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# Observation and analysis of Cosmos 1408 fragmentation.

**Andrea Muciaccia[a]*, Luca Facchini[a], Marco Felice Montaruli[a], Giovanni Purpura[a], Roberto Detomaso[a], Camilla Colombo[a], Mauro Massari[a], Pierluigi Di Lizia[a], Alessandra Di Cecco[b], Luca Salotti[b], Germano Bianchi[c]**

[a] *Department of Aerospace Science and Technology, Politecnico di Milano, Via Giuseppe La Masa 34, 20156, Milan, Italy,* andrea.muciaccia@polimi.it
[b] *Agenzia Spaziale Italiana (ASI), Via del Politecnico snc, 00133, Rome, Italy*
[c] *Istituto Nazionale di Astrofisica, Istituti di Radioastronomia, Via Gobetti 101, 40127, Bologna, Italy*

* Corresponding Author

**Abstract**

The population of objects in space has increased dramatically over recent decades. Space debris now represents the majority of objects in space resulting from inactive satellites, breakups, collisions and fragmentations. It has become a concern for institutions all over the world and, as such, it has led to the fostering of several programmes to counter the issues. Among these, the use of ground-based sensors for Space Surveillance Tracking (SST) activities and services and tools for analysing fragmentations play a crucial role.
This work presents the activities carried out by Politecnico di Milano, Italian Space Agency and Italian National Institute of Astrophysics in this framework, using data from SST networks and the observation measurements from Bistatic Radar for LEO Survey (BIRALES), an Italian bistatic radar belonging to EUSST, which contributed most to the monitoring of the cloud of fragments. Exploiting TLEs of observed fragments, a reverse engineering approach is used to reconstruct a fragmentation in orbit through the use of the software suite PUZZLE developed at Politecnico di Milano. The analyses focus on studying the fragmentation of the Cosmos 1408 satellite occurred on November 15th 2021, following an Anti-satellite Missile test (ASAT). More than 1000 trackable pieces and millions of smaller debris (estimated from numerical analysis) were produced by this event, increasing the population of inactive objects around the Earth, and threatening nearby orbiting objects.
First, the processing method adopted from BIRALES in observing Cosmos debris is presented and discussed and a critical analysis about the derivable information is conducted. Then, these data and those from SST networks observations are used to identify the epoch and the location of the fragmentation. In this procedure, the software toolkit PUZZLE, developed by Politecnico di Milano within a project funded by the Italian Space Agency and extended through the European Research Council, is used.
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**Keywords:** Space debris, Low Earth Orbit, Fragmentation, Space Surveillance & Tracking, Radar

## Acronyms/Abbreviations

| | |
|---|---|
| ASAT | Anti-Satellite Test |
| ASI | Italian Space Agency |
| BIRALES | BIstastic RAdar for LEo Survey |
| CW | Continuous Wave |
| FMCW | Frequency Modulated Continuous Wave |
| EUSST | EUropean Space Surveillance and Tracking |
| FoV | Field of View |
| INAF | Italian National Institute of Astrophysics |
| LEO | Low Earth Orbit |
| RSO | Resident Space Objects |
| SGP4 | Simplified perturbations model 4 |
| RCS | Radar Cross Section |
| SNR | Signal-to-Noise Ratio |
| SST | Space Surveillance & Tracking |
| TDM | Tracking Data Message |
| TLE | Two-Line Element |
| TRF | Radio Frequency Transmitter |

## 1. Introduction

Over the last decades, man-made satellites have become valuable assets for different purposes, from science and research, to observation, telecommunication, navigation, as well as for military purposes. The number of launches has steadily increased in the last few years and hence the number of orbiting objects. Currently, almost 9000 satellites are still in space, but the overall population of Resident Space Objects (RSO) consists of more than 31000 objects greater than 10 cm. This is because the majority of RSO is made of space debris, and it is estimated that the number exceeds 130 million for pieces smaller than 1 cm [1]. The increasing threat of potential collisions that would damage active satellites and create new debris, as well as the risk of uncontrolled re-entries that could damage ground infrastructure, has thus led to the development of space surveillance networks and Space Surveillance & Tracking (SST) initiatives to mitigate these risks, catalogue new objects, and provide information and services to stakeholders. Most of the debris were generated from over 600 recorded fragmentation events, the most notable ones being the 2007 Fengyun-1C Anti-Satellite Test (ASAT), the Iridium 33/Cosmos 2251 collision in 2009, and the recent Cosmos 1408 ASAT, occurred on 2021-11-15 at around 02:47 UTC [2], which resulted in more than 1000 new pieces of debris. This paper focuses on the observations of the Cosmos 1408 breakup performed by Politecnico di Milano, the Italian National Institute of Astrophysics (INAF) and the Italian Space Agency ASI and details the use of the PUZZLE software for the characterisation of the fragmentation.

The paper is organised as follows: Section 2 describes the BIRALES sensor architecture, Section 3 describes the PUZZLE model and its updated versions, Section **Error! Reference source not found.** presents t he analyses carried out with BIRALES and PUZZLE on the Cosmos 1408 fragmentation, and Section 5 summarises the main results.

## 2. BIRALES sensor

BIstasti RAdar for LEo Survey, or simply BIRALES, is one of the Italian radar sensors belonging to the EUropean Space Surveillance and Tracking (EUSST) framework.

The transmitter, Radio Frequency Transmitter (TRF), is a 7 m wide parabolic antenna located at the Italian Joint Test Range of Salto di Quirra in Sardinia. The receiver is part of the Northern Cross radiotelescope, situated at the Medicina Radio Astronomical station where it is operated by INAF. In this case the antenna consists of an array of 8 parallel cylinders, each 23.5 m long and 7.5 m wide, arranged along the North-South directions. Each cylinder contains 4 receiver elements along its focal line, hence a total of 32 receivers are available, as shown in Figure 1. The cylinders can be moved only in declination and their pointing remains unchanged throughout the observation.

The radar couples two different systems: the TRF can transmit a Frequency Modulated Continuous Wave (FMCW) chirp centred at 412.5 MHz and with 4 MHz bandwidth and/or an unmodulated Continuous Wave (CW) signal at 410.085 MHz. The former system is used to measure the range of the targets, while the latter provides Doppler measurements. A total maximum power of 5 kW can be supplied, and it can be split as needed between the two signals according to the observations needs, i.e. to increase the sensitivity of one of the two systems. Range processing is performed by combining the received data from 3 cylinders (12 elements) into a single analog beam; instead, Doppler measurements are obtained exploiting multiple digital beams formed combining all 32 elements. In this way it is possible to cover the complete receiver Field of View (FoV) that spans about 6° in both North-South and East-West directions.

However, due to the sensor's arrangement, grating lobes are present in any receiver beams and so it is difficult to determine which lobe is illuminated (which is linked to the angular position of the object). A more detailed description of BIRALES architecture and a planned upgrade to derive the angular track is provided in [3].

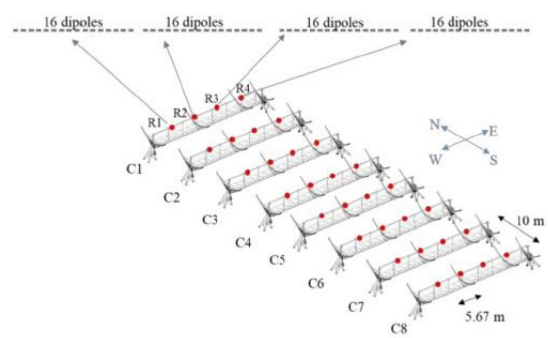


*Figure 1. BIRALES receiver configuration.*

## 3. PUZZLE

PUZZLE is a software toolkit developed at Politecnico di Milano [4], initially under a contract with ASI, and later improved, under an ERC project, including a long-term analysis [5] and uncertainty propagation [6]. The objective is to identify which objects, included in a set from a catalogue, originated via a breakup and, whenever a fragmentation is identified, to characterise it in terms of position and epoch of the event. Moreover, the software has a routine to model the fragmentation to identify the orbital regions at risk of possible collisions in the future.

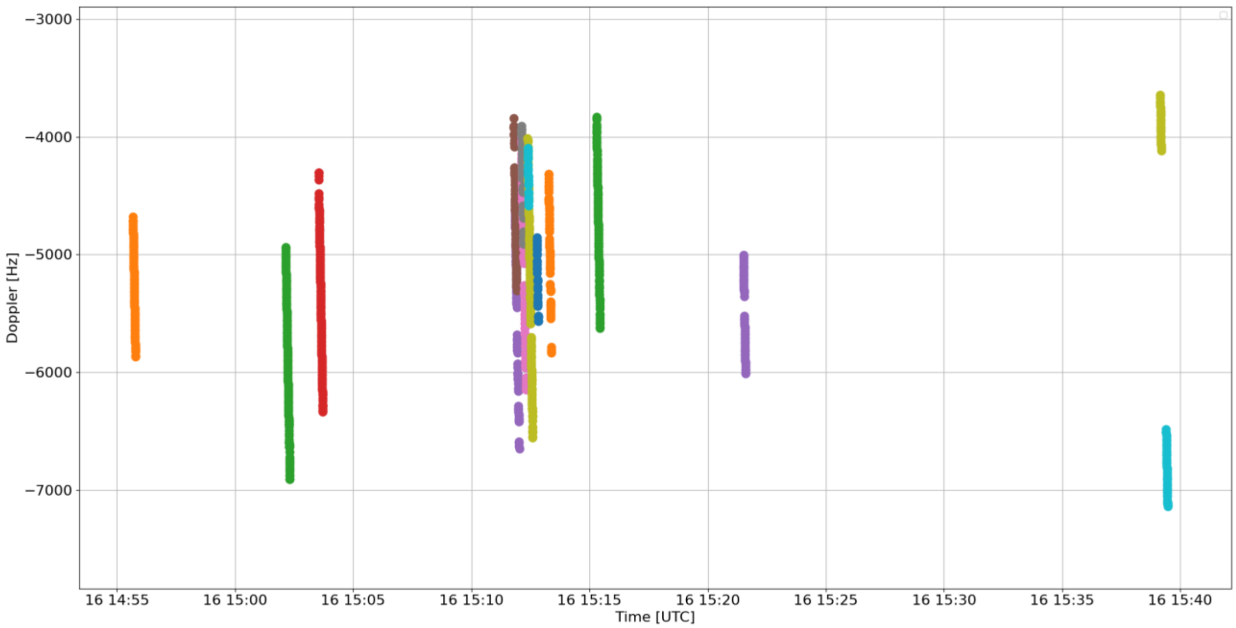


*Figure 2. BIRALES detections on November 16th 2021.*

The model investigates the evolution of the orbits of a set of unclassified objects in the form of Two-Line Element (TLE) (retrieved from daily catalogues) by propagating them backwards (using the SGP4 [7] [8]) and searching for possible clustering of objects, that could represent a fragmentation. The propagation is coupled with pruning and clustering algorithms (e.g., geometrical filters exploiting the minimum orbit intersection distance [9] or the hierarchical clustering method [10]) used to identify close approaches between the analysed objects and to remove the undesired ones. The close encounters are then used to find epochs characterised by concentration of fragments, which are considered as fragmentation. In case the latter is detected, the information on the location and time of the event are used to scan a set of active or inactive objects (both spacecraft and rocket bodies) to associate the parent(s) that generated the found fragments. In the end, the NASA standard breakup model [11] is used to estimate the area-to-mass and relative velocity distributions of the ejecta fragments to model the fragmentation. It is important to state that the entire procedure is carried out without assuming a priori any recent breakup event. In addition, the initial set of TLEs is scanned through a filter to remove possible outliers from the process.

PUZZLE was further improved including uncertainty propagation inside the routine [6]. A hybrid non-linear uncertainty propagator was developed, coupling gaussian mixture model and unscented transformation algorithms. The former is used to split the initial Gaussian normal distribution associated to the state and a given value of uncertainty of an object into a sum of N kernels, which are then used to generate additional TLEs to be backward propagated with the nominal one. The unscented transformation algorithm is instead exploited to improve the performances of the parent(s) identification routine, where objects families and their correspondent parent(s) are identified.

## 4. Analyses for reconstructing an ASAT event

The aim of the following analyses is to reconstruct the fragmentation of the Cosmos 1408, occurred on November 15th 2021.

Section 4.1 describes the analysis performed using the TLEs from a catalogue to see if PUZZLE can associate the TLEs to the fragmentation. Then, Section 4.2 and Section 4.3 presents the analyses on the observations with BIRALES and the reverse engineering study to reconstruct the fragmentation with PUZZLE using the TLEs produced with those observations.

### *4.1 Fragmentation detection using TLEs from a catalogue*

The first analysis presented in this section is performed including in the initial set the TLEs associated to the Cosmos 1408 fragmentation, only. Then, a second test is presented in which additional TLEs were added to those associated to the Cosmos 1408 fragmentation.

*4.1.1 Cosmos 1408 TLEs*

The first analysis focuses on a set of objects comprising only the TLEs of the Cosmos 1408 debris, released by SpaceTrack [12] on 1 December 2021 (first available data), 16 days after the event. The catalogue includes 185 objects associated to the fragmentation. The objectives are to verify that the software can identify the fragmentation and to count how many fragments can be included in the final set. The analysis is carried out playing with one of the input parameters, that is the close encounters distance margin. This parameter states whether the close encounter between two analysed objects can be considered for the investigation of the event location (i.e., if the objects can be considered close enough) or not. The selection of small values is typically required to avoid the count of many close encounters which do not represent real cluster of objects. However, being the propagation time near the limit in terms of accuracy for the SGP4 propagator and knowing a priori that the fragments belong to the fragmentation, it is possible to enlarge the distance margin for the test. Figure 3 shows the results of the analysis. Choosing a lower distance margin implies a lower number of identified fragments (34 of 185 with 10 km). However, by enlarging this value, it is possible to include up to 112 fragments (i.e., ~ 60%).

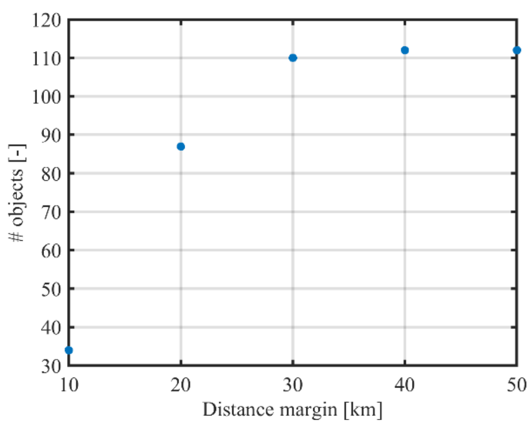


*Figure 3. Number of objects identified as function of the close encounters distance margin.*

It is important to mention that selecting wider margins for all the filtering parameters (not investigated in this work) could lead to an increase in the number of included objects.

Finally, all the simulations estimated the epoch of the event on November 15th 2021 at 02:47 UTC ± 1.67 min.

*4.1.2 Cosmos 1408 and additional TLEs*

A test was then performed considering a set of objects including the Cosmos 1408 and 24 of its debris along with TLEs of known objects available on SpaceTrack on 1 December 2021. The fragmentation is searched for within the 17 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 TLEs set is composed of 1588 TLEs referring to 745 unique objects from different orbital regions. Table 1 shows the main parameters used for the analysis and the main results.

*Table 1. Main parameters used to detect the Cosmos 1408 breakup and main results.*

| | |
|---|---|
| Initial size of TLE set | ~ 1600 |
| Date of generation | 1st December 2021 |
| Time interval selected | 17 days |
| Estimated epoch of the event | 15th November 2021, 02:47:59 |
| Number of objects involved | 24 |
| Probable parent object(s) | Cosmos 1408 (ID 13552) |
| Computational time | 8.3 min |

617 TLEs passed the filtering steps (more detail about them in [4]), including all those related to the fragmentation. Then, setting the close encounters distance margin to 20 km, the software correctly detected the fragmentation (estimation of the event epoch in Table 1). Figure 4 shows the close approaches below 20 km detected within the search time frame.

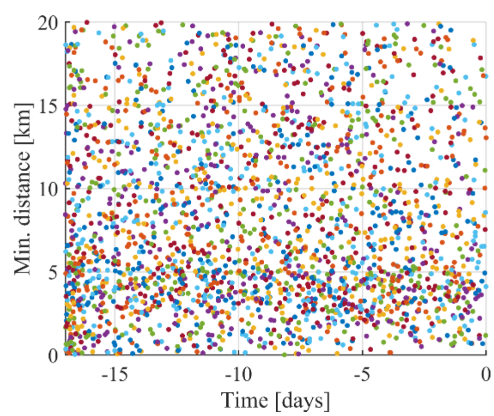


*Figure 4. Distribution in time and distance of the close encounters between the objects - Cosmos 1408 test using SpaceTrack TLEs.*

*4.2 BIRALES observation*

The fragmentation of Cosmos 1408 was monitored by BIRALES in the following days starting on November 16th. The Tracking Data Message (TDM) collected by BIRALES were readily sent to the Italian Air Force who then performed independent analysis.

The strategy adopted was to perform survey observations pointing to the inertial position of Cosmos 1408 at the epoch of fragmentation, where all debris would pass. It was also decided to transmit only the CW signal to maximize the sensitivity. Figure 2 shows the detections seen on November 16th 2021 which are compatible with debris fragments (for reference, the expected Doppler of the parent would have been about -5030 Hz) and for which TDM were produced, although more streaks could be seen in the spectrogram by the operators. A reason for this is that most of them had a very low Signal-to-Noise Ratio (SNR) due to small Rada Cross Section (RCS) which made them difficult to detect.

For each TDM produced an orbit determination process was carried out. The procedure employed was a batch filter minimising the weighted residuals between the real measurements and the values projected from the computed orbit. Different weights were assigned to angles and Doppler measurements, due to the fact that the angular accuracy is lower than that of Doppler measurements. To guarantee the compatibility of the orbit with the parent, the objective function was augmented with an a-priori residual (with a certain weight) that considers the relative position between Cosmos and the backward propagation of the solution at the epoch of fragmentation using SGP4 model. In this way completely unfeasible solutions are penalised but without enforcing an exact constraint to the minimization problem. The reason for not doing so is to take into account that there is an uncertainty in the position where the fragmentation occurred and in the used propagation model, and also because it would make the convergence more difficult. The solutions were searched for by providing the parent TLE as initial guess using the TLE parameters as optimisation variables. Overall, 14 TLEs were obtained which are used in the following analysis. This is because the SGP4 backpropagation becomes more unreliable in the following days. The Gabbard diagram of the corresponding debris is shown in Figure 5.

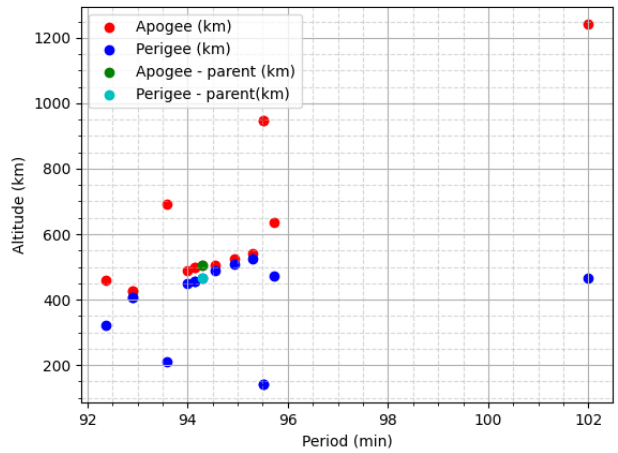


*Figure 5. Gabbard diagram of fragments identified by BIRALES.*

*4.3 Fragmentation detection using BIRALES data*

This test includes now in the initial set the TLEs generated by the observation performed with BIRALES. The objective is to understand whether PUZZLE can identify the fragmentation using this type of data and assess the quality of the TLE data.

First, an analysis was carried out using the original version of the software, thus without the uncertainty propagation. The test considers just the TLEs associated to BIRALES, without adding additional TLEs from other catalogues. The tests gave negative results, probably due to the greater uncertainty associated with this type of data.

A second examination was carried out using the updated version of the software which includes the uncertainties as explained in Section 3. Even with the updated version, the software was initially unable to identify the fragmentation. Further investigations, using a graphical approach, showed that some of the TLEs generated had close encounters far from the event (in particular near the initial date), thus not allowing its proper identification.

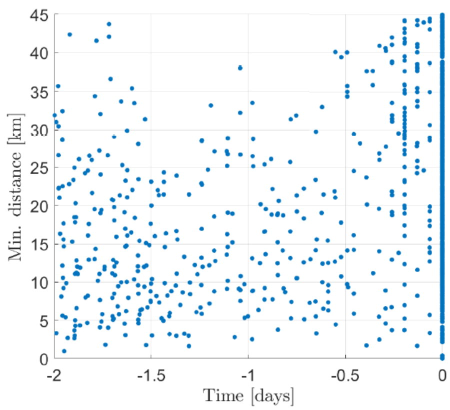


*Figure 6. Distribution in time and distance of the close encounters between the objects – TLE generated using BIRALES observations.*

By removing those objects (5 of 14), the software can identify the fragmentation. Using the input parameters summarised in Table 2, the epoch of the event is estimated on 15 November 2021 at 02.46 UTC ± 1.67 min, including all the 9 objects. 1% of uncertainty was added to each Keplerian orbital element, while 15 kernels were used to generate the additional TLEs to be propagated to search the breakup.

Table 2. Input parameters - PUZZLE with uncertainty propagation.

| Number of objects | Distance margin [km] | Number of kernels | Uncertainty level |
|---|---|---|---|
| 9 | 30 | 15 | 1% |

The distance margin for the close approaches is wide due to the low accuracy of the data. However, selecting a lower value still allows the detection of the fragmentation, but with a greater error in estimating the epoch of the event.

## 5. Conclusions

The increasing levels of human activity in space (e.g., for science or military purposes), along with new mission architecture (e.g., large constellations), have led to an acceleration in the growth of space population around the Earth. This has caused, in parallel, the increase of the of space debris population at an alarming rate. Indeed, this involves more breakup events, some of which are hardly predictable (e.g., collisions), while others even unpredictable (e.g., explosions). The early detection of this events becomes a key objective to keep the population of active objects safe, thus showing the importance of having Space Surveillance Tracking (SST) activities and services. This paper presented the joint work of Politecnico di Milano, ASI and INAF about the COSMOS 1408 fragmentation, showing the methodology adopted and the main results achieved.

The event was monitored by BIRALES and it was possible to retrieve TLE associated to different fragments. Some of the fragments were missed due to small RCS, but in the future, thanks to the upgrade of the full system (transmitting and receiving antennas) and in particular the refurbishment of more cylinders of the Northern Cross that will result in a larger collective area, it will be possible to observe more and smaller fragments (down to a few centimetres). In addition, the implementation of a newly developed processing method is also underway. All these upgrades will result in an improvement of the sensor capability to respond to SST services.

Regarding the software PUZZLE, developed at Politecnico di Milano to reconstruct occurred fragmentations, this event represented an excellent opportunity to test its performances. Results showed that the software is able to identify most of the fragments included in the catalogue, even though the epoch of the TLEs was 16 days after the event (near the limit in terms of accuracy for the SGP4 propagator). Moreover, PUZZLE was able to correctly identify the fragmentation using a set of mixed data (i.e., data related to the fragmentation plus additional random objects). This was also a precious opportunity to test the updated version of the software which includes the uncertainty propagation. Benefits were identified when studying the TLEs generated from BIRALES observations. The basic version was not able to identify the fragmentation, while the updated version was with a good accuracy. However, the availability of more operational data produced nearer to the event could enhance the study process, and hence to show the real capability of the toolkit.

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