the algorithm in question, alongside an in-depth analysis of the logic applied in order to evaluate the availability of the input data and the branching of the module into the two methods. Sec. 3 describes the numerical simulations conducted to test the module on a real past break-up event, and the analysis of the results. The conclusions drawn from this work are illustrated in Sec. 4.

2. OFELIA fragmentation reconstruction module

The purpose of the backward propagation and fragmentation reconstruction module is to identify and characterize fragmentation events a posteriori, using available Two-Line Element (TLE) data as a starting point. This capability enables a rapid assessment of the potential aftermath of a break-up, particularly in terms of the collision risk it may pose to operational satellites. Such timely evaluations are essential for supporting prompt decision-making in areas like collision avoidance maneuvers and observation scheduling. Key outputs of the reconstruction process include the identification of the objects involved - namely, the cataloged fragments and the parent body or bodies which have generated them - as well as an estimate of the epoch of the event.

As mentioned in Sec. 1, the module is capable of managing two different scenarios, related to different sets of input and output information. For the two cases, two different approaches have been developed, which are described in detail in Sec. 2.1 and Sec. 2.2.

2.1 Fragmentation is known

In cases where the fragmentation event is known, both the parent object and the resulting fragments are identified in advance from external sources, and the method takes the corresponding TLEs as input. As the input data are assumed to be reliable, the reconstruction process focuses solely on estimating the break-up epoch, omitting preliminary steps such as data pruning. Similarly, object clustering is not performed, since all provided fragments are presumed to belong to a single family originating from the event. Based on the number of TLEs provided, the algorithm selects one two available methods (namely *first method* or *second method*) for the analysis. An overview of this procedure is illustrated in Fig. 1a.

The first method, employed as a stand-alone approach when a sufficiently large number of TLEs are available, is based on the framework developed by Romano et al.[15] . It begins by processing the TLEs within the SGP4 propagation model, selecting one representative TLE per object. Following this, a triple-loop filtering process, adapted from the method of Hoots et al.[9] , is applied to each pair of objects. This filtering sequence involves two geometric criteria followed by a temporal check. The first step is an apogee-perigee filter, which evaluates the orbital compatibility of two objects by comparing the maximum of their perigees and the minimum of their apogees. If the difference between these two values falls below a specified threshold (provided as an input), the pair is retained for further analysis. The second geometric filter computes the MOID using Gronchi's analytical formulation[8] ; only pairs with a MOID below the defined threshold, indicating a potential close approach, are accepted. Pairs that pass both geometric filters are then subjected to a temporal filter. This stage defines angular windows around the MOID location and converts them

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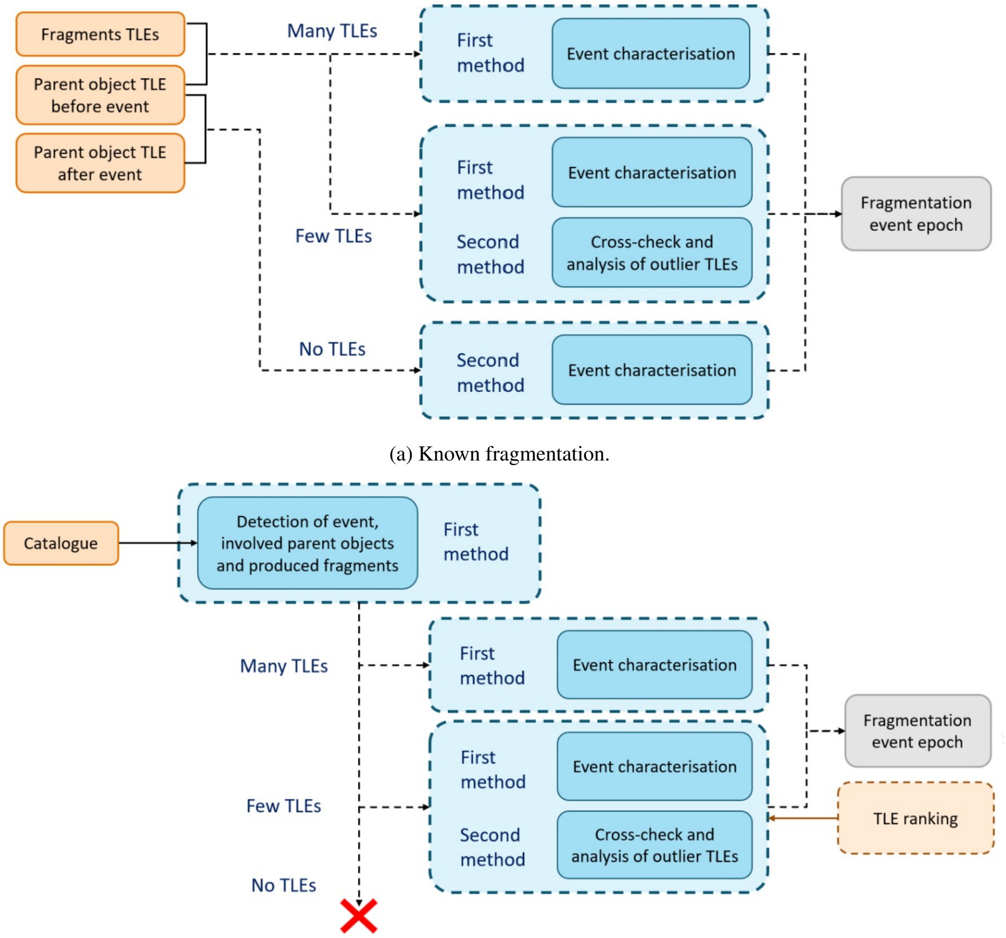

(a) Known fragmentation.

(b) Unknown fragmentation.

Figure 1: Block diagram of the fragmentation reconstruction module when the fragmentation is known (a) and not known (b).

into corresponding time intervals, verifying whether both objects are within the same angular window simultaneously. This condition is essential to confirm the possibility of a close encounter. Given that all input objects are assumed to originate from the same fragmentation event, it is expected that they will generally pass this filtering process. The triple-loop filter is integrated with a backward propagation over a user-defined time interval. During this step, the algorithm iteratively determines the times and distances of closest approaches between each object pair, using the SGP4 propagator and osculating orbital elements. The estimated epoch of fragmentation is then identified as the time bin containing the highest concentration of close encounters.

However, when only a small number of TLEs are available, the effectiveness of this method diminishes, as the sparse data result in too few detected encounters to reliably estimate the fragmentation epoch. To address this limitation, the algorithm combines the first method with a second one in such cases, thereby enhancing the robustness of the epoch estimation. The second method builds upon FRED tool[12] , with an enhancement to the algorithm aimed at improving the reliability of the candidate fragmentation epoch estimation. As in the original work, this approach starts from the orbital state of the fragment(s), derived from TLE data (interpreted as the mean state), and associates it with a synthetic covariance. The parent object orbital state is taken from its latest available TLE before the event and treated as deterministic. Using a multivariate normal distribution, a Monte Carlo sampling is performed on the fragment state to generate multiple possible realizations. For each parent-sample pair, the epochs at which the parent passes through the MOID[8] are computed within a specified time window. This window spans from the epoch of the last available TLE of the parent up to 10 days afterward, using the parent orbital period as the sampling step. The MOID values - first computed using Gronchi's analytical method[8] - are iteratively refined to account for perturbations modeled within the SGP4 propagation framework. Then, in contrast to the original FRED implementation[12] , the epochs of MOID transit are not directly treated as fragmentation epoch candidates. Instead, these epochs serve as initial guesses for a refinement step: an optimization process is applied to compute the Times of Closest Approach (TCAs) between the parent and

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each sample fragment. For each time interval within the window, the method refines the initial guess by searching for the epoch at which the relative distance $\boldsymbol{r}_{rel}$ between the parent and the fragment sample reaches a minimum. This process yields a more accurate estimation of TCAs, which are then used to infer candidate fragmentation epochs, as detailed in Eq. 1.

$$\frac{d}{dt}\left(\boldsymbol{r}_{rel} \cdot \boldsymbol{r}_{rel}\right) = 0 \tag{1}$$

Eq. 1 is verified when the relative distance is perpendicular to the relative velocity between the two objects. This provides the solution to Eq. 2, which is solved iteratively.

$$\boldsymbol{r}_{rel} \cdot \boldsymbol{v}_{rel} = 0 \tag{2}$$

In this process, a series of TCA epochs is obtained for each parent-sample fragment pair over the defined time window. This set is then filtered to remove outliers and subsequently clustered in time to identify potential fragmentation epochs. For each resulting cluster, the three-dimensional MOID and the relative distance distributions are computed. Since, at the actual fragmentation epoch, the MOID and the relative distance must coincide, each candidate epoch is evaluated by comparing these two distributions. To perform this comparison, the distributions are transformed into curvilinear coordinates[18] , and their similarity is quantified using a weighted Euclidean distance between the distributions quantiles, to give less relevance to their tails. The fragmentation epoch candidates are then ranked based on the distance values, with the cluster mean exhibiting the smallest one selected as the most likely event epoch. This method thus provides an estimated fragmentation epoch along with its mean and standard deviation.

A final case considered under the known-fragmentation scenario arises when no fragment TLEs are available, but the parent object is identified and two of its TLEs are known - one acquired shortly before the event and the other after it. In this case, the second method is applied as previously described, but instead of using a fragment orbital state, the state to randomly sample is taken from a post-event parent TLE. This enables the estimation of the fragmentation epoch and its uncertainty even when only the parent object data is available.

2.2 Fragmentation is unknown

In the case where the fragmentation event is unknown, the input data set is assumed to consist of both fragments originating from the event and unrelated external objects. Neither the specific fragments produced by the break-up nor their parent object are known beforehand. Consequently, the main objective of the reconstruction method in this context is to identify which objects were involved in the event - namely, the fragments cloud and their corresponding parent(s) - and to estimate the epoch of the fragmentation.

The overall procedure for this scenario is outlined in Fig. 1b. The input TLEs are initially read and processed using the SGP4 propagator, and then undergo a pre-filtering phase designed to detect statistical outliers using the methodology developed by Lidtke et al.[11] . As with the known event case, a representative TLE is selected for each object, and the triple-loop filter is applied to every pair of objects. Unlike in the known-event scenario, this filtering is necessary prior to any branching based on the number of TLEs, as the data set includes objects unrelated to the break-up. The triple-loop filter serves to isolate only those pairs for which a close approach could have occurred, thus retaining objects that are most likely linked to the fragmentation event. Following this, the algorithm adjusts its workflow depending on the number of TLEs associated with the filtered objects. When a sufficient number of TLEs is available, the method proposed by Romano et al.[15] is employed.

As in the previous case, the fragmentation epoch is determined using a temporal binning approach based on the density of close approaches. However, the process does not stop at identifying the epoch. It continues by detecting clusters of objects-families of fragments that likely share a common origin. To do this, the algorithm uses the Hierarchical Clustering Method (HCM) introduced by Zappala et al.[19] , originally developed for identifying asteroid families. In line with the modifications introduced[15] , the method uses a distance function, δv, defined for each pair of objects to quantify their orbital separation. This metric considers the osculating elements and includes not only the semi-major axis (a), eccentricity (e), and inclination (i), but also the right ascension of the ascending node (Ω) and the argument of perigee (ω). The final expression for this distance function is as follows in Eq. 3

$$\delta v = na\left[k_1\left(\frac{\delta a}{a}\right) + k_2(\delta e)^2 + k_3(\delta i)^2 + k_4(\delta\Omega)^2 + k_5(\delta\omega)^2\right]^{1/2} \tag{3}$$

where n is the mean motion, the k_j coefficients are of the order of unity, depending on each parameter to which they are associated. After identifying object families, the method calculates the average mutual distance within each group to ensure it remains below a predefined threshold, an indicator that the cluster may indeed originate from a

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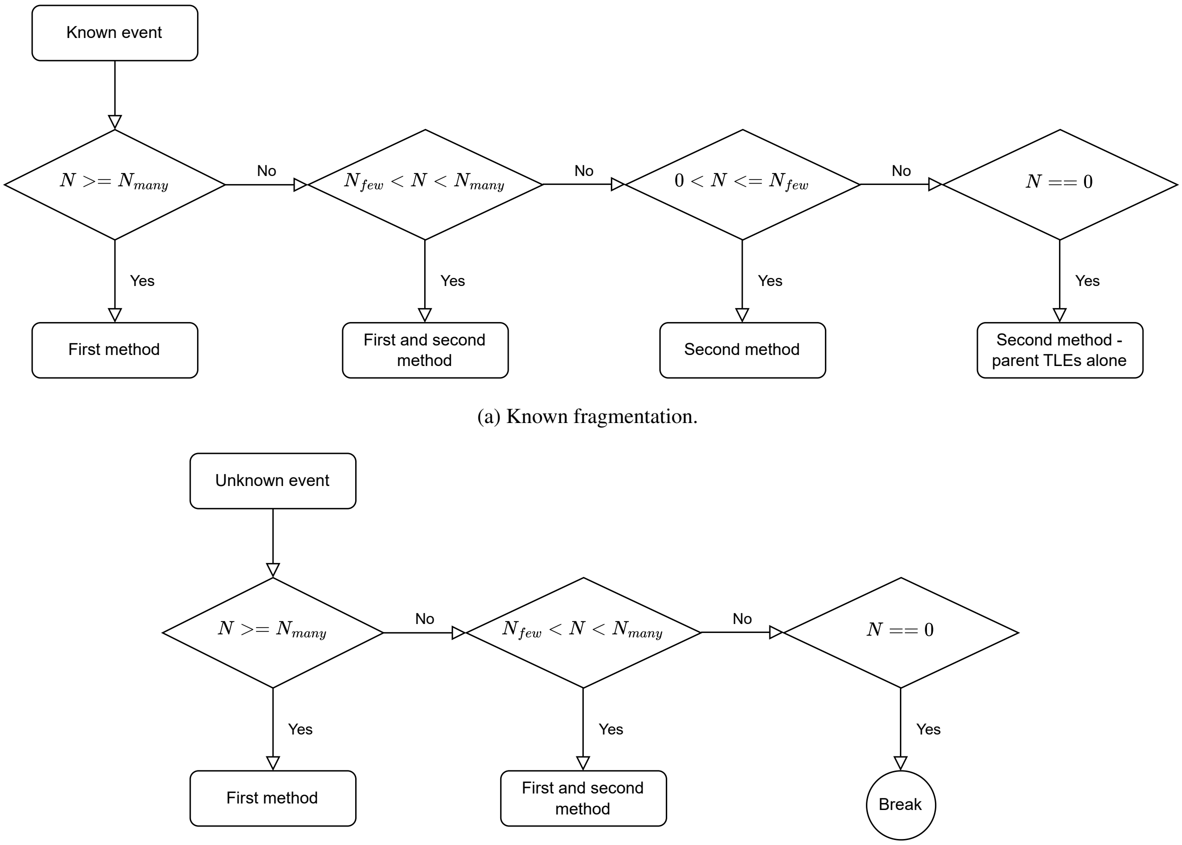
fragmentation event. As a final step, the spatial position of each group is compared with that of known cataloged objects. The parent object is then identified as the one located closest to the clusters center.

In cases where the triple-loop filtering yields a number of TLEs insufficient to apply the first method with high confidence, both the first and second methods are executed in sequence. To improve the overall accuracy of the fragmentation reconstruction, a selection process is introduced after the application of the first method. Specifically, the involved TLEs are ranked based on their calculated miss distances at the estimated fragmentation time, under the assumption that a smaller miss distance implies a higher likelihood of the object being a true fragment. The five objects with the lowest miss distances are then chosen and passed, along with the identified parent TLE, to the second method. This second phase is conducted exactly as outlined in Sec. 2.1, with the distinction that the orbital states of the parent and fragments used as inputs are those obtained through the preceding analysis rather than assumed or external.

2.3 Thresholds definition

As mentioned in Sec. 2.1 and Sec. 2.2, the approach branches in the first method and second method (or both) according to the number of fragments TLEs that are either available as input or identified by the first method. In particular Fig. 2 illustrates, for both scenarios, how the module selects the most suitable method to apply, according to this number of available TLEs, defined in the diagram as N. For the method to be applicable in general, the required



(a) Known fragmentation.

(b) Unknown fragmentation.

Figure 2: Flow diagram of the fragmentation reconstruction module when the fragmentation is known (a) and not known (b), with the logics on the number of available fragments TLEs N.

amount of TLEs that should be available for the activation of either approach must be defined a priori through a series of thresholds (N_{many} and N_{few}). In order to achieve this objective, different test-cases have been conducted on the module. The performance resulting from varying numbers of available TLEs have been gathered and then analyzed. The results of this iterative analysis are presented in Tab. 1 for the known-event scenario and in Tab. 2 for the unknown-event scenario. The resulting thresholds incorporated within the codes, derived from the performance outcomes, are presented in Tab. 3.

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Table 1: Iterative test-cases performed to assess the most suitable intervals for the number of TLEs thresholds (known-event scenario).

		Method result		
Test-case	**TLEs number**	**First**	**Second**	**Both**
NOAA-16	8 to 10	green	/	/
	7	red	/	/
	6	red	/	/
	5	red	green	green
FENGYUN-1C	4 to 10	green	/	/
	3	/	green	/
COSMOS-IRIDIUM	14	/	/	green
	10	green	/	/
	8	green	/	/
	6	red	green	green
	5	red	green	green
	4	/	green	/
CZ-6A	8 to 10	green	/	/
	5 to 7	red	green	green
	4	/	green	/

Table 2: Iterative test-cases performed to assess the most suitable intervals for the number of TLEs thresholds (unknown-event scenario).

		Method result		
Test-case	**TLEs percentage**[a]	**First**	**Second**	**Both**
COSMOS-IRIDIUM	35%	green	/	/
	17%	green	green	green
	11%	green	/	/
	9%	red	green	green
	6%	green	/	/
	3%	red	green	green
CZ-6A	67%	green	/	/
	50%	green	/	/
	33%	green	/	/
	17%	green	green	green
	9%	red	green	green

[a] *TLEs percentage* refers to the percentage of TLEs of fragments actually produced by the event with respect to the total number of TLEs of the input catalogue, including non related object.

In these tables the colour green is used to denote a successful outcome, whereas red is used to indicate a failure. As can be observed from Tab. 1, a standard behaviour is not exhibited in the trial and error simulations. The accuracy of the available TLEs and their epoch with respect to the event epoch, that is to be detected, is the primary factor impacting the results of the two methods. The thresholds are established primarily for the sake of convenience and to ensure a module capable of functioning across a range of operational scenarios, with different amount of information retrieved post break-up. This assertion may be similarly applied to the scenario of an unknown event. As reported in Tab. 2, the primary distinction with respect to Tab. 1 is that the thresholds in this case are established as dynamic, contingent on the quantity of data available from the catalogue in input for analysis. This data may encompass both fragments and unrelated objects. It is assumed then that the first method is capable of identifying the majority of the involved fragments through filtering. However, given that the number of these identified objects is a priori unknown, the thresholds on the required TLEs should be dependent on the initial set of data.

Even if no standard results occur when varying the number of TLEs in input, common conclusions can be drawn for both scenarios by looking at the color legend of Tab. 1 and Tab. 2. As demonstrated in Tab. 1, in the majority of test cases where a higher number of TLEs is available (averaging more than seven), the first method is capable of

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accurately detecting the epoch of the event. In circumstances where a number of TLEs lower than seven is available, and the first method proves unsuccessful, the second method can be utilised to support epoch estimation. Consequently, in such instances, it is recommended to trigger both methods in succession, thereby enhancing the robustness of the reconstruction process. In the case of a number of TLEs that are on average lower than four, the second method is applied directly, since it is capable of successfully detecting the event epoch. Conversely, for the scenario of an unknown event (see Tab. 2) the first method is capable of successfully reconstructing the entire event if the number of fragments TLEs is over 70% of the initial data set. In instances where the available TLEs fall short of this percentage, the second method is employed to rectify any issues arising from the failure of the first method in epoch detection. Consequently, both methods are to be implemented in such circumstances. It is important to note that the second method alone is not applicable in this particular scenario. This is due to the fact that the parent and the involved fragments must first be identified using the first method. From these consideration, the fixed thresholds for the known-event scenario and the dynamics for the unknown-event scenario have been derived and gathered in Tab. 3.

Table 3: TLEs number thresholds.

Scenario	N_{many}	N_{few}
Known event	8	4
Unknown event	70%[b]	2

[b]The value in percentage denotes the number of identified fragments TLEs over the total number of TLEs included in the specified input catalogue.

With regard to the results presented in Tab. 2, the percentage selected for N_{many} in the unknown-event scenario is notably elevated (Tab. 3). The purpose of this conservative threshold is twofold: firstly, to counteract the largest uncertainty in the number of objects resulting from the screening of the input catalogue, and secondly, to counteract the uncertainty in the accuracy of their TLEs.

3. Numerical simulations

The OFELIA fragmentation reconstruction module is tested on a past break-up event. In particular, the collision between Iridium 33 and Cosmos 2251 (NORAD: 22675), occurred on the 10th of February 2009 at 16:56, is analysed. This section aims to assess the module capability in accurately determining both the epoch of the fragmentation and the specific objects involved.

3.1 Fragmentation is known

In this section, the foreseen scenario is that of fragmentation being known, i.e. the input TLE file is composed of the already known parent and the fragments involved in the event. In this scenario, the only analysis to perform accurately is that of the detection of the event epoch, and the pruning process is not required.

The first input data set consists of 6 TLEs corresponding to 6 unique objects, all fragments from Cosmos satellite, retrieved from Space-Track[16] ten days after the fragmentation event. The second input data is the last parent (Cosmos) object TLE available at an epoch before the event, retrieved from Space-Track[16] . Given the number of fragments TLEs involved, according to the thresholds defined in Tab. 3, the first method is initially applied to estimate the epoch of the event and the second method is then applied as well to confirm or refine this estimate. The second method for this test-case employs 1,000 samples for the Monte Carlo procedure. However, it should be noted that this value can be customized by the user. The key results obtained from the first method are shown in Tab. 4, while those obtained from the second method are reported in Tab. 5.

Table 4: Cosmos-Iridium fragmentation reconstruction results with first method, in the known-event scenario.

Initial size of TLEs set	6
Search window	14 days
Estimated event epoch	09/02/2009 at 02:28:38.51 UTC

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Table 5: Cosmos-Iridium fragmentation reconstruction results with second method, in the known-event scenario. Fragment n°3 is discarded by the filters.

Fragment n°	1
Clusters score	1.00 2.19e-02 1.09e-02
Mean epoch	10/02/2009 at 16:56:02.7024 UTC 10/02/2009 at 15:15:21.7076 UTC 10/02/2009 at 13:34:42.2297 UTC
Standard deviation [s]	1.19e-07 0.00 5.96e-08
Fragment n°	2
Clusters score	1.00 7.55e-01 4.59e-01
Mean epoch	10/02/2009 at 13:34:38.1897 UTC 10/02/2009 at 18:41:03.2938 UTC 10/02/2009 at 11:49:19.1478 UTC
Standard deviation [s]	5.96e-08 0.00 0.00
Fragment n°	4
Clusters score	1.00 1.54e-01 7.77e-02
Mean epoch	10/02/2009 at 16:55:35.2146 UTC 10/02/2009 at 15:15:20.9218 UTC 10/02/2009 at 13:34:41.8621 UTC
Standard deviation [s]	5.96e-08 5.96e-08 0.00
Fragment n°	5
Clusters score	1.00 4.19e-01 3.95e-01
Mean epoch	10/02/2009 at 16:52:53.5140 UTC 10/02/2009 at 15:11:18.9072 UTC 10/02/2009 at 18:24:50.5247 UTC
Standard deviation [s]	5.96e-08 5.96e-08 1.19e-07
Fragment n°	6
Clusters score	1.00 2.19e-02 1.09e-02
Mean epoch	10/02/2009 at 16:56:02.7024 UTC 10/02/2009 at 15:15:21.7076 UTC 10/02/2009 at 13:34:42.2297 UTC
Standard deviation [s]	1.19e-07 0.00 5.96e-08

Looking at Tab. 4, it is evident that the first method is incapable of accurately determining the day of the event in this scenario, when utilizing a limited number of input TLEs. In such a case, it is strategic to trigger the second

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method subsequent to the first one, with the objective of enhancing the estimate. As demonstrated in Tab. 5 the second method is capable of producing a highly accurate estimate of the event epoch in the first-ranked cluster for the vast majority of TLEs in the input data. It is to be noted that one of the fragments is discarded by the method, possibly due to all candidate epochs being filtered out by the internal filters of the algorithm, with the aim of deleting the outlier samples. It is evident that for all five of the retained fragment objects, with the exception of n° 2, the epoch estimate derived from the first of the three best-ranked clusters exhibits a discrepancy of milliseconds (and at most three seconds) from the actual epoch. Therefore, it is observed that the day and time of the event have been accurately identified. Additionally, the uncertainty in these estimates, as reported in the "Standard deviation" rows of Tab. 5, is minimal, and this corresponds to a more robust result of the method. For all fragments retained in the algorithm, only the initial three clusters ranked are reported. Whilst it is indeed possible to draw parallels between the results obtained by the various clusters in the context of an uncertain event, still the epoch considered correct by the method is the mean of the first ranked cluster epochs.
Fig. 3 presents the clusters of TCA candidate epochs computed by the second method, with respect to the time windows in which the fragmentation is searched. The graph indicates the negligible uncertainty surrounding the epoch candidates for each cluster, as the samples appear to be highly concentrated at each "periodicity". This verifies the low standard deviation values that are presented in Tab. 5.

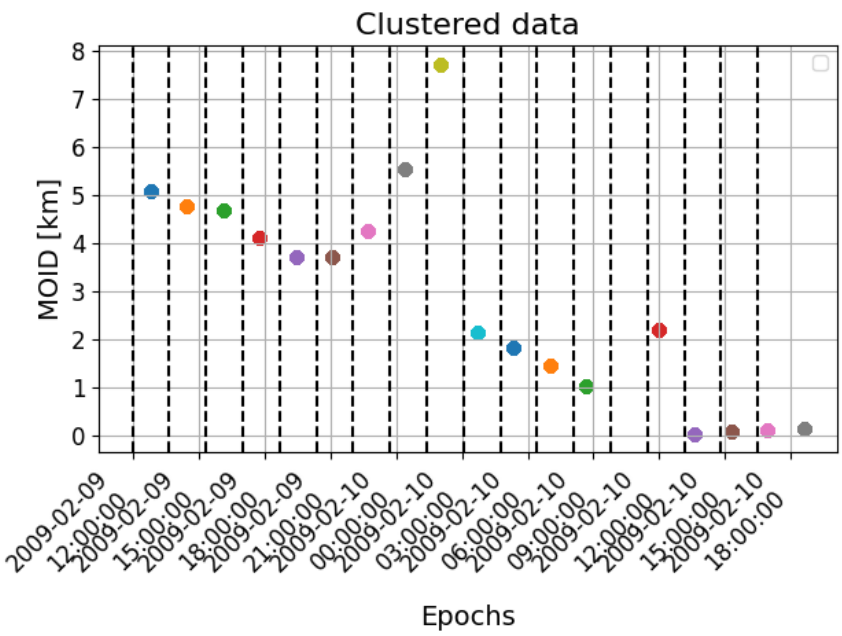

Figure 3: Cosmos-Iridium MOID distance for each cluster of TCA epoch candidates, with respect to the search time intervals.

3.2 Fragmentation is unknown

In this section, the foreseen scenario is that of fragmentation not being known, i.e. the input TLE file is composed of TLEs of the fragments (and the parent) as well as of other unrelated objects. This enables the evaluation of the efficacy of the pruning process, as the objects involved in the event are not assumed a priori.

The input data set consists of 131 TLEs corresponding to 98 unique objects, including 30 fragments from the event, retrieved from Space-Track[16] ten days after the fragmentation. Following the application of the pre-filtering procedure, 12 outlier objects are removed. The triple-loop filter is then used to identify object pairs with potential close encounters, ultimately retaining 91 objects for further analysis. Given the number of objects involved on the entire set of input TLEs, according to the thresholds defined in Tab. 3, only the first reconstruction method is triggered in this case. The key results obtained from the first method are shown in Tab. 6, and they demonstrate that with a such large number of available TLEs related to possible fragments the reconstruction of the event is highly precise.

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Table 6: Cosmos-Iridium fragmentation reconstruction results with first method, in the unknown-event scenario.

Initial size of TLEs set	131
Search window	14 days
Estimated event epoch	10/02/2009 at 16:55:56.87 UTC
N° of involved objects	15
Identified parent	NORAD: 22675

The first method alone identifies the correct fragmentation epoch, placing it on 10/02/2009. Furthermore, it detects the time of the event as 16:55:57, when the time considered as reference for this test-case is 16:56 UTC. The detected time is then off for less than one second. In addition, the first method is capable of identifying the correct parent object, as observed in Tab. 6. 14 objects are recognized as fragments generated in the event out of 30, leading to the correct identification of 47% of the input fragments.
Fig. 4 presents the close encounter distance with respect to the time window in which the fragmentation is searched, for each pair of objects under analysis, as computed by the first method. The graph indicates that the occurrence of close encounters is concentrated at approximately nine days prior to the epoch of the TLEs. This suggests the presence of a break-up event at the computed epoch.

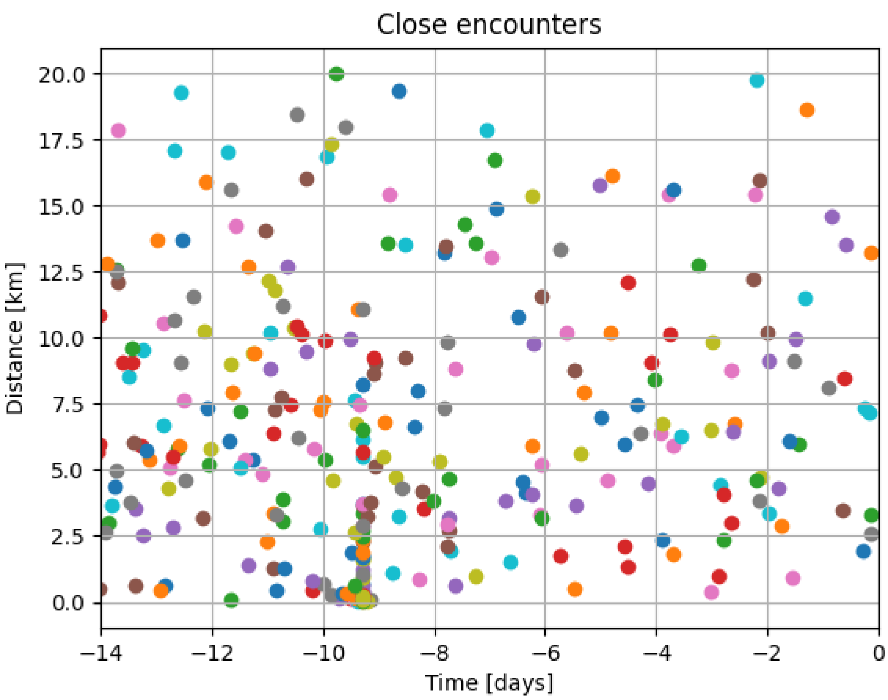

Figure 4: Cosmos-Iridium close approach distance with respect to time of the fragmentation search computed by the first method.

3.3 Outliers analysis

An additional analysis, which is present in the module and can be activated by the user, concerns the objects TLEs discarded by the filters of method 1. These are referred to as 'outliers', and are analysed by method 2 to determine whether they were erroneously discarded and if the event epoch can be estimated, or whether they can be discarded permanently. The incorporation of this supplementary analysis was driven by two primary objectives. Firstly, it is intended to enhance the robustness of the method, thereby ensuring its reliability and reproducibility. Secondly, it is designed to verify the outcomes of "suspicious" objects in instances where the primary analysis yielded uncertain results, needing additional validation. The cross-check analysis is conducted in the known event scenario with a case of few TLEs available, the same as presented in Sec. 3.1. Among the six TLEs processed by method 2, those which are identified as outliers are then provided as input to method 2, with a view to their permanent rejection or the extraction of a valid epoch estimate.

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In the test-case, one TLE is discarded by method 1. This TLE is related to NORAD 33780, suggesting that an actual fragment is in this case erroneously discarded by method 1. In such circumstances, it is important to consult the second algorithm to assess whether such a TLE can result in an accurate estimate of the epoch, given its precise correlation with an object generated during the event. Therefore, the TLE is subsequently fed into method 2 for the purpose of outlier cross-check. The results of these analyses are displayed in Tab. 7.

Table 7: Cosmos-Iridium fragmentation reconstruction results with second method, for the outliers cross-check analysis. The results are related to the fragment TLE discarded by the first method.

Clusters score	1.00 6.16e-01 3.14e-01
Mean epoch	10/02/2009 at 16:54:29.5528 UTC 10/02/2009 at 15:15:33.7253 UTC 10/02/2009 at 13:34:54.7596 UTC
Standard deviation [s]	5.96e-08 5.96e-08 0.00

The numbers in table demonstrate that this TLE processed with method 2 results in a precise epoch estimation for the first ranked cluster, which closely aligns with the actual time of the event. The uncertainty associated with this estimation is negligible. It can thus be confirmed that the module robustness can be enhanced through the supplementary outliers cross-check analysis.

4. Conclusions

The rising number of space debris and fragmentation events poses a serious threat to the long-term sustainability of space operations. To address this challenge, the fragmentation reconstruction module of OFELIA tool has been developed to carry out two main tasks: identifying the parent and fragment objects involved in any break-up event and estimating the epoch at which it occurred. This module is developed to achieve these objectives in the early phases subsequent to a fragmentation event, in a short-term framework. The fragmentation reconstruction module combines backward propagation of the fragments with pruning and clustering techniques, alongside a stochastic method based on the time of closest approach epochs computation, to enhance the robustness of the reconstruction process. It is designed to handle both known fragmentation events, where details about the parent object(s) are available, and unknown events. A quantitative analysis of the available input data is also conducted to facilitate the selection of the most appropriate approach from the implemented ones to be triggered, thereby ensuring the optimization of this tool in various scenarios. Its application to a well-documented break-up has yielded satisfactory results, demonstrating the effectiveness of the approach and its potential to become an operative module for the fragmentation events reconstruction.

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