Bringing in break-up events within a space objects catalogue

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1 Introduction

The 18th Space Defense Squadron (SDS) maintains one of the most complete and publicly available catalogue of space objects. It is published on Space-Track [1] and contains more than 25,000 objects of which more than half are classified as fragmentation debris. With the improvements in the Space Surveillance and Tracking (SST) sensor technologies, it is expected a significant increase in complexity of catalogue build-up and maintenance activities.

Break-up events represent the dominant source of objects in space catalogues. The number of such events includes explosions, collisions or anomalous events resulting in fragmentation and is estimated to be higher than 630 known events until now [2]. The contribution of each event towards the overall space objects population is complex and diverse. Two of the most massive events, involving a number of fragments in the order of the thousand are the Fengyun 1C anti-satellite weapon test in 2007 and the accidental collision of Cosmos 2251 and Iridium 33 in 2009, accounting for over 30% of all catalogued space objects until December 2021. In 2021, three main break-up events happened: the failure of NOAA 17 (10th March), an accidental collision of YunHai 1-02 with a small mission-related debris object (18th March) and the destruction of Cosmos 1408 in an anti-satellite weapon test (15th November). As of today, the number of detected and catalogued fragments by the 18th SDS associated to these events is 115 (1 decayed), 37 (4 decayed) and 1561 (243 decayed) objects respectively [1].

The early detection of the fragments generated during these irregular events, almost four per year on average over the last decade, poses a complex challenge for space objects catalogue build-up and maintenance processes. Fragments are a dense cloud of debris, making the identification of individual objects difficult. Then, a trade-off between detection time and reliability arises, where time favours the spreading of the objects along the orbit, thus reducing the probability of false associations and the uncertainty of the estimated trajectories. Latter step could be performed when sufficient data is available. However, the provision of Space Situational Awareness (SSA) products and services during the few first days after a break-up event can be crucial to avoid collisions between the fragments and other space objects, particularly in highly congested regimes, as in Low Earth Orbit (LEO). Reducing the time required to establish the trajectories of the fragments may enable the execution of collision avoidance manoeuvres of operational satellites with manoeuvre capabilities, and analyse potential collision cascade events which may endanger the space environment. The evolution of the cataloguing process of the fragments from Cosmos 1408 is a clear example of this complexity: 185 fragments detected and catalogued two weeks after the event (1st December), 718 the next month (903 total as of 1st January) and 494 the month following that (1397 total as of 1st February) [9]. Figure 1 [6] shows the number of tracked fragments for which orbit data was published on Space-Track [1].

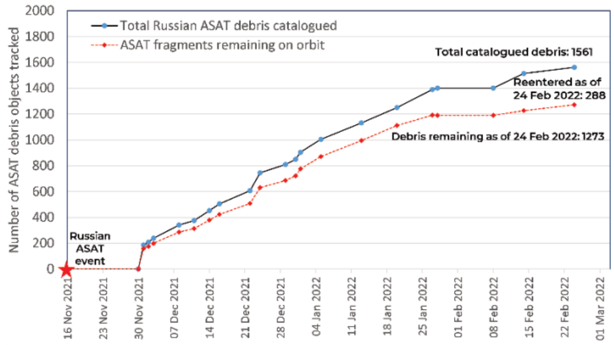

Figure 1: Cosmos 1408 debris fragments tracked to date [6].

This work tackles the whole cataloguing process after a break-up event, starting from a catalogue with no fragments from the fragmentation under-analysis, and until a well-established orbit is obtained for all the fragments. The procedure makes use of a ground-

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based radar sensor network, as well as the subsequent maintenance of the orbits. Association and catalogue maintenance performance is analysed on a time basis. This includes the confusion matrix evolution (true positives, false positives, and false negatives) during both the track-to-track and track-to-orbit as well as the accuracy of the estimated tr the fragments. The considered metrics a ating the robustness and efficiency of the conceived for real operational environme include the distributions of the figure of hypotheses during the association proces sociation process is formulated as a functi elements, association time and time sinc up, among other attributes identified spe mentation events. In addition, the tempo of the accuracy of the catalogued orbits and discussed, along with their correspo tainty.

2 Simulated dataset

Given the lack of publicly available sensin the Cosmos 1408 break-up event, the p fragments have been simulated. Since th yses on the resulting debris cloud sugges bution of fragments not matching the Na nautics and Space Administration (NAS Breakup Model (SBM) [5], we have u available Two Line Elements (TLEs) [1] to simulate the fragments trajectory. Firstly, Cosmos 1408 TLE data was fitted to obtain a state vector at the pinch point (15^{th} November 2021 at around 2:50 UTC [4, 3]). Secondly, the delta-v of each of the fragments (with respect to the parent object state at the pinch point) was obtained using TLE data as observations. Thirdly, trajectories of all the fragments were obtained by propagating the previously obtained states with a high-fidelity dynamical model. The resulting fragments' trajectories distributions and its consistencies are compared against NASA SBM and publicly available Gabbard plots. Finally, observations from a ground-based sensor network are simulated, including standard known sensor measurement noises.

3 Methodology

The simulated observations, packed as tracks, are provided to an operational multi-sensor multi-target track-to-track association framework [8] in charge of grouping tracks belonging to the same objects. In this context, a hypothesis, $\mathcal{H}$, represents an association of N tracks, $\{\mathcal{T}_i\}_{i=1,\ldots,N}$, assumed to have been originated from a common object. To resolve the ambiguity, particularly shortly after the event, hypotheses are generated, scored, pruned, and promoted, as shown in Figure 2 [8], leading to the initialisation of new objects in the catalogue. These steps include several gating and complexity reduction techniques to filter out most of the false hypotheses and thus avoid a brute-force approach.

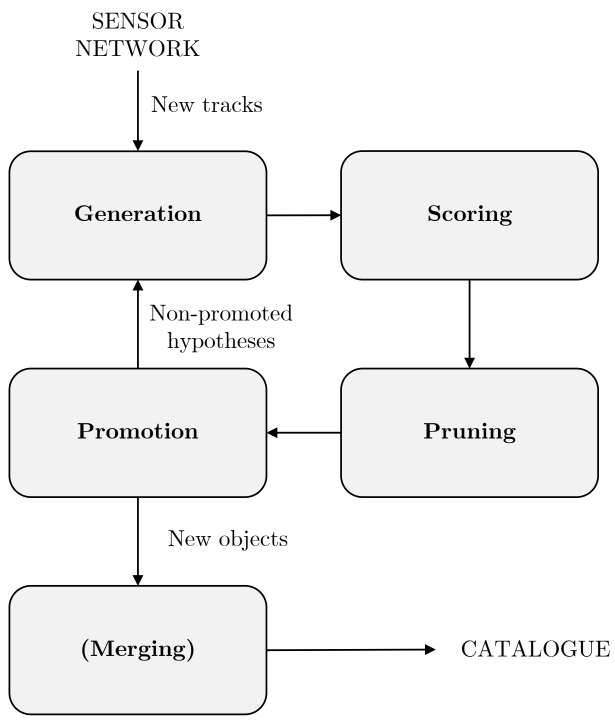

Figure 2: Steps of the track-to-track association methodology [8].

The generation step is in charge of creating new hypotheses by combining two already existing ones. Therefore, from two hypotheses of N tracks, $\mathcal{H}_A$ and $\mathcal{H}_B$, a new one, $\mathcal{H}_A \cup \mathcal{H}_B$, of $N+1$ tracks is generated, i.e.:

$$\begin{aligned} \mathcal{H}_A \cup \mathcal{H}_B &= \left\{ \bigcup_{k=1}^{N-1} \mathcal{T}_k \right\} \cup \{\mathcal{T}_{A,N}\} \cup \{\mathcal{T}_{B,N}\} \\ \mathcal{T}_k &= \mathcal{T}_{A,k} = \mathcal{T}_{B,k} \qquad \forall k = 1,\ldots,N-1 \end{aligned} \tag{1}$$

where $\mathcal{T}_{\alpha,k}$ is the k-th associated track of $\mathcal{H}_\alpha$. Note that according to the condition imposed before on the number of tracks of the new hypothesis, it is required that $\mathcal{H}_A$ and $\mathcal{H}_B$ have all but one track (N-th) in common.

Not all possible track combinations are considered during hypotheses generation since it would lead to a computationally unaffordable growth of the hypotheses tree. The following gating criteria are considered in this step:

1. Lower bound time span: the time span between the associated tracks must be higher than a certain fraction of the average orbital period, to

avoid associating tracks that are not sufficiently spaced in time (undesirable situation in terms of orbit observability).

2. Upper bound time span: the time span between the associated tracks must be lower than certain number of days to avoid dynamical model mismatching.

3. Estimated state difference: the difference between the estimated states is evaluated to avoid combining two associations that clearly belong to different orbital regions.

The figure of merit used for the scoring of a hypothesis consists in the difference between the actual observations, $\boldsymbol{z}$, and the a-posteriori computed observations, $\hat{\boldsymbol{z}}$, projected on the a-priori measurement covariance $\boldsymbol{P}_z^0$ [8], i.e.:

$$d^2\left(\mathcal{H}\right) = \frac{1}{|\mathcal{H}|}\sum_{\mathcal{T}\in\mathcal{H}}\frac{1}{|\mathcal{T}|}\sum_{\boldsymbol{z}\in\mathcal{T}}\left(\boldsymbol{z}-\hat{\boldsymbol{z}}\right)^T\left(\boldsymbol{P}_z^0\right)^{-1}\left(\boldsymbol{z}-\hat{\boldsymbol{z}}\right) \tag{2}$$

where $\boldsymbol{P}_z^0$ is the a-priori covariance of the measurements, a diagonal matrix containing the squared sigma of the expected noise of each measurement of the corresponding observation, assumed to be zero-mean Gaussian, and $|\cdot|$ denotes cardinality. Note that this figure of merit is a reduced chi-squared statistic (when the number of observations is much greater than the number of estimated parameters) and can also be seen as a Mahalanobis distance but evaluated in the measurement space rather than in the orbit space and projected in the a-priori covariance space. This figure of merit is used for hard decisions, such as hypothesis pruning (upper-bound threshold) and hypothesis promotion (lower-bound threshold).

This work follows [7] but considering radar instead of optical sensors and thus, a more challenging scenario from the cataloguing point of view given the greater number of fragments and dynamical model complexity: LEO instead of Geostationary Earth Orbit (GEO). Besides, not only the catalogue build-up process is tackled but also the maintenance counterpart. To do so, once the fragments are detected and catalogued, we correlate incoming tracks with the orbits via track-to-orbit association and update the estimated trajectory via orbit determination. This alleviates the track-to-track association and enables the update of the orbital estimates, required for maintaining the catalogue.

Finally, the use of dynamical models of varying fidelity, including analytical, semi-analytical and numerical propagators, during the track-to-track association, track-to-orbit correlation and orbit determination processes is investigated to enable a real-time capability while not jeopardising the accuracy of the final SSA products.

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