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Detection and characterisation of in-orbit fragmentations over short and long periods of time

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Abstract

The recent years have seen a fast increase in space traffic as humanity relies ever more on satellite-based services. Despite the adoption of regulations for space debris mitigation, the already large population of objects orbiting the Earth is destined to grow. With it, the chance of accidents involving any of those objects grows as well, threatening current and future satellite operations. Since not all such events can be predicted or avoided, space debris must be studied and identified as soon as possible upon their formation in a reliable and efficient manner, to detect fragmentations and reduce the risk they pose for other satellites.

The PUZZLE software package was developed for this purpose at Politecnico di Milano, initially under a contract with the Italian Space Agency. As presented in previous works, the tool analyses a set of unclassified objects in the form of Two-Line Element (TLE) data to detect possible fragmentations occurred in the recent past. These objects are propagated backwards to search for a common origin in space and in time, and then matched with known objects possibly involved in the event. The fragmentation is then characterised in terms of mass and energy using the available NASA standard breakup model, which simulates the distributions of the fragments produced in the event.

In this work, we extend the functionalities of the tool to operate on periods of the order of months or years: since the accuracy of the analytical SGP4 model is limited to a few days, the long-term propagation is performed using averaged Keplerian elements, which ignore the short-periodic effects of perturbations to provide a faster integration without loss of accuracy. The choice over short- and long-term analysis is done according to the options input by the user and to the findings of an optional short-term investigation. Furthermore, to ensure an accurate long-term propagation, an estimation of the ballistic coefficients of the objects is obtained starting from the B* parameters of the given TLEs: different factors, ranging from the atmosphere model adopted for the analysis to the number of available TLEs, are considered in the estimation.

The operations performed during the analysis will be explained, and the application of the approach to actual fragmentation events will be shown alongside numerical results and performance data.

Keywords: Space debris characterisation, In-orbit fragmentations, low Earth orbit fragments, Breakups

Nomenclature

a	Semimajor axis [km]
a_{TLE}	Semimajor axis included in TLE [km]
e	Eccentricity [-]
i	Orbit inclination [deg]
n	Mean motion
t	Time [s]
t_{estim}	Epoch estimate [s]
t_{real}	Event epoch real time [s]
t_{last}	Time at the beginning of the Propagation [s]
ϵ	Relative error
Ω	Right ascension of ascending node [deg]
ω	Argument of perigee [deg]

Acronyms/Abbreviations

BC	Ballistic coefficient
LEO	Low Earth Orbit
GEO	Geostationary Earth Orbit
HCM	Hierarchical Clustering Method
MAD	Mean Absolute Deviation
MOID	Minimum Orbit Intersection Distance
PlanODyn	Planetary Orbital Dynamics
RAAN	Right Ascension of the Ascending Node
SBM	Standard Breakup Model
SGP4	Simplified perturbations model 4
SOFT	Simulation of On-Orbit Fragmentation Tool
TEME	True Earth Mean Equator
TLE	Two-Line Element

1. Introduction

Since 1957, the number of man-made space objects has grown constantly, undergoing an increase in the recent years due to the introduction of several satellite-based services. This, however, has led to an increase in the collision or explosion probabilities, involving the generation of new debris [1]. Indeed, despite the presence of guidelines for the space debris mitigation and collision avoidance, some events are difficult to predict (e.g., collision between objects) or even unpredictable (e.g., explosion of a rocket body). The growth of the space debris population is a serious concern since it poses space regions under higher risks, that can even lead to chain effects. Among all the possible fragmentations investigations, it is important to know their history and the origin of a new detected fragments, to perform more in-depth analysis useful to increase the safety for the new designed space missions. Indeed, detecting new fragmentations or assigning newfound fragments to the correspondent parent(s) plays an important role when collision risk analyses or the definition of orbital region at risk are required.

In this field lies the PUZZLE software package, developed at Politecnico di Milano initially under a contract with the Italian Space Agency. The first version of the software focused on short term investigations (i.e., order of days) [2], while this work will present an updated version which includes a long term analyses (i.e, order of months up to years) routine. The two routines have the same objectives: the detection of occurred breakups (epoch estimation and parent(s) identification) and the characterisation of the events in terms of energy, mass, and orbital elements. However, the model adopted for each methodology is different; the major difference is in the type of orbital elements used to retrieve the history of a generic objects considered for the analyses: the short term investigation makes use of osculating orbital elements exploiting the Standard General Perturbations 4 (SGP4) propagator [3] [4], while the long term investigation is performed using mean Keplerian orbital elements coupled with the semi-analytical propagator Planetary Orbital Dynamics (PlanODyn) [5]. This involves of dealing with the problem looking at different strategies. While for the short time span analysis it is possible to exploit the study of the relative position of the objects to find possible cluster of objects, for the long time span is more difficult due to the higher level of uncertainties introduced during the propagation in time and by the adoption of mean elements. Consequently, the long term study turns out to be more challenging and with an higher order of uncertainties. In addition to this, the PlanODyn propagator require the knowledge of the Ballistic Coefficient (BC) of each object to retrieve their history, which is not directly included in the TLEs data but must be estimated. Consequently, the first version of the long term investigation only considers LEO orbiting objects, so that it is also possible to exploit some natural feature of this orbital region.

A more detailed description of the architecture is reported in Section 2. Section 3 presents the application of the software to actual fragmentations, looking at numerical results and performance data. Finally, Section 4 summarises the results and introduce some future works to improve the actual version of the software.

2. Software architecture

This Section describes the architecture of the PUZZLE software, both for the long term and the short term methodologies. Fig. 1 displays the block diagram of the entire procedure, which includes some features that are shared by the two types of analyses, while other modules are peculiar for each study case. The input data are given in the TLEs data format and t, which are introduced more in detail in a previous paper [2]. The first step is a pre-filtering of the input TLEs data to improve their quality, as they may include some outliers. Then, according to the type of investigation required, the model presents a series of modules with specific tasks. The short term analysis directly perform

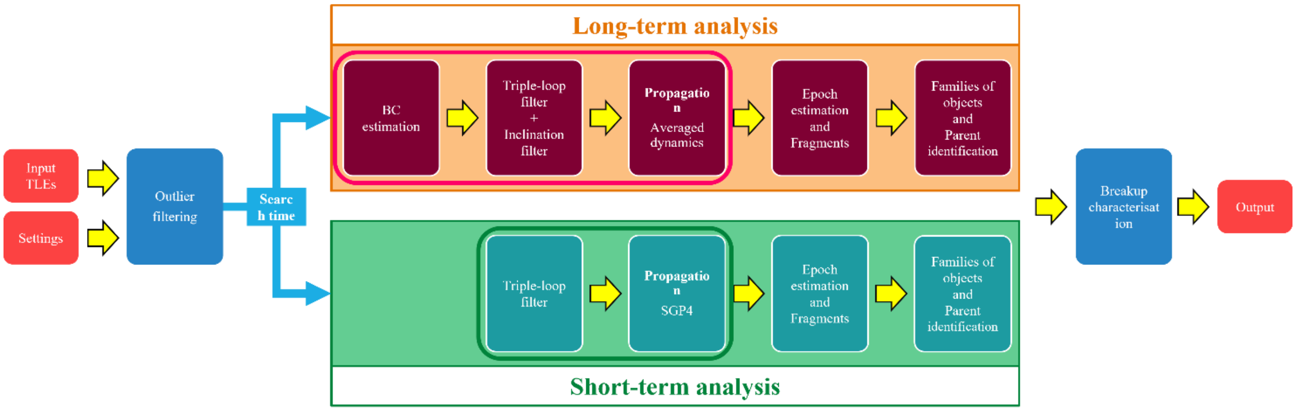

Fig. 1. Puzzle software architecture.

the propagation, coupled with the triple-loop filter (presented in 2.3) to estimate the epoch of the event, and, after, exploit a Hierarchical Clustering Method (HCM) (described in 2.3) to subdivide the fragments and the possible parent(s) candidates into families to identify the objects involved in the detected events. The long term investigation, instead, needs the estimation of the BC and then perform a preliminary pruning of the fragments to reject from the process those that are not compatible with the unknown ones. Afterwards, the propagation is performed to identify clusters in RAAN and estimate the event epoch. In the end, with the use of filters, the parent(s) involved in the event are identified. The last module is devoted to the characterisation of the events from different point of views. The following subsections describe more in detail all the modules of the software.

2.1 TLEs outlier filtering

The first module, that is always performed, is dedicated to the improvement of the quality of the input data. TLEs sequences acquired as input data are scanned with the use of filtering technique to remove possible outlier values, which can be included due to errors in the initial orbit determination process. It is important to note that each sequence of TLEs investigated by this module is associated to the same Satellite Catalogue Number. The filtering method [6] can be summarised by the following steps:

- Rejection of the TLEs considered to be a correction of the immediately previous one by defining an update threshold between two consecutives TLEs;
- Identification of large time gaps between subsequent TLEs (such that the elements cannot be considered as correlated any more) and consequent definition of windows within which the outliers will be searched;
- Rejection of TLEs including inconsistent mean motion values. The method makes use of a regression technique to determine the path of the mean motion evolution in time and of search window to scan the sequences; with the definition of tolerances, it is possible to identify mean motion values that does not follow the correct evolution pattern;
- Rejection of TLEs including inconsistent inclination and/or eccentricity values. The outliers are identified coupling the use of search window and the definition of the MAD which is a useful statistical parameter used in this type of analyses;
- Rejection of TLEs including negative values of the B* parameter, which are usually associated with manoeuvres, with cases where the drag effects are overcome by other perturbations or with intrinsic uncertainties of the model.

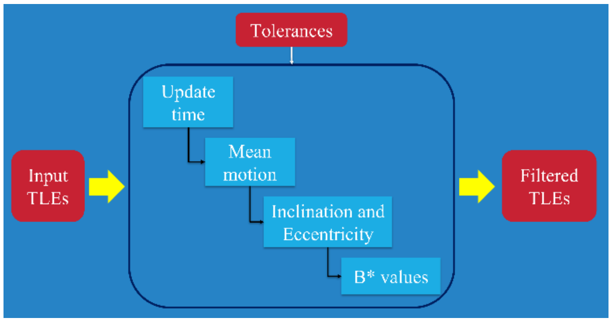

Fig. 2. TLEs pre-processing module.

2.2 BC estimation

The estimation of the BC is required whenever a long term investigation is considered. This because the TLEs does not directly include this parameter, but rather the B*, which is a way of modelling the aerodynamic drag parameters when using SGP4 propagation. The method adopted is the one proposed by Gondelach et al. [7] and it is summarised in Fig. 3. The main assumption introduced in this estimation process is that the change in the semi-major axis between two TLEs is associated to the drag perturbation only. Indeed, other effects, like long periodic variations (gravitational and SRP), are negligeable in the orbital region considered [8]. The first step is the evaluation of the variation of the semi-major axis between two TLEs

$$\Delta a_{\mathrm{TLE}} = a_{\mathrm{TLE2}} - a_{\mathrm{TLE1}} \tag{1}$$

Then, the second step consist of evaluating the same change (i.e., considering the same time span) but exploiting the propagator. The letter is performed considering the perturbations affecting the orbital motion of LEO objects, but the change is computed considering only the effects of the drag

$$\Delta a_{prop} = \int_{t_1}^{t_2} \frac{da}{dt}\Big|_{drag}\, dt \tag{2}$$

In case the difference between the two values obtained (i.e., $\Delta a_{DIFF} = \Delta a_{\mathrm{TLE}} - \Delta a_{prop}$) is below 10^{-4}km the stigmatisation process end and the BC found is associated to the analysed object. Otherwise, the BC estimate is updated using a simple secant method

$$BC_n = BC_{n-1} - \Delta a_{DIFF}(BC_n - 1)\frac{BC_{n-1} - BC_{n-2}}{\Delta a_{DIFF}(BC_{n-1}) - \Delta a_{DIFF}(BC_{n-2})} \quad (3)$$

where BC_n is the n^{th} BC estimate, and the procedure is repeated until the tolerance selected is satisfied. To initialise the process, the first guess is computed considering the Vallado formulation [9]

$$BC_1 = 12.741621 \cdot B^* \quad (4)$$

while the second guess is computed as

$$BC_2 = \frac{\Delta a_{TLE}}{\Delta a_{prop}(BC_1)} BC_1 \quad (5)$$

The process is repeated for all the fragments and objects used for the event detection and the parent identification. The estimation is carried out using a sinusoidal model to recover the evolution of the solar activity over time; this decision introduces possible uncertainties both in the estimation process and in the propagation one. However, it is necessary to perform a compromise between the accuracy of the model and the computational time of the process.

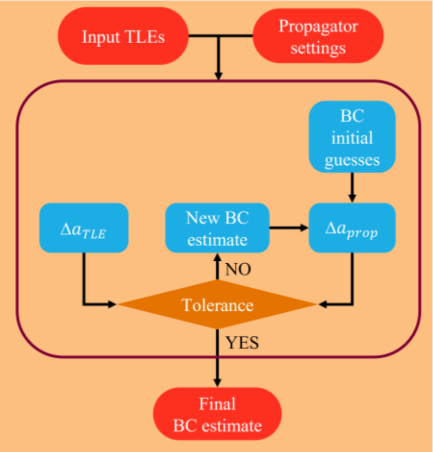

Fig. 3. BC estimation process.

2.3 Filtering/Pruning

The objects included in the initial sets of fragments and parent(s) candidates are generated by different events or belongs to different families, consequently it is necessary to introduce filtering or pruning techniques able to discard all those unrelated to the event under investigation. Different methods are used along the entire analysis process:

- A Hierarchical Clustering Method (HCM, proposed by Zappala et al. [10]);
- A triple-loop filter, which is a modified version of the one introduced by Hoots et al. [11];
- An orbit inclination filter;
- An orbit RAAN filter.

The HCM is exploited by the short term routine to properly identify the parent(s) involved and the fragments generated (those already catalogued) by the detected events. The method is based on the definition of a similarity distance function δv (which has the dimensions of a velocity increment) to perform analyses of the objects in the space of orbital elements. Differently from the metric proposed by Zappala et al., the model used here consider all the orbital parameters to perform the comparison check. The similarity function is here defined as

$$\delta \mathrm{v} = \mathrm{na}\sqrt{\left(\mathrm{k}_1\left(\frac{\delta \mathrm{a}}{\mathrm{a}}\right)^2 + \mathrm{k}_2(\delta \mathrm{e})^2 + \mathrm{k}_3(\delta \mathrm{i})^2 + \mathrm{k}_4(\delta \Omega)^2 + \mathrm{k}_5(\delta \omega)^2\right)} \quad (6)$$

where n is the mean motion, k_i are a weighting parameter.

The triple-loop filter is instead involved in both the routines, but with different tasks. The short term analysis exploit it during the epoch estimation phase (coupled with the propagator) to identify clusters of objects in terms of position (i.e., close encounters) in time, while the long term analysis exploit it to perform a filtering of the objects considered before the propagation phase. As the name suggest, three filtering step are performed: an apogee/perigee check, the evaluation of the MOID and a temporal filter. The first is a simple geometrical filter, adopted to check if the relative geometry of the two objects under investigations allows possible close encounters. To pass to the second stage of the filter the maximum of the two perigees q and the minimum of the two apogees must satisfy the following relation

$$q - Q \leq D_{th} \quad (7)$$

where D_{th} is a selected distance threshold.

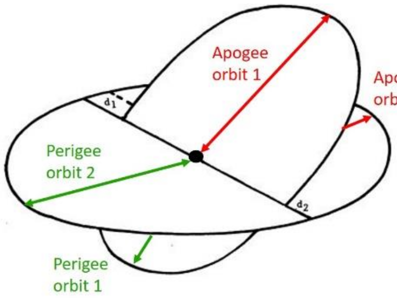

Fig. 4. Apogee/perigee of two analysed objects.

The second filtering step is again a geometrical comparison, but this time it is evaluated the MOID between the two considered objects, computed here using the algebraic method proposed by Gronchi et al. [12]. The method evaluates the roots of a 16th degree univariate polynomial to identify the critical points between the two orbits and, among all the solutions, the minimum one is considered as the MOID. As for the first geometrical filter, also here it is defined a threshold that, if satisfied, allows to pass to the next step. The last filter involves a time examination, useful to detect possible occurred close encounters. Angular windows are generated around the position of the MOID along the two orbits, then converted into time window exploiting the Kepler's equation, and it is checked the possibility of finding both the objects inside this window at the same time, considering a fixed time span for the search. In case of overlaps, the two objects are analysed to find the epoch and the location of the close encounter. It is important to state that this last filter is not exploited during the long term process since, far from the event, it loses of accuracy, while for the short term analysis is a powerful tool.

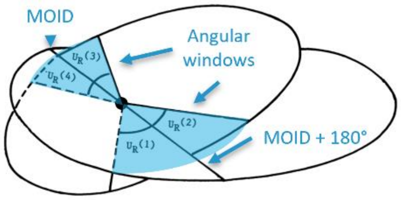

Fig. 5. Angular window for the time filter.

The orbit inclination and RAAN filters are only considered for the long term simulations. The first is very useful when dealing with objects orbiting in the LEO region since it is little affected by perturbations, remaining bounded in time. So, it is possible to generate a window in terms of orbit inclination around the unknown objects considered to remove those far from them. This filter is the first applied during the pruning phase and it is used both before the epoch estimation phase and at the beginning of the parent(s) identification. The RAAN filter, instead, plays an important role near the event epoch. This because, near the event, it is expected that all the fragments generated and the parent itself are characterised by the same value of this angular orbital parameter. So, to discard the parent(s) candidates, the RAAN is a powerful parameter, even when dealing with satellite constellations/ families. Indeed, only the correct parent (or however a very small subset of candidates) will present a compatible RAAN value.

2.4 Propagation

The backward propagation of the various objects is done differently depending on the type of the analysis, whether short or long term.

In the case of short term propagation, the analytical SGP4 model is used [3] [4]. This propagator uses a set of averaged orbital elements that are specific to the TLE format. It considers secular and periodic perturbations due to Earth's oblateness and gravitational resonance effects, solar and lunar disturbances, and orbital decay using a drag model. The SGP4 model computes the orbital state in cartesian coordinates in the True Equator Mean Equinox (TEME) reference frame depending on the epoch of the initial TLE data. Due to the simplifications introduced by the analytical modelling of the perturbations, the accuracy of the propagation is generally limited to intervals of the order of a few days [13].

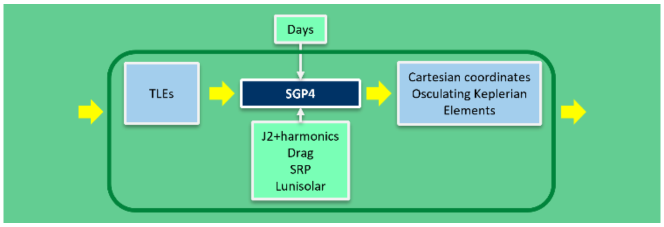

Fig. 6. Short term propagation.

In the case of the long term analysis, the propagation is performed using the semi-analytical propagator PlanODyn [5]. The propagator is based on single and double averaged dynamics, is written in Keplerian orbital elements and exploits different type of perturbing forces. The latter are:

- The aerodynamic drag, modelled according to King-Hele [14];
- The SRP, modelled using a cannonball method and ignoring the eclipses and following Kirov et al. [15];

- The geopotential effects, modelled following Kaula [16] (first degree expansion of the zonal and of the tesseral harmonics) and Brouwer [17] (second order zonal harmonics);

- The third-body effects, modelled following Kaufman et al. [18] and Meeus [19] (to retrieve the ephemerides of the perturbing bodies).

The type of perturbations can be selected according to the type of analysis to be performed.

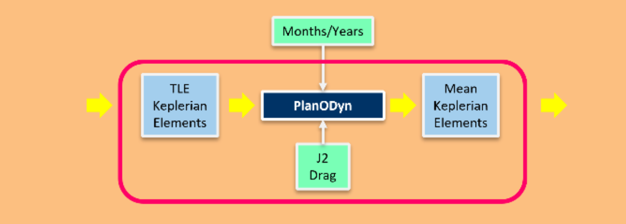

Fig. 7. Long term propagation.

2.5 Epoch estimation and parent identification

This module is devoted to the achievement of the first of the two goals of the toolkit, that is the detection of occurred fragmentations.

Starting from the short term method, the epoch estimation is performed coupling the triple-loop filter with the propagator (performing a backward propagation) to detect possible cluster of objects in terms of position in time (as in Fig. 8). The identification of a cluster can be associated to a breakup event (either a collision or an explosion), that consequently must be analysed. Then, using the HCM method, the parent(s) and the fragments involved in the detected event are identified by matching using a catalogue and the orbital intersection previously found.

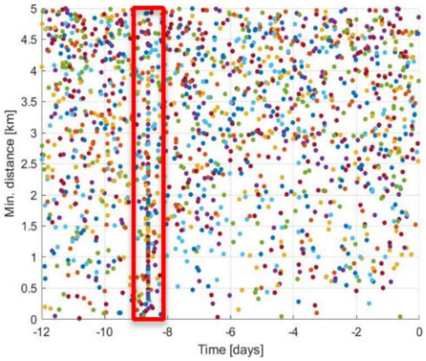

Fig. 8. Close encounters between objects.

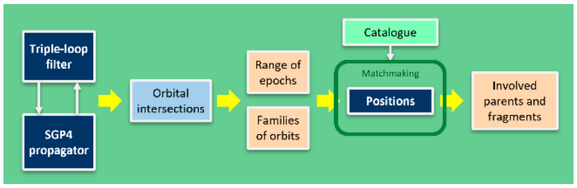

Fig. 9. Short term event detection.

Differently, the long term investigation exploits the RAAN as study parameter. Near the event, all the fragments generated will present the same value of this angular orbital parameters, letting the identification of a breakup looking for cluster of fragments in RAAN. Since the event date is considered as unknown, to not waste computational time propagating backward the fragments for a too long time span, a preliminary estimation of the possible event epoch is performed assuming a linear variation in time of the RAAN of the analysed objects and checking the intersection of the RAAN 'lines'. As visible in Fig. 10, near the event epoch the RAAN 'lines' will present an intersection, which allows a rough estimation of the event epoch. Indeed, the propagation process is performed after the pruning/filtering step and, consequently, it is assumed that the fragments included in the study set belong all to the same parent. The boundary of the propagation is set considering the rough estimation as the midpoint of the analysis. Then, the real propagation is performed (again backward) looking for cluster of objects in RAAN and exploiting a 2D histogram (whose axis are the sine and the cosine of the RAAN) to counts the number objects in each angular region. The adoption of the histogram tool is based on the possibility of having foreign fragments in the study set after the pruning phase. In this way, it is possible to identify a bin containing the maximum number of fragments near the event epoch (where all the foreign objects should be outside it), as in Fig. 11. Among all the possible epoch where the bin with the maximum number of objects is found, the one selected is characterised by the minimum of $\Delta RAAN$ between the most distant objects in the bin. All the objects outside the bin are rejected from the process.

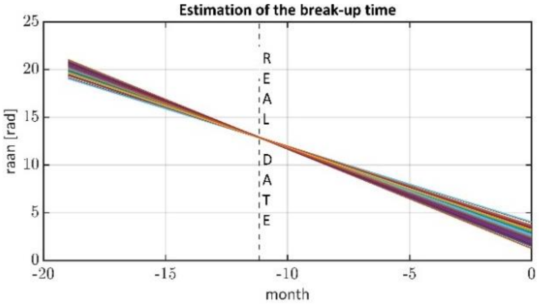

Fig. 10. Preliminary estimation of the breakup time - Iridium 33 breakup.

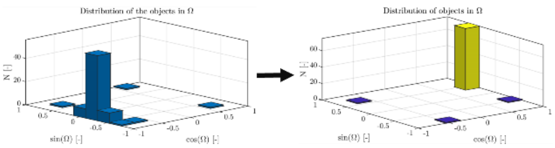

Fig. 11. 2D histogram method to estimate the event epoch.

Once the epoch has been estimated, the parent(s) involved in the event are identified by matching the fragments available in the final set with a catalogue of possible candidate. The matching process is subdivided into three steps:

1. Filter the candidates in terms of orbit inclination (performed before backward propagate the objects);
2. Filter the candidates using the triple-loop to reject the objects that are not geometrically compatible with the set of fragments (performed near the event date);
3. Filter the candidates using the RAAN filter to reject the final undesired objects.

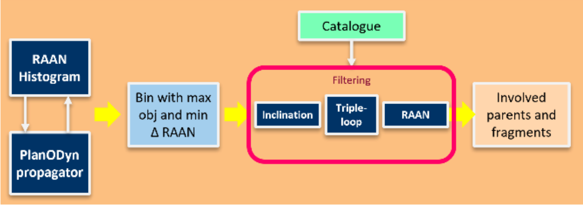

Fig. 12. Long term event detection.

2.6 Breakup characterisation and modelling

The last module, shared by both the long and the short term analyses, is devoted to the characterisation of the detected breakup. The NASA Standard Breakup Model [20] [21] is adopted to estimate the number of fragments generated by the event and some useful physical attributes of the fragments by the event (i.e., mass, size, area to mass ratio, relative velocity). The results retrieved are linked to the type of the fragmentation (i.e., collision or explosion), the type of object(s) involved in the event, the total mass involved, and the collision speed.

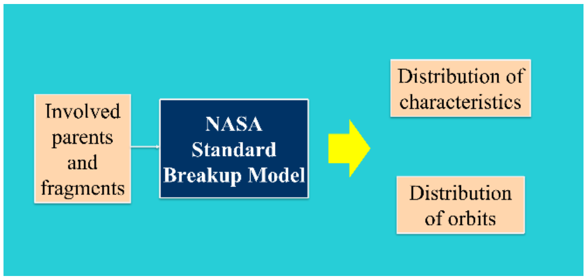

Fig. 13. Block diagram of the event characterisation.

3. Fragmentations' scenarios

This section is dedicated to the presentation of validation tests performed to see the behaviour of the two routines.

3.1 Short term

The application of the software to a short term search is done by analysing the case of the collision between the Iridium 33 and Cosmos 2251 communication satellites occurred on 10th February 2009.

The initial data consists of a TLE set obtained seven days after the event and contains TLEs from both known objects and the few fragments produced in the collisions that were detected in that day. The fragmentation is searched for within the 15 days prior to the reference epoch of the TLEs. The analysis will be evaluated in terms of the correct detection of the fragmentation, the correct identification of the fragments among the objects in the TLE set and of the parent objects, and the computational time required.

The initial TLE set is composed of ~2000 TLEs referring to ~1400 unique objects from different orbital regions (spanning from LEO to GEO). Of those 1400 objects, the 2 parents and 17 fragments produced in the collision are the ones involved in the event. Tab. 1 shows the main parameters used for the analysis and the main results.

Tab. 1. Main parameters used to detect the Iridium-Cosmos fragmentation and main results.

Initial size of TLE set	~ 2000
Date of generation	17th February 2009
Time interval selected	10 days
Estimated epoch of the event	10th February 2009, 16:55:55
Number of objects involved	19
Probable parent object(s)	Iridium 33 (ID 24946), Cosmos 2251 (ID 22675)
Estimated number of fragments	1208 (367 from Iridium 33, 841 from Cosmos 2251)
Computational time	10.8 min

After the initial prefiltering, the application of the triple-loop filter reduces the set to ~1100 objects, with ~1800 close approaches below 5 km detected within the search time frame, as shown in Fig. 14.

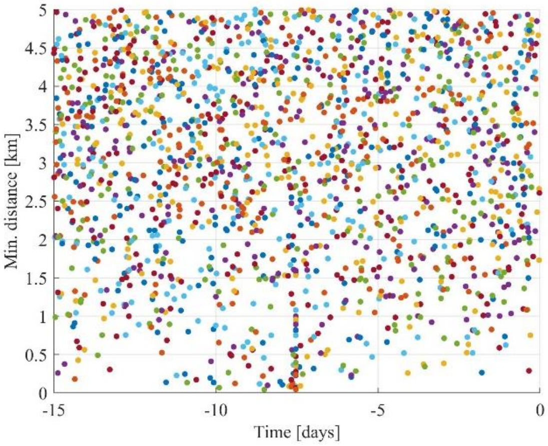

Fig. 14. Distribution in time and distance of the close encounters between the objects used to search for the Cosmos-Iridium collision event.

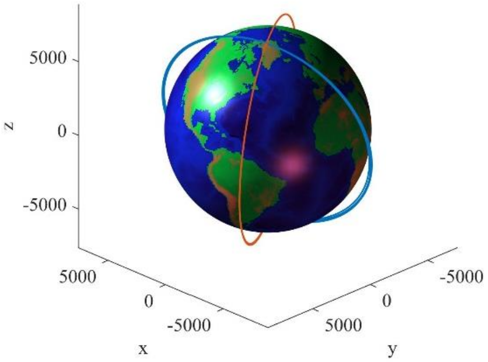

Fig. 15. Plot of the orbits of the two involved family of objects.

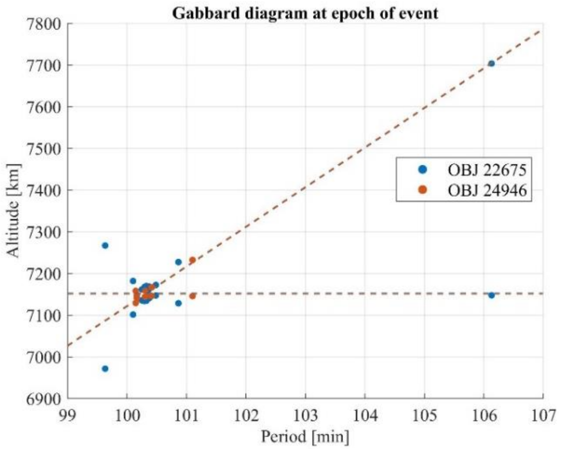

Fig. 16. Gabbard diagram associated to the collision breakup detected.

3.2 Long term

The test case analysed here for the long term routine refers to the Fengyun 1C breakup, dated 10 January 2007 [22] (more tests are available ref) and the initial data are taken 10 months after the event. The examination is carried out computing the relative error between the estimated date and the real one as

$$\epsilon_{rel}(\%) = \frac{t_{estim} - t_{real}}{t_{last} - t_{real}} \cdot 100 \qquad (8)$$

and assessing the quality of the parent identification routine exploiting different thresholds for each adopted filter, as described in the following bullet points

- Inclination $\Delta\, i$: from 0.05 deg up to 5 deg with step 0.05 deg;
- Apogee/perigee and MOID filters: [5/1. 10/5, 20/10, 40/20, 60/30, 80/40, 100/50] km;
- Δ RAAN: from 0.05 deg up to 5 deg with step 0.05 deg.

The propagation is performed considering the drag (with a simple sinusoidal model for the solar cycle evolution) and the gravitational effects.

The initial set of analysed objects is generated by creating a core composed by fragments belonging to the Fengyun 1C and by randomly adding other fragments, and it is composed by 405 objects (72 of which are Fengyun 1C fragments). The fragments to be considered as unknown is randomly selected among the Fengyun fragments and, to see the response of the method, three different objects are selected: 29780, 29729 and 29765 (NORAD ID). After passing through the filters (whose thresholds are $\Delta\, i$ = 1 deg, apogee/perigee distance = 25 km and MOID distance = 20 km), several objects are rejected by the process, and the one survived are reported in Tab. 2.

Tab. 2. Fragments survived after the pruning phase.

	29780	**29729**	**29765**
# Total Objects	12	25	15
# Fengyun 1C Fragments	12	21	15

Those fragments are backward propagated to estimate the event epoch. The relative error associated to each study case is displayed in Fig. 17Fig. 17. Relative error in the epoch estimation associated to each study case. As visible, all the errors are quite low and remains around 10%.

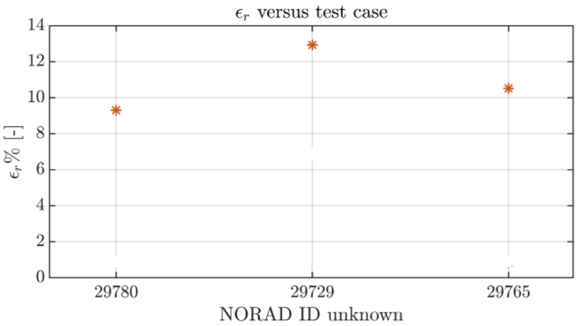

Fig. 17. Relative error in the epoch estimation associated to each study case.

Then, the fragments included in the set after the propagation are used to identify the parent(s) involved in the event. The initial set of possible parent(s) is composed by 1497 objects. Fig. 18 shows the number of candidates that pass the inclination filter as function of the Δi. As visible, the algorithm becomes more powerful when selecting thresholds lower than 1 deg.

Fig. 18. Number of objects survived after the inclination filter as function of the inclination threshold.

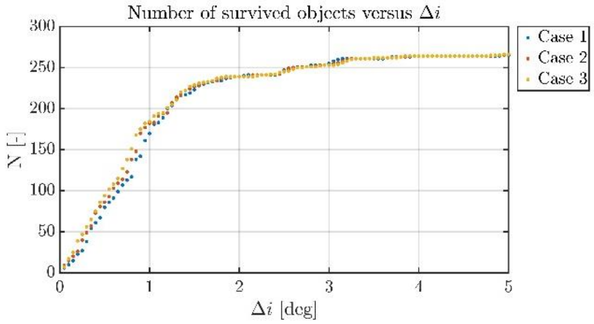

Fig. 18. Number of objects survived after the inclination filter as function of the inclination threshold.

Finally, Tab. 3 summaries the results of the parent identification routine. In the table are shown the smallest thresholds that allows to find the minimum number of parent(s) candidates and that include the correct one. For the first and the third cases it is possible to define threshold able to find the correct parent, while for the second case two objects remain at the end of the process. The latter is however a good achievement since the initial set of analysed objects has ben narrow down to a very small subset of candidates.

Tab. 3. Parent identification results.

	29780	**29729**	**29765**
Single Candidate	Yes	No	Yes
A/P - MOID (km)	5-1	-	5-1
$\Delta\Omega$ (deg)	0.3	-	0.1
# Multiple Candidates	-	2	-
A/P - MOID (km)	-	5-1	-
$\Delta\Omega$ (deg)	-	1.4	-

4. Conclusions

The PUZZLE software was initially under a contract with the Italian Space Agency with the aim of study fragmentations considering a time span for the search of the order of days. The goals of the toolkit are the detection of occurred fragmentations in terms of estimation of the event epoch and the identification of the object(s) involved, and the characterisation of the detected event in terms of mass, energy, and orbital elements.

The work proposed here presents an updated version of the software, which now includes a long term simulation for breakup detection and characterisation. The methodology of the new modules is different from the already existing one and, the actual version of the software, consider them as not connected. The idea is, however, to link the two routines such that to perform the short term analysis as a refinement of the long term one. The present version focuses only on the fragmentations occurred in the LEO and consider a time span of the order of months up to years for the event detection. Moreover, the analyses are carried out exploiting the semi-analytical propagator PlanODyn, which exploits mean Keplerian orbital elements to recover the evolution in time of the objects' parameters.

The validation scenarios shown accuracy in terms of epoch estimation for both the routines, with a slightly higher relative errors for the long term simulations which are associated to the level of uncertainties introduced by the type of the investigation. The model is also able to identify the correct parent(s) or to narrow down the number of candidates to a very small subset if compared to the initial number of considered objects. These results are achieved exploiting various type of algorithms that are able to discriminate the analysed objects identifying common features: cluster in terms of position for the short term case, or cluster in RAAN (after a filtering process based on the study of the orbits geometry, focusing in particular on the orbit inclination) for the long term case. Moreover, differently from the first version of the software, the new one includes also a BC estimator needed by the long term propagator.

To further improve the actual version of the entire software, some possible future works are introduced. First, the BC estimation must be enhanced, in particular for high area to mass ratio objects which are more affected by the variation in the solar activity. The idea is to improve the estimation by comparing the results obtained with real data. Then, it is necessary to introduce a probability index to be assigned to the parent(s) identified in case more than one objects is associated to the event. This would increment the quality of the output data since, in some cases, it is not possible to find the correct parent, while a very small subset of possible candidates remains at the end of the process. The long term investigation needs to be expanded also to other orbital regions like the GEO or the MEO to have a more global vision of the debris population. Both for the long and the short it necessary to introduce new pruning and clustering algorithms to deal with orbital region denser of objects, where it is difficult to reject from the process all the fragments that are not related to the event to be detected. In the end, the characterisation of the event could be further expanded introducing a collision risk analysis based on the results obtained.

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