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Space break-up forensics: unravelling the secrets of explosions and collisions in Space

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Abstract

Space debris is a growing problem that threatens the safety and sustainability of space activities. Break-up events can occur due to collisions with other satellites or debris, as well as due to internal explosions within a satellite. To understand and learn from this phenomenon, it is important to understand the dynamics and consequences of such events. This paper will describe the tasks performed within the European Space Agency-funded activity "On-Orbit Break-up Forensics" to provide innovative methodologies for the analysis and characterisation of space fragmentation events. OFELIA is a unique tool integrating 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 as standalone or used together to complete a full pipeline of operations. In this paper, the overall structure of the software will be explained together with the functionality of each module. Preliminary results of some of the modules will be also shown applied to recent fragmentations.

1 Introduction

Space debris is a growing problem that threatens the safety and sustainability of space activities. Break-up events can occur due to collisions with other satellites or debris, as well as due to internal explosions within a satellite. Satellite break-ups create clouds of fragments, increasing collision risk for another spacecraft. To fully understand and learn from the current situation, it is 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 will describe the tasks performed within the activity "On-Orbit Break-up Forensics" to provide innovative methodologies for the analysis and characterisation of space fragmentation events. The project is funded by the European Space Agency through the ESA's Technology Development Element and aligned to contribute to the technology objectives from ESA's Space Safety Programme.

The OFELIA – Orbital Fragmentation rEconstruction moduLe for forensIcs Analysis – tool is being devised 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 as standalone or used together to complete a full pipeline 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. OFELIA 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. It will employ new

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metrics and methods to characterise the dynamics of a cloud of debris and aim to optimise the tasking of sensors for dedicated observation campaigns. Rapidly observing fragments after a satellite break-up in orbit is critical as they rapidly disperse and become more challenging to accurately track. As a result, a new tool for reverse engineering a fragmentation starting from observed fragments is also integrated.
In this paper, the overall structure of the software will be explained together with the functionality of each module. Preliminary results of some of the modules will be also shown applied to recent fragmentations.
The paper is structured as follows: first, an introduction to the operating modes of OFELIA is given in Section 2, then the test cases are described and used to test the single modules composing the tool in Section 3. Lastly, conclusions are drawn, and future steps are described in Section 4.

2 OFELIA operating modes

The OFELIA tool can be operated in 3 modes:
1. OFELIA fragmentation reconstruction and characterisation mode
2. OFELIA improved observational campaign mode
3. OFELIA single module mode

2.1 OFELIA fragmentation reconstruction and characterisation mode

In the OFELIA fragmentation reconstruction and characterisation mode the user starts by inputting an initial TLE set from DISCOS, space-track or any other database in the defined file format. The Backward propagation and fragmentation reconstruction module is called to reconstruct backward in time the fragmentation event and output the parent object/s velocity, time of the event and velocity distribution. Such input is passed to the Break-up model calibration module that calibrates the breakup model and can also perform the Breakup simulation, forward in time, of the breakup event though either the selection of COLBUSS or POEM ESA tools. The outputs are the calibrated model parameters and the fragment characteristics and velocity distributions.
Such input is passed to the Cloud propagation module that uses OREKIT as orbit propagator and gives as output the fragment's orbit at different time snapshot and the spatial density of fragments. This information is passed to 2 modules. The Could expansion metric module uses it to characterise the fragmentation event and define the cloud expansion metric; the Observability metric module uses it to define the Observability metric that will be used to define the sensor tasking through the Sensor tasking module and to guide a New observational campaign. The OFELIA fragmentation reconstruction and characterisation mode stops at this point as showed in Figure 1.

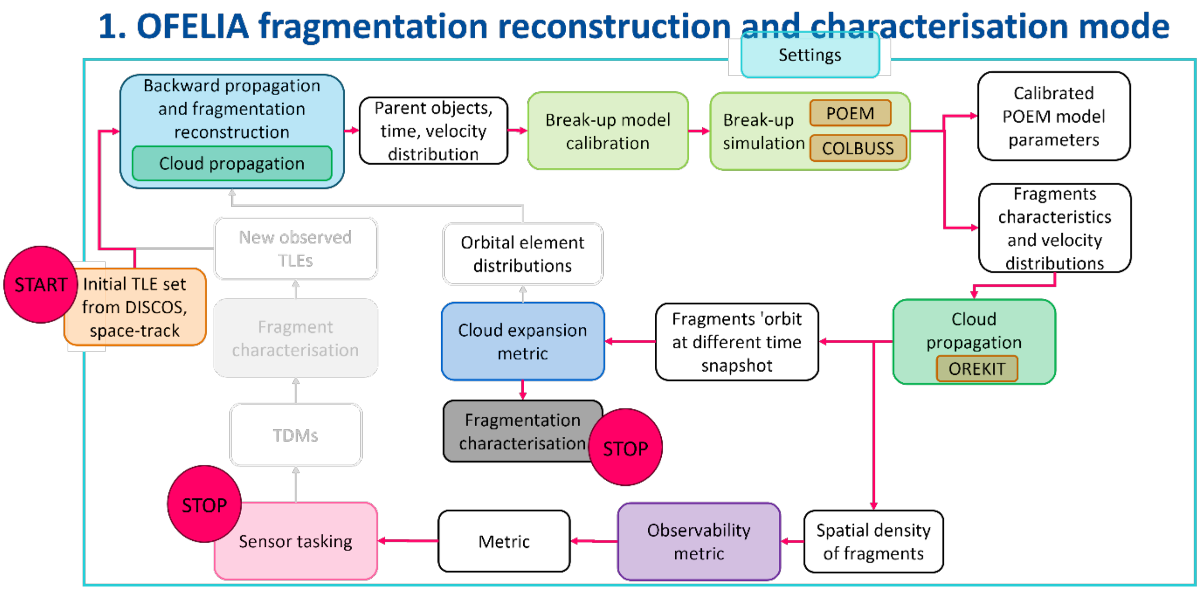

Figure 1: OFELIA fragmentation reconstruction and characterisation mode.

2.2 OFELIA improved observational campaign mode

The OFELIA improved observational campaign mode can start at the end of the first round of the OFELIA fragmentation reconstruction and characterisation mode. Indeed, the Cloud expansion metric module gives as output the orbital element distribution from a simulated fragmentation that is fed into the Backward propagation and

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reconstruction. On the other side the New observational campaign that was performed in an asynchronous manner hopefully has identified new TDMs that can be passed to the Fragment characterisation module. Such module produces new TLEs from the new observed fragments that can be added to the existing initial TLE set from the available catalogues to start another time the OFELIA fragmentation reconstruction and characterisation mode (1). See Figure 2.

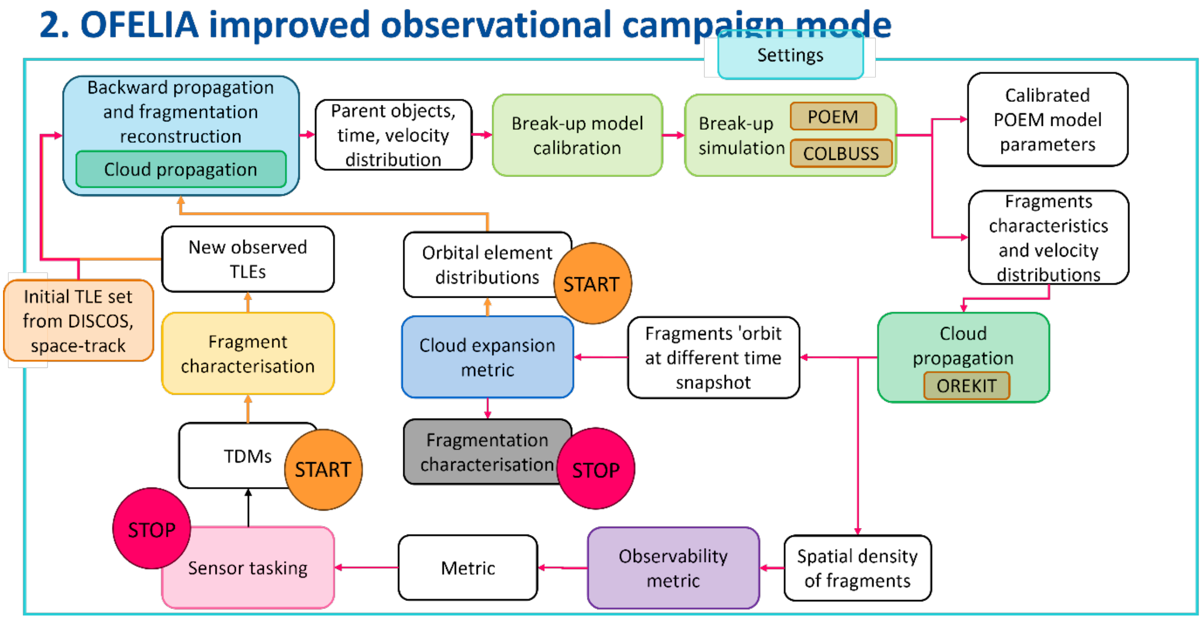

Figure 1: OFELIA improved observational campaign mode.

The two modes (1) and (2) can then be repeated as many times as wanted depending on the New observational campaigns that can be allocated and also, they can be run anytime a new fragment appears in the catalogue coming from External observational campaign. This process could be automated in the future.

2.3 OFELIA single module mode

The expert user can also use each single module separately and input the required input for each module in the predefined file format to get the described output for each module

3 OFELIA single model mode description and applications

The OFELIA tool was presented in [1] and [2]. In the following sections a brief presentation of each module is given but the focus is given to show the applicability of each single module to some test case scenarios.

3.1 Test cases

The test cases selected for this work are the Fengyun 1C breakup occurred on 11/07/2007 22:26 GMT, to be treated as a collision as it is the result of an ASAT test and the NOAA 16 breakup occurred on 25/11/2015 09:50 GMT to be treated as an explosion. The TLEs of the two events are reported in Table 1. It must be noted that usually, ASAT tests are treated as explosion because there is an explosive charge in the missile that hits the satellite. However, in the case of Fengyun 1C instead, the missile was a kinetic kill vehicle, which means a projectile weapon based solely on a projectile's kinetic energy to inflict damage to a target, instead of using any explosive. Moreover, the relative velocity was of the same order as the orbital velocity of the target, as the missile was in direct ascent trajectory. This is the reason why the involved energy was that of a collision and the event can be treated as such.

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Table 1. TLE of the two objects which generated the fragmentation events under analysis.

Fengyun 1C
1 25730U 99025A 07010.91400754 -.00000150 +00000-0 -59123-4 0 9992
2 25730 098.6462 000.7849 0013479 269.9603 090.0028 14.11820243395328
NOAA 16
1 26536U 00055A 15328.89398578 +.00000053 +00000-0 +52329-4 0 9991
2 26536 098.9249 034.5719 0011295 134.6627 225.5467 14.13117180078857

3.2 Backward propagation and fragmentation reconstruction module

The aim of the backward propagation and fragmentation reconstruction module is to detect and characterise fragmentation events a posteriori, starting from a set of available TLEs given as input to the tool. This allows for a fast evaluation of the potential consequences of a breakup in terms of collision risk posed to other active satellites and for swift operations for tasks such as collision avoidance manoeuvres and observation planning. The method is able to reconstruct the breakup in two scenarios: when the event is known, i.e. the generated fragments are known and so is the parent, and when the event is not known, i.e. the parent is unknown and it is uncertain which objects were generated, yet the alert for an event was given. The user inputs which scenario is analysed, and the algorithm then branches accordingly, following different procedures. The module can apply one of two methods, or both of them [2].

When the fragmentation is known, it is assumed that the information on both the parent object which fragmented, and the generated fragments is available. Therefore, the TLEs of these objects are given as input to the module together with the thresholds for the two methods. The objective in this case is an estimation of the epoch of the breakup. The procedure depends on the number of available TLEs, indeed if many TLEs are available the first method (method 1) based on the previous works in Romano et al. [3], Muciaccia et al. [4] and Ottoboni et al. [5], consisting in a series of pruning criteria is applied [6], while if there are only few TLEs available both method 1 and the second method (method 2) – based on the work of Montaruli et al. [7] are used, to increase the reliability of the reconstruction. If there are less than four objects as input, only method 2 is used.

In the second scenario, i.e. when the fragmentation is not known, there is no a priori information on the objects involved in the event. For this reason, the purpose of the reconstruction is both the estimation of the epoch of the event and the identification of the involved objects. The input to the module is a TLE set composed of fragments as well as other catalogued objects, however the number of fragments in the set is unknown. The adopted procedure depends on the number of objects that are kept in the analysis after the application of the triple-loop pruning step for the assessment of the possibility of close encounters. Indeed, when the triple-loop pruning step [7] saves more than 70% of the initial TLEs, the first method is applied by itself as it is assumed that many fragments TLEs are in the set and therefore the first method can reconstruct the epoch and the objects of the event accurately. Conversely, both methods are used.

The flexibility of the pipeline allows to perform the reconstruction and analysis of the events in a multitude of scenarios, so as to cover all the possible cases that the OFELIA tool may investigate, while maintaining reliability in the results. The module was applied to the two test cases described in Section 3, i.e. the Fengyun 1C case and the NOAA 16 breakup.

3.2.1 Fengyun 1C scenario

In the Fengyun 1C test case, the fragmentation was considered known. The input set was composed of 7 TLEs belonging to fragments, dated 11 days after the breakup event, and the analysis was aimed at detecting the correct date of fragmentation. Due to the limited number of TLEs in input, both method 1 and 2 were applied. Method 1 identified a close approach around 11 days before the epoch of the TLEs, as is depicted in Figure 1, which shows the close encounters between each pair of objects backward in time with respect to the distance of close approach. The method places the breakup on 11/01/2007 at 09:23, hence getting the correct date but the wrong hour. Method 2 instead evaluates the possible event epochs for five fragments, placing the epoch on 11/01/2007 at 22:26 for the majority of them, as shown in Figure 2.

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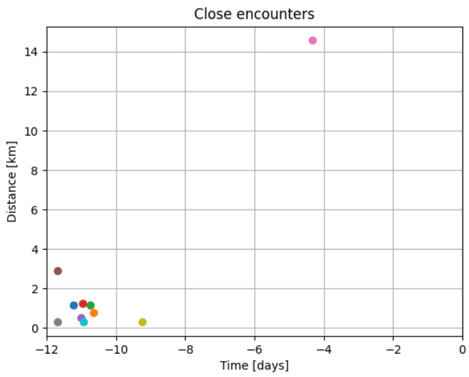

Figure 1 Close encounter plot showing the distance of close approach with respect the time of close approach for each pair of objects, output of method 1 for the Fengyun 1C test case.

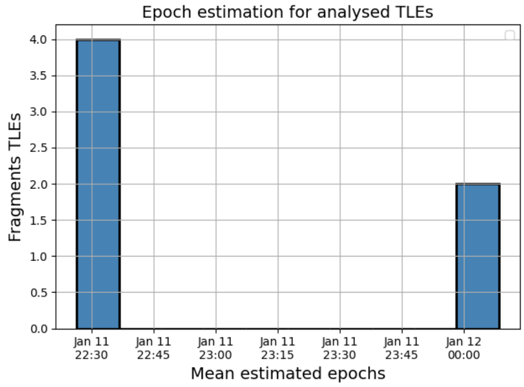

Figure 2 Cumulative mean estimated fragmentation epochs for all analysed fragments, output of method 2, for the Fengyun 1C test case.

The module then checks which epoch was found in the majority of the cases, selecting it as the most likely epoch of the event. Therefore, the result of the module for this test case is a fragmentation epoch dated 11/01/2007 at 22:26, which corresponds to the correct date and time.

3.2.2 NOAA 16 scenario

For the NOAA 16 test case, the fragmentation was considered unknown, to test the capabilities of the module in this scenario which requires the identification of the involved objects and their parent. The input TLE set was composed of 145 TLEs, both belonging to the fragments generated in the breakup and other random objects taken from the SpaceTrack [8] catalogue about 10 days after the fragmentation event. The module performs the pruning process saving less than 70% of the initial TLEs, hence it assumes that the majority of the objects in the input set are not fragments TLEs and applies both methods. The results for both of them are in Figure 3 and Figure 4.

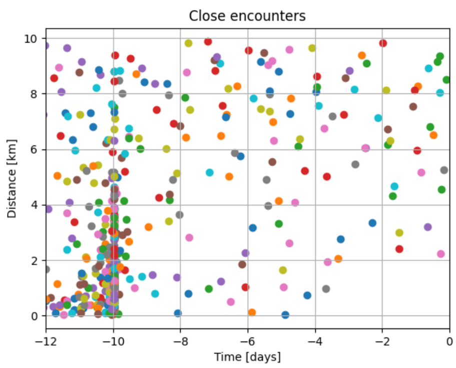

Figure 3 Close encounter plot showing the distance of close approach with respect the time of close approach for each pair of objects, output of method 1 for the NOAA 16 test case.

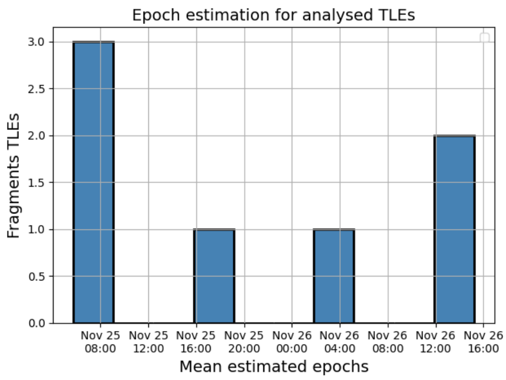

Figure 4 Cumulative mean estimated fragmentation epochs for all analysed fragments, output of method 2 for the NOAA 16 test case.

Method 1 places the fragmentation epoch on 25/11/2015 at 07:19, moreover it identifies 37 objects possibly involved in the fragmentation and the correct parent as NOAA 16. Method 2 evaluates the possible epoch of fragmentation for 7 fragments, giving the most likely epoch on 25/11/2015 at 07:20. Therefore, the final selected epoch is 25/11/2015 at around 7:19, which is off with respect to the real fragmentation epoch by 2 hours.

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3.3 Break-up model calibration module

The goal of the Break-Up Model module (BUM) is to calibrate and run one of the two ESA tools, POEM or COLBUSS, selected for the simulation of the entire cloud of fragments generated after the satellite breakup. This means that the module implements the mathematical equations of the two models implemented in these tools, namely an adaptation of the NASA Break-Up Model for POEM [9][10] and the COLBUSS probability distributions [11], and is able to change the selected model parameters in order to match the available data related to the event under analysis. The user can select the model, POEM or COLBUSS one, and can choose to calibrate all the parameters of the model or a subset of them through the BUM configuration file. If the calibration of one or more parameters fails, the module puts information about this failure in the log and continues its operations, considering the original value of the parameter as defined in the model or the starting guess provided in input by the user. Both POEM and COLBUSS tools allow to change model parameters through dedicated inputs, and this feature is exploited by the BUM module itself in order to run them with calibrated parameters.

The calibration of the selected tool is performed taking into account the available data on catalogued fragments of the event that is under analysis. The set of catalogued fragments needs to be representative, in order to have a successful calibration. Even when many fragments are catalogued, the considered set of fragments cannot be the entire set actually in orbit, since the smaller fragments, the ones that are below the minimum detectable threshold, cannot be observed and consequently will never be catalogued. The incompleteness of the input can be taken into account when performing the calibration, by activating the corresponding option.

The module can automatically run both the tools POEM and COLBUSS, as it implements interfaces for both. Hence, once the calibration is completed, the module proceeds by running the selected tool using the calibrated parameters just computed.

3.3.1 POEM calibration and run

The pipeline for POEM calibration is illustrated in Figure 5. The BUM module acquires in input:

1. The file containing the data of catalogued fragments (size, A/M, delta-velocity);
2. The configuration file, where the user can select the tool POEM and the parameters to be calibrated for the current run;
3. The file of breakup data where the breakup event characteristics and the involved parent(s) is(are) specified or alternatively the POEM event file (usually called event.dat).

Then, the “calibration”, which is the core algorithm of the module, is performed. The idea of this step comes from the following considerations. The standard NASA break-up model (NASA SBM) describes the distribution of three quantities related to fragments, i.e., the size, the area-to-mass ratio (A/m) and the module of the delta-velocity [9]. The directions of delta-velocities are assumed to be distributed uniformly on the unit sphere. POEM assumes a slightly modified version of those models (cf. [10]). Then, in POEM model each quantity relies on the same set of parameters as the NASA SBM, using the NASA SBM values as defaults.

In the calibration step, we are analysing a single fragmentation event for which the list of size, A/M and delta-velocity values are supposed to be available for a set of fragments that have been detected and catalogued and the purpose is to tune the model parameters for best representing the observed data.

Once the optimal parameters are obtained, then the BUM module runs POEM with those values and finally converts POEM output into OFELIA internal format. Specifically, the file of simulated fragments and the file of fragment orbits are generated and passed to the propagator.

Useful additional outputs produced during this pipeline are new versions of the files poem.prm and event.dat, which are inputs for the POEM tool and are updated inserting calibrated parameters.

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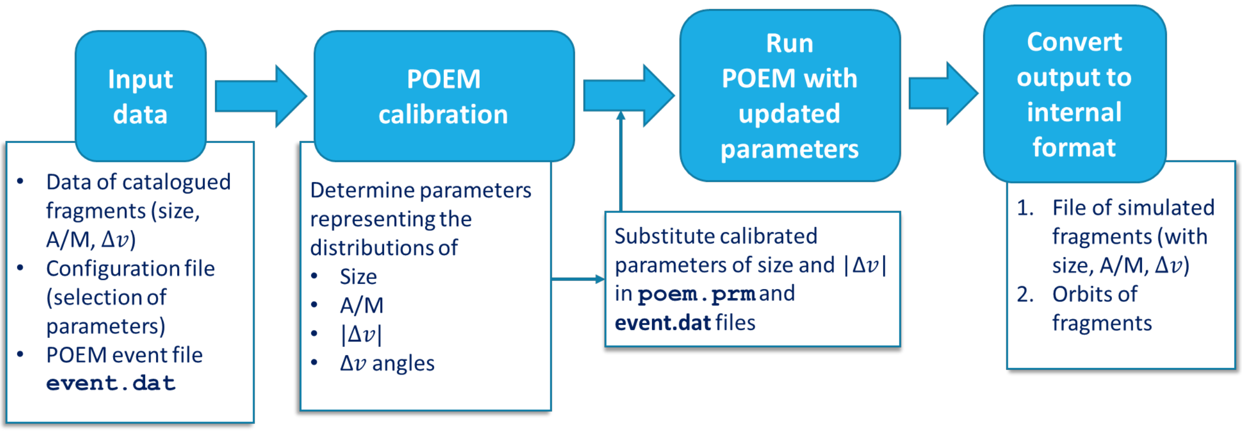

Figure 5: Pipeline for POEM calibration.

3.3.2 Fengyun 1C with calibrated POEM model

The initial tests performed for the BUM module exploits data generated using the NASA SBM. The advantage is that these data are complete, in the sense that for each fragment information on size, A/M and delta-velocity is available. Incompleteness in the set of catalogued fragments is simulated by removing an increasing percentage of fragments as the fragment diameter decreases. The POEM calibration results for Fengyun 1C are showed in Figure 6 to Figure 9, representing the distributions of the characteristic sizes and of the delta-velocities of the fragments before and after calibration.

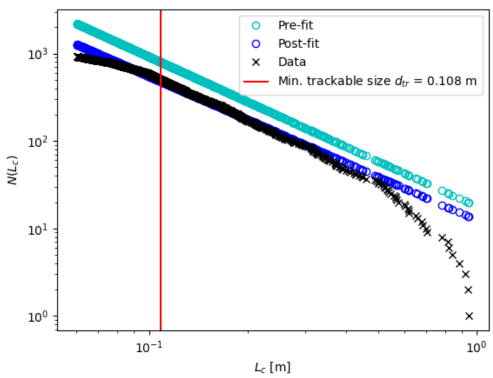

Figure 6 Pre-calibration (light blue circles) and post-calibration (blue circles) POEM model for the cumulative number of fragments greater than a given characteristic size after the Fengyun 1C breakup. The data set used for this test is a filtered set of fragments simulated with the NASA SBM (black crosses).

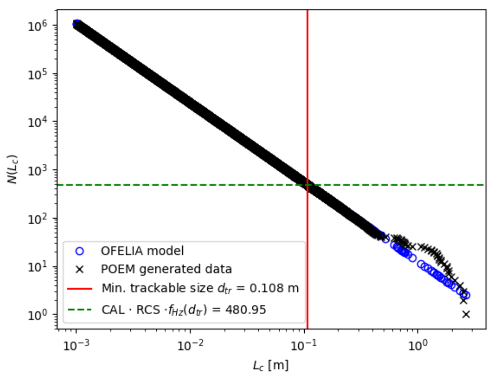

Figure 7 Comparison between the calibrated model computed by OFELIA (blue circles) for Fengyun 1C breakup and the set of fragments generated with POEM (black crosses), using calibrated parameters.

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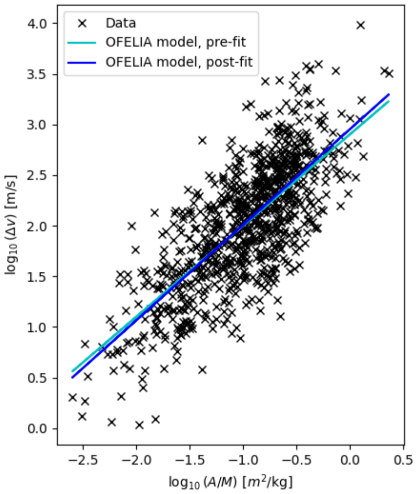

Figure 8 Pre-calibration (light blue line) and post-calibration (blue line) POEM model for the mean of delta-velocity distribution as function of A/M. The data set used for this test is a filtered set of fragments simulated with the NASA SBM (black crosses).

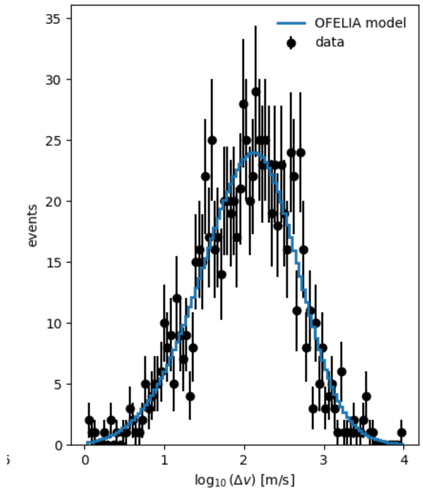

Figure 9 Comparison between the calibrated conditional model of delta-velocity given A/M computed by OFELIA (blue curve) for Fengyun 1C breakup and the conditional histogram generated from the data set (black points with variances).

3.3.3 NOAA 16 with calibrated POEM model

The POEM calibration results for NOAA 16 are showed in the Figure 10 and Figure 11, representing the distributions of the characteristic sizes of the fragments before and after calibration.

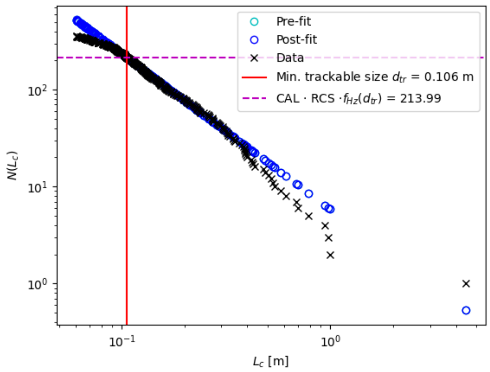

Figure 10 Pre-calibration (light blue circles) and post-calibration (blue circles) POEM model for the cumulative number of fragments greater than a given characteristic size after the NOAA 16 breakup. The data set used for this test is a filtered set of fragments simulated with the NASA SBM (black crosses).

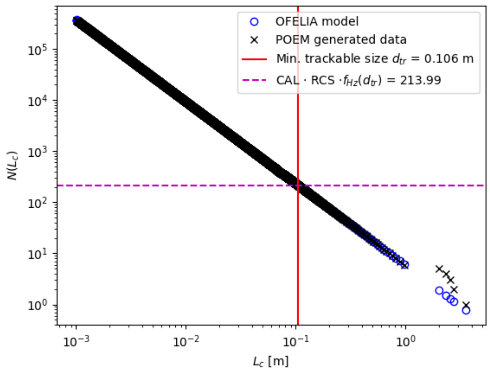

Figure 11 Comparison between the calibrated model computed by OFELIA (blue circles) for NOAA 16 breakup and the set of fragments generated with POEM (black crosses), using calibrated parameters.

3.3.4 COLBUSS calibration and run

COLBUSS stands for COLlision Break-Up Software System. The tool was developed for ESA in the years 2021-2022 under the ESA contract “Exploiting numerical modelling for the characterisation of collision break-ups” [11].

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COLBUSS implements a simplified numerical break-up model, able to generate information on the cloud(s) of fragments produced after a collision between two Earth orbiting objects. The simplified model is derived from a complex validated numerical model, through the statistical analysis of the results obtained during a simulation campaign performed with the validated tool, which is the CSTS - Collision Simulation Tool Solver developed by CISAS - University of Padova [12].
COLBUSS starting point is the availability of a database of simulations performed with the CSTS, whose results are represented in the form of statistical distributions of the sizes, A/M ratios and delta-velocities of the fragments. For any particular collision scenario defined by the user, COLBUSS computes the statistical model that describes the cloud(s) of fragments generated after that specific collision, through interpolation among the statistical models of the database (see Figure 12).
Each statistical model is defined through:

- the marginal distributions for the 5 scalar quantities giving sizes, A/M ratios and delta-velocities of fragments;
- the 5×5 correlation matrix for the considered 5 scalar quantities.

Once defined the statistical model for the case at hand, COLBUSS randomly generates the fragments according to the given marginal probability distributions and correlations, using the algorithm of Bradley and Fleisher [13].
Figure 12 shows through a diagram how COLBUSS uses the information stored in its database to compute the statistical model to be applied for the collision specified by the user through the input. COLBUSS first converts the input collision scenario to a location in its 6-dimensional interpolation space. Then it checks if the location is among the ones already stored in the database, i.e. if it is a node of the interpolation grid. If not, it performs interpolation among the cases of the database in order to obtain a new statistical model to be applied for the case at hand. Otherwise, if the event location is already stored in the database, it uses the statistical model stored there in correspondence of that location. Finally, COLBUSS generates the cloud of fragments according to the selected statistical model.

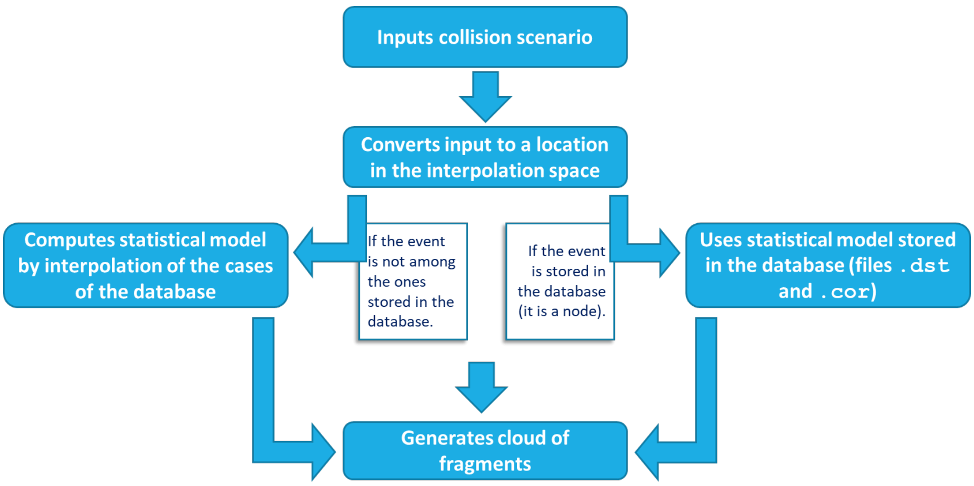

Figure 12. Diagram showing the workflow of the COLBUSS tool.

We want to avoid COLBUSS computing a new statistical model by interpolation, because we want to use a model calibrated by the BUM module to available data. The idea is to store the considered event and its calibrated model in the database, so that COLBUSS uses it. The resulting pipeline is shown in Figure 13. The inputs are the same as in the case of POEM calibration. The final outputs, composed of the file of simulated fragments and the file of fragments orbits, are the same as in the case of POEM and are produced using the same format. In this way, the I/O external interfaces of BUM module used by the user or by the other OFELIA modules do not change. The intermediate outputs, containing calibrated parameters, are different instead, as they correspond to the input needed to run the particular tool selected using the resulting calibrated parameters. In the case of COLBUSS, the calibrated parameters are inserted in the COLBUSS database of reference distributions.

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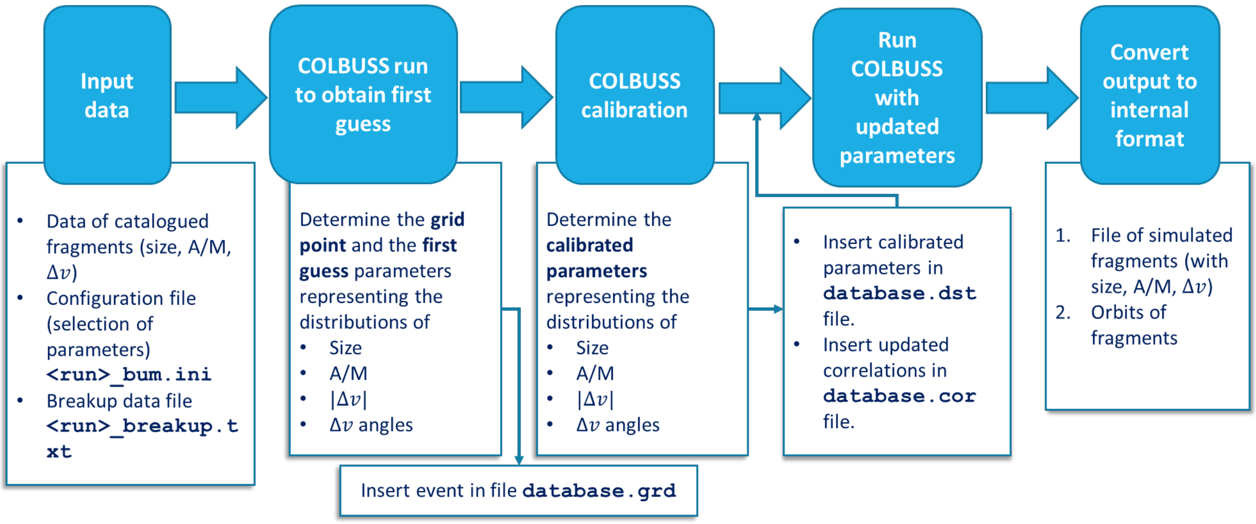

Figure 13. Pipeline for COLBUSS model calibration and generation of the cloud according to this model.

3.3.5 Fengyun 1C with calibrated COLBUSS model

The COLBUSS calibration results for Fengyun 1C are showed in Figure 14 to Figure 17, representing the distributions of the characteristic sizes, of the A/M and of the delta-velocities of the fragments before and after calibration. The same data set used for the test of POEM calibration reported in Section 3.3.2 was used also for this test.

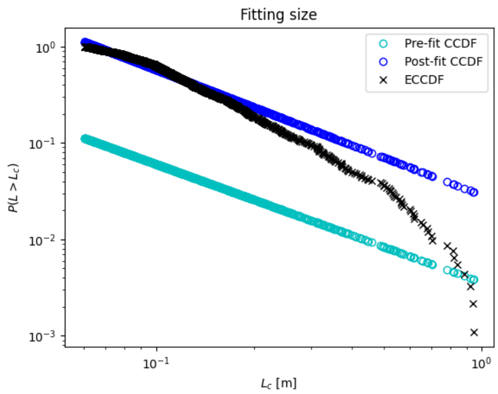

Figure 14 Pre-calibration (light blue circles) and post-calibration (blue circles) COLBUSS model for the complementary cumulative distribution function of the characteristic sizes of fragments produced after the Fengyun 1C breakup. The data set used for this test is a filtered set of fragments simulated with the NASA SBM (black crosses).

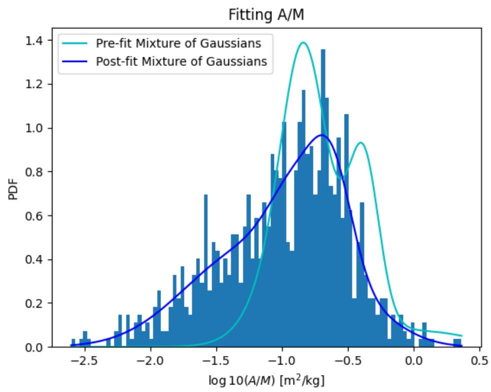

Figure 15 Pre-calibration (light blue curve) and post-calibration (blue curve) COLBUSS model for the A/M probability distribution function, compared with the normalized histogram obtained from the data set for Fengyun 1C breakup.

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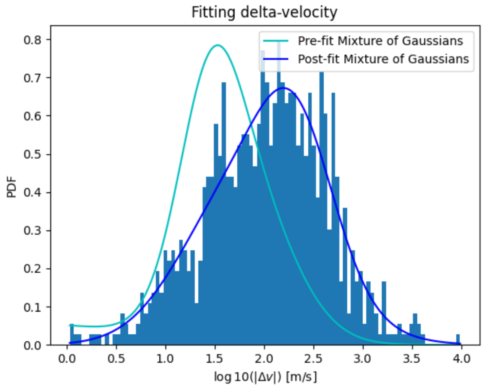

Figure 16 Pre-calibration (light blue curve) and post-calibration (blue curve) COLBUSS model probability distribution function of the delta-velocity modules of fragments generated from the Fengyun 1C breakup, compared with the normalised histogram obtained from the data set.

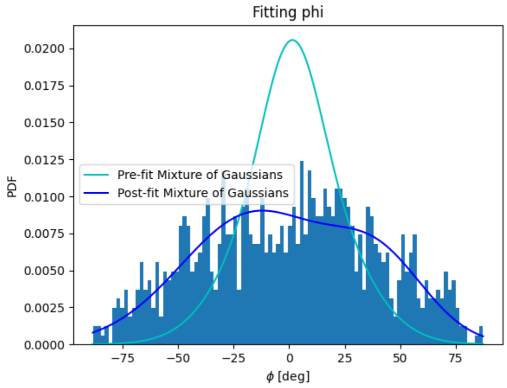

Figure 17 Pre-calibration (light blue curve) and post-calibration (blue curve) COLBUSS model probability distribution function for one of the direction angles of delta-velocity, compared with the normalized histogram obtained from the data set for Fengyun 1C breakup.

3.4 Cloud propagation module

The Cloud Propagation module (PRO) computes the time evolution of a debris cloud's fragments orbits, returning the fragments orbits time history in a given time window. The module utilizes the Orekit library [14] to compute fragments orbits time propagation. Three options are allowed for the choice of the orbit propagation method: numerical propagation [15], semi-analytical propagation (DSST) [16] and analytical propagation (SGP4) [17]. The methods provide different trade-offs between accuracy and computational cost, ranging from high accuracy and cost (numerical propagation) to very low cost but somewhat limited accuracy (SGP4), with the DSST method in the middle. Integration and force fields parameters of numerical and semi-analytical methods can be customized, allowing for further optimization of the accuracy/cost balance.

The Orekit library is embedded in OFELIA, through the implementation of the needed interfaces in Python. Orbits can be taken in input and returned in output as TLEs or with the format they are given in output by the BUM module. In particular the PRO module can optionally provide in output the cloud density time evolution in the format required for the Observability Metric module. Parameters defining the computed cloud density can be specified in the density section of the configuration file.

Example of simulated clouds propagated with this module are shown in Figure 18 to Figure 21 for the Fengyun 1C and the NOAA 16 breakups simulated with POEM after calibration by the BUM module.

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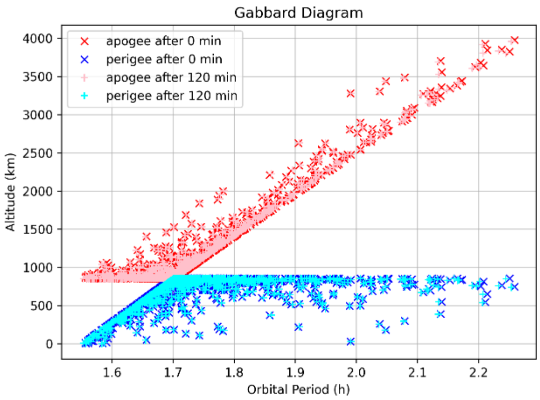

Figure 18 Gabbard Diagrams for the Fengyun 1C fragments simulated with the BUM module using the calibrated POEM model. Two diagrams are represented, the one at the time of breakup and the one after 120 minutes of propagation by the PRO module.

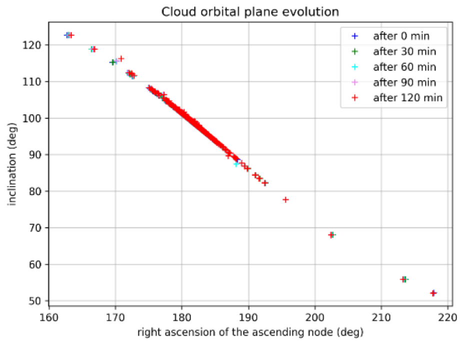

Figure 19 Representation of orbital plane dispersion obtained in 120 minutes of propagation of the cloud of fragments of the Fengyun 1C breakup simulated with the POEM calibrated model and propagated by the PRO module.

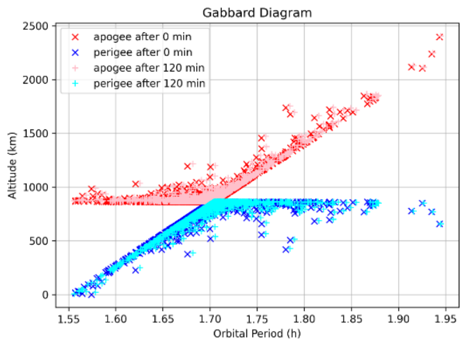

Figure 20 Gabbard Diagrams for the NOAA 16 fragments simulated with the BUM module using the calibrated POEM model. Two diagrams are represented, the one at the time of breakup and the one after 120 minutes of propagation by the PRO module.

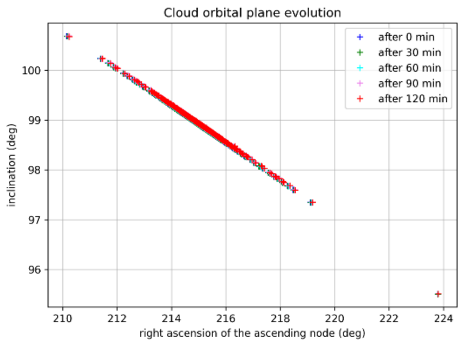

Figure 21 Representation of orbital plane dispersion in the RAAN-inclination plane, obtained in 120 minutes of propagation of the cloud of fragments of the NOAA 16 breakup simulated with the POEM calibrated model and propagated by the PRO module.

3.5 Observability metric module

The observability metric module within the OFELIA tool implements a two-stage framework for characterizing a ground-based sensor network performance in monitoring a fragmentation event in terms of spatial coverage and resolution.
In the first stage, the Spatial Position Metric (SPM) is computed by applying weighting factors from the Fragmentation Environmental Index (FEI) [18] to fragments discretized via a continuum-based propagation model [19]. At each epoch, debris densities are binned in phase space and subjected to visibility constraints, such as topocentric azimuth/elevation bounds, range and range-rate thresholds, blocking zones and Sun/Moon separation angles. For optical sensors, each visible bin weight derives from normalized irradiance and angular velocity components; for radar sensors, is obtained from signal-to-noise ratio relative to a minimum detectable size. Summation of the weights over all visible fragments yields a time-varying SPM, while a quality coverage index integrates the number of observable fragments with aggregate weights to produce a preliminary sensor ranking.
In the second stage, the Resolution Capability Metric (RCM) quantifies each sensor ability to resolve individual fragments. Three-dimensional spatial densities within visible bins are interpolated and projected onto the sensor

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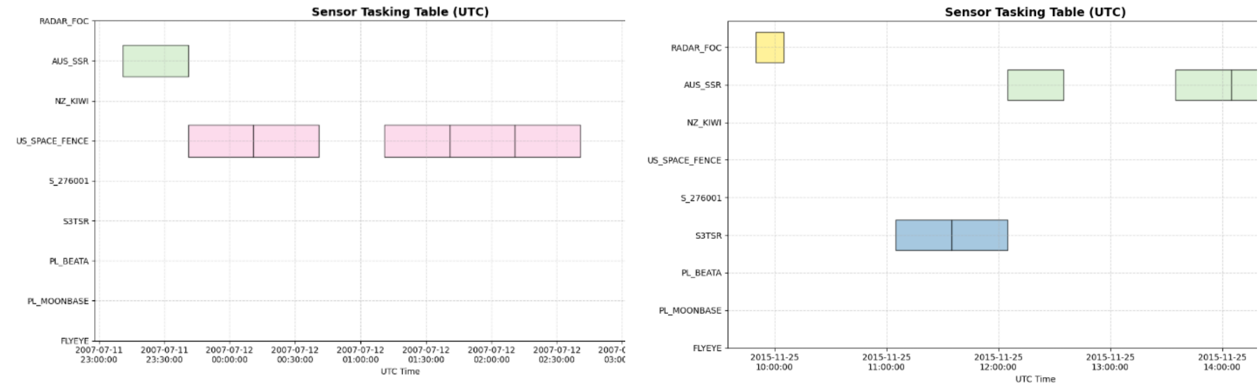
topocentric frame, converting volume densities into two-dimensional densities. Comparison of these densities against sensor angular resolution limits identifies the number of resolvable fragments per bin; the RCM at each epoch is defined as the sum of resolvable fragment counts. This process enables the Sensor tasking module to select the most suitable sensor and define optimal observation windows, ensuring comprehensive detection coverage and high-resolution fragment characterization across the monitoring network.
Observability metric routines were applied to the two test cases-the Fengyun 1C and NOAA 16 fragmentation events-with suggested tasking tables computed for the five hours following each breakup. The resulting tasking intervals (Figure 22) enable identification of the sensors yielding the maximum number of resolved fragments at each epoch, in accordance with both SPM and RCM figures of merit. In the Fengyun 1C scenario, Sensor 4 achieved the highest overall coverage and, at peak times, resolved over 140 visible fragments within its field of regard; in the NOAA 16 case, four sensors exhibited comparable top-tier coverage and resolution performance, designating them as the most suitable assets for fragment-cloud monitoring.



(a) Fengyun 1C.

(b) NOAA 16.

Figure 22 Suggested tasking table computed through the observability metric module, for the two test cases under analysis.

3.6 Sensor tasking module

Sensor tasking module within OFELIA is responsible for producing scheduling for available sensors based on observation windows returned by the Observability metric module.
First, the Sensor tasking module filters the time windows during which the sensors are available, as specified by the user. Then, the module reads all snapshots containing binned density data for each time window and projects this data onto the corresponding sensor's topocentric frame.
Next, the module estimates the spatial density of fragments using the weighted Kernel Density Estimation (KDE) method with a Gaussian kernel function and the spatial density of bins as weights. Estimating the density using the KDE method results in a smooth azimuth and elevation dependent function, enhancing the optimizer's ability to converge to a solution. The KDE method does not require any assumptions about the original density distribution. The estimated density map and binned spatial density data are shown in Figure 1.
The resulting density map is then used by the pointing optimizer. For the optimization process, the Particle Swarm Optimsation method is employed [20]. This method is efficient in handling nonlinear optimization problems, does not require the objective function to be differentiable, and does not need a good initial guess. The optimization problem is defined as maximizing the cumulative density in a region visible to the sensor across all snapshots for a given pointing, defined in azimuth/elevation coordinates.
The results of the module are lists of optimized observation requests. Each request includes a start and end date, as well as azimuth/elevation pointing. An example result is shown in Figure 23. Figure 24 illustrates an example of optimised pointing on the KDE-estimated density map, while Figure 25 shows the same pointing in the binned density data scatter plot.

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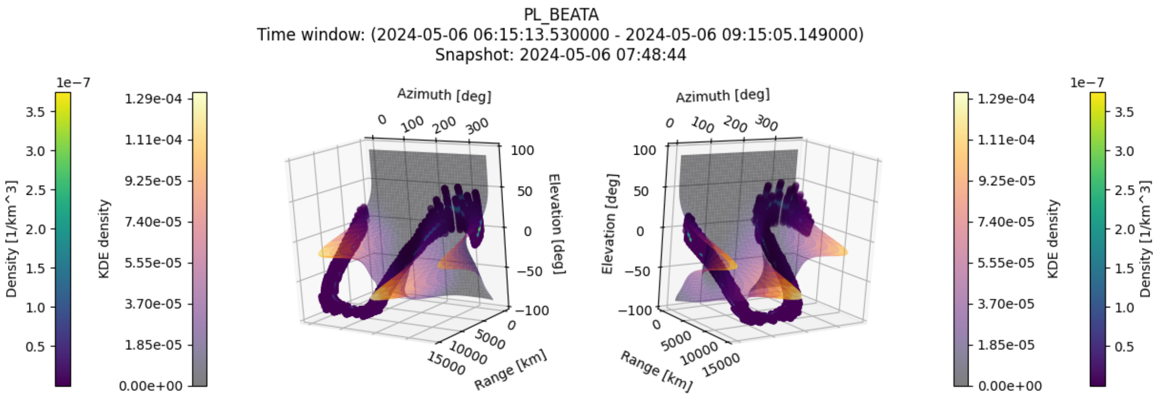
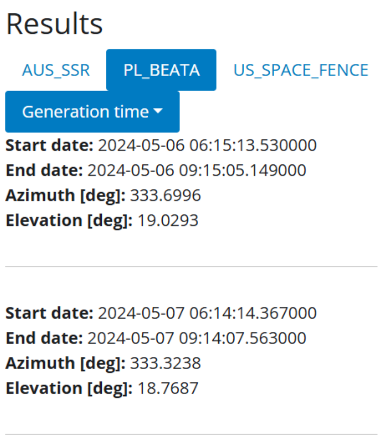


Figure 23 Fragments density in time window and density map estimated using KDE.



(a) Result in GUI.


```xml
<?xml version='1.0' encoding='UTF-8'?>
<Observation_Request>
  <observations>
    <observation>
      <Start_Date>2024-05-06T06:15:13.530000</Start_Date>
      <End_Date>2024-05-06T09:15:05.149000</End_Date>
      <Az>333.6995676666112</Az>
      <El>19.02930867904925</El>
    </observation>
    <observation>
      <Start_Date>2024-05-07T06:14:14.367000</Start_Date>
      <End_Date>2024-05-07T09:14:07.563000</End_Date>
      <Az>333.3237776858423</Az>
      <El>18.768723570932075</El>
    </observation>
  </observations>
</Observation_Request>
```


(b) Result as XML output file.

Table 2 Example of sensor tasking module output.

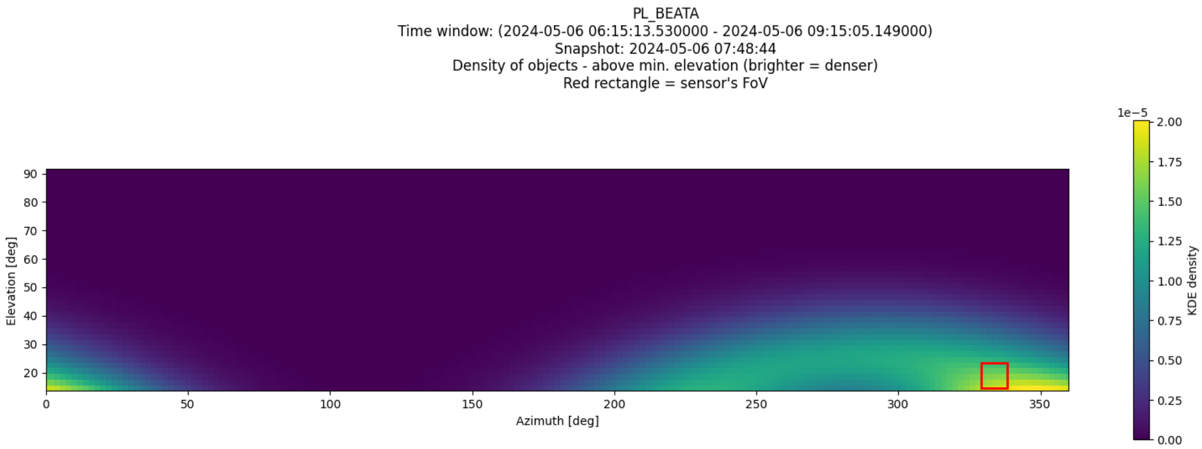


Figure 24 Example of optimised pointing shown on the estimated density map (above sensor's minimum elevation).

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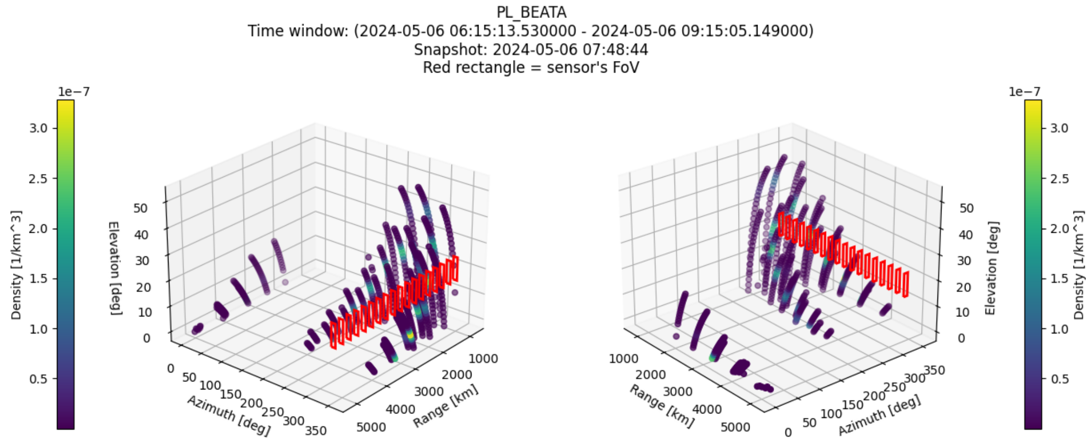

Figure 25 Example optimized pointing shown on the binned density data

3.7 Fragment characterisation module

The Fragment characterisation module is responsible for processing incoming observational data in form of TDM files and generating TLE files for new fragments. The module is split into two stages: track-to-orbit and track-to-track association.

The track-to-orbit association stage is responsible for detecting whether observation data can be correlated with an already catalogued object. The track-to-orbit correlation is determined using a Mahalanobis norm between observations and estimated observations based on the objects TLE file. If the calculated norm is smaller than the threshold for at least one object in the catalogue, it is assumed that the new observations can be correlated with an already known object. Observations that cannot be correlated with any object in the catalogue are then processed in the track-to-track association stage.

The track-to-track association stage processes observations that are not correlated with any known objects. Before addressing the methodology, it is necessary to define some terms used to describe it:

- Measurement – single value of a geometrical or physical property of an object observed by the sensor at certain time,
- Observation – set of measurements gathered by a single sensor at common time,
- Track – set of observations gathered by the same sensor during a period of time of continuous observation of an object,
- Hypothesis – association of n tracks assumed to originate from the same object.

The track-to-track association stage is based on the work [21]. In the methodology, tracks are associated sequentially on a first-come, first-served basis. When a new track arrives in the system, the first step is the generation of new hypotheses, involving not only this track but also previous hypotheses, i.e., associations with previous tracks. During the estimation step, the orbit determination solution and solution residuals are updated for every hypothesis. After that, the scoring step calculates the figure of merit (Mahalanobis norm) based on the residuals of the hypotheses' solutions. Then, the pruning step discards hypotheses whose figure of merit exceeds given thresholds, indicating that the hypothesis is clearly false. The hypotheses that are not rejected in the pruning step are processed in the promotion step. The promotion step identifies those hypotheses with enough information (i.e., number of associated tracks) and whose figure of merit suggests that the associated tracks are likely to belong to the same object.

After promoting hypothesis that merging step is performed. It is responsible for combining already promoted hypotheses to avoid the addition of duplicated objects to the catalogue, i.e., two different promoted hypotheses corresponding to the same object.

When all the steps of the track-to-track association stage are completed, TLE files are generated based on the promoted hypotheses. In addition to the TLE files, the module also outputs area-to-mass ratio, size, and mass estimates based on RCS/visual magnitude measurements for every object added to the catalogue.

The module was applied to a set of five tracks, resulting in a single TLE generated from the association of four tracks from the dataset. The resulting TLE file is presented in Figure 26, and the resulting catalogue displayed in the GUI is shown in Figure 27. The area-to-mass ratio, size, and mass estimates for the identified object are presented in Figure 28 and Figure 29 in the module's GUI.

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```
1 00001U 09000    09065.84149508  .00000000  00000-0  51226-3 0    01
2 00001  86.3634 111.0305 0014610  80.2592 320.8830 14.34120795    13
```

Figure 26 Resulting TLE file

Catalogue

ID	Epoch	B star	Inclination [deg]	RAAN [deg]	Eccentricity	Argument of perigee [deg]	Mean anomaly [deg]	Mean motion [revs/day]
00000001	2009-03-06 20:11:45.174912	0.0005123	86.36	111	0.001461	80.26	320.9	14.34

Figure 27 Resulting catalogue in GUI

```
!! File of fragments
!! =================
!! identifier area/mass[m^2/kg] size[m] mass[kg] Delta-V [km/s]
00000001 5.345331e-02 5.612374e-02 1.851265e-01 -
```

Figure 28 Catalogued fragments additional data

Catalogued fragments data

ID	Area to mass ratio [kg/m2]	Size [m]	Mass [kg]
00000001	5.345331e-02	5.612374e-02	1.851265e-01

Figure 29 Catalogued fragments additional data in GUI

4 Conclusions

The OFELIA – Orbital Fragmentation rEconstruction moduLe for forensIcs Analysis – tool devised to integrate in a unique tool the different functionalities needed for on-orbit break-up reconstruction and characterisation was described. The overall structure of the software is explained together with the functionality of each module. Preliminary results of some of the modules are shown applied to recent fragmentations.
The paper is structured as follows: first, an introduction to the operating modes of OFELIA is given in Section 2, then the test cases are described and used to test the single modules composing the tool in Section 3. Lastly, conclusions are drawn, and future steps are described in Section 4.

5 Acknowledgments

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