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Assessment of the CZ-6A R/B and the H-2A DEB fragmentation events

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Abstract

In the last decades, several Space Surveillance and Tracking (SST) related initiatives have been promoted to tackle the problem of the resident space objects overpopulation and, in particular, of the so-called space debris. Within this framework, the Fragmentation Analysis service of the European SST (EUSST) consortium is managed by the Italian Space Surveillance and Tracking Operation Center (ISOC) - Situational Awareness Centre (CSSA). This work presents the analyses carried out by Politecnico di Milano and ISOC-CSSA, regarding two fragmentations occurred on November 12th and November 17th, 2022, which involved the objects CZ-6A R/B and H-2A DEB respectively.

1. Introduction

In the last decades, in orbit population has become a major issue for space agencies and institutions worldwide. Among orbiting objects, just a small fraction is represented by co-operative satellites and the main part is represented by space debris, which include inactive satellites, rocket bodies, and fragments of all sizes.[4] Space debris represent a threat to space activities. Indeed, their presence may jeopardize the operative mission of active satellites, given that the possible impact with a space debris ranges from cumulative erosion of satellite surface to the possible satellite destruction, with the generation of thousands of additional pieces of debris and inevitable environmental drawbacks and possible cascade effects. Therefore, different strategies have been implemented to guarantee safe operations, and an international commitment is currently taking place in the Space Surveillance and Tracking (SST) field. Europe deals with this topic through two programmes: the European Space Agency (ESA) Space Situational Awareness (SSA) programme[6] and the European Space Surveillance and Tracking (EUSST) framework.[5] The latter, established in 2015, groups European national agencies and institutions, and is in charge of carrying out the following services: conjunction analysis,[1] fragmentation analysis[15] and re-entry prediction.[2] These services exploit measurements obtained through ground-based sensors, which are optical telescopes (they provide highly accurate angular track), radars (in addition to angles, they provide either range or Doppler shift measurements or both) and lasers (they provide extremely precise range measurements).[14] A key role is provided by the survey radars, which allow to characterize an unknown object orbit at the first detection.[13]
In particular, the EUSST consortium Fragmentation Analysis service is managed by the Italian Space Surveillance and Tracking Operation Center (ISOC) - Situational Awareness Centre (CSSA). This work presents the analysis carried out by Politecnico di Milano in collaboration with the ISOC-CSSA, regarding two fragmentation events occurred on November 12th and November 17th, 2022, which involved the objects CZ-6A R/B and H-2A DEB respectively. These two events caught the attention of the SST operators because of their temporal proximity and possible implications, also considering that H-2A DEB was a conical adapter (with no on-board energy source) and its explosion was supposed to be unlikely.
The paper is organised as follows. First the epoch of both CZ-6A R/B and H-2A DEB fragmentations are characterised, in Sec. 2 and Sec. 3 respectively. Then, the possible relationship between the two events is discussed in Sec. 4, both on real data and simulations.

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2. CZ-6A Fragmentation

A key point of the Fragmentation Analysis service is to assess the break-up epoch, which is fundamental to apply break-up and fragments cloud evolution models, as well as to properly plan observations through on-ground sensors, and to update the space objects catalogue.
To this purpose, Politecnico di Milano has developed two algorithms: FRED and PUZZLE. FRED stands for Fragmentation Epoch Detector and is capable of determining a set of fragmentation epoch candidates in a stochastic way starting from the ephemerides of both the parent and one single fragment, the latter provided with uncertainty.[12] The fragmentation epoch candidates are then ranked according to the stochastic compliance between the MOID and the relative distance distributions (where MOID stands for Minimum Orbital Intersection Distance). PUZZLE, instead, is a software toolkit whose aim is to characterise fragmentations in terms of epoch, location and parent(s) of the event starting from a set of unknown objects.[16] This is achieved by backward propagating a set of objects and by applying filtering techniques (e.g., the MOID, the hierarchical clustering method[18]) to detect the fragmentation and reject objects that are not related to the fragmentation. Both FRED and PUZZLE can be exploited to determine the CZ-6A fragmentation epoch, as follows.
FRED can be applied by referring to the parent object ephemeris present on Spacetrack,[17] both before and after the event, that was guessed to have taken place on November 12th, 2022, between 05:24 and 05:29 UTC.[3] Indeed, the first ephemeris after the event represents a fragment still correlated to the parent object, and an uncertainty based on[7] is added to stochastically describe it. The two objects orbital parameters are reported in Tab. 1. FRED is run searching for the fragmentation epoch in an analysis time window ranging from the last available ephemeris to the 08:00:00 UTC of November 12th.

	Epoch [UTC]	a [km]	e [-]	i [deg]	Ω [deg]	ω [deg]	θ [deg]
Parent	03:24:14	7214.4	0.0028	98.725	320.896	10.263	349.639
Fragment	15:15:29	7216.6	0.0033	98.737	321.425	9.569	350.332

Table 1: CZ-6A R/B fragmentation: parent and fragment orbital parameters used in FRED algorithm. The epochs refer to November 12th, 2022.

Figure 1 shows the fragmentation epoch distribution computed by FRED algorithm in the plane time-MOID, and Tab. 2 reports the fragmentation epoch candidates computed by FRED algorithm, stochastically ranked. It is possible to notice that the candidate featuring the best compliance (index equal to 1) belongs to the guessed fragmentation time window reported in[3] (and mentioned above).

	Index	Fragmentation epoch [UTC]	Standard deviation [s]
Candidate 1	1	05:26:05	39.57
Candidate 2	0.9	03:44:32	39.52
Candidate 3	0.8	07:07:39	39.63

Table 2: CZ-6A R/B fragmentation: fragmentation epoch candidates according to FRED algorithm. The epochs refer to November 12th, 2022.

Similar analyses are conducted using PUZZLE. In this case, the investigation starts from a set of about 400 real TLEs of fragments evaluated on November 21th, 2022, and by backward propagating them for 15 days. Within the time window considered, the software search for the epoch when most of the fragments have close encounters with each other (i.e., a cluster of objects), as visible in Figure 2.
The epoch found is reported in Tab. 3. Also in this case, the estimated epoch belongs to the guessed fragmentation time window reported in.[3]

	Fragmentation epoch [UTC]	Standard deviation [s]
Candidate	05:26:48	25

Table 3: CZ-6A R/B fragmentation: fragmentation epoch candidates according to PUZZLE algorithm. The epochs refer to November 12th, 2022.

Then, by considering the estimated epoch of the event and a new set of TLEs including spacecrafts and rocket bodies (including the actual parent), the tool is able to identify the families involved (1 family), and thus associating the event with an explosion.

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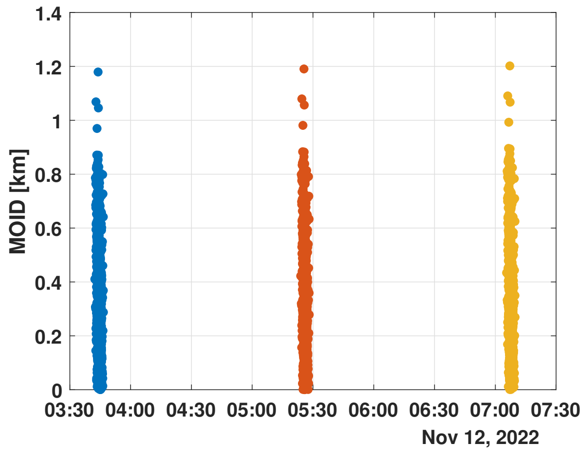

Figure 1: CZ-6A fragmentation: distribution of the fragmentation epoch candidates in the plane time-MOID obtained through FRED algorithm.

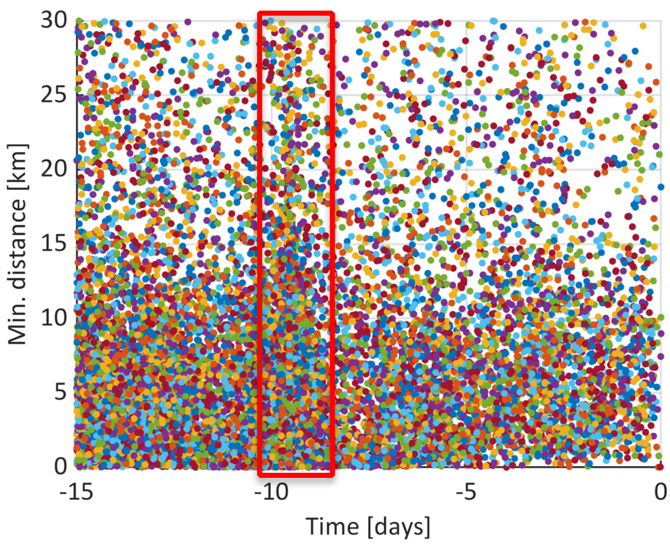

Figure 2: CZ-6A fragmentation: close encounters between the investigated objects over time obtained through PUZZLE algorithm.

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	Epoch [UTC]	a [km]	e [-]	i [deg]	Ω [deg]	ω [deg]	θ [deg]
Parent	2022-11-17T20:42:44	6.9923e+03	9.0157e-04	98.3138	63.7015	43.0850	316.8571
Fragment	2022-11-18T22:33:17	6.9923e+03	9.6135e-04	98.3120	64.8233	39.8995	319.9998

Table 4: H-2A DEB fragmentation: parent and fragment orbital parameters used in FRED algorithm.

	Index	Fragmentation epoch [UTC]	Standard deviation [s]
Candidate 1	1	18-Nov-2022 02:01:35	208.95
Candidate 2	0.9	17-Nov-2022 21:10:50	206.66
Candidate 3	0.10485	18-Nov-2022 02:49:08	217.80
Candidate 4	0.10374	18-Nov-2022 01:12:44	226.31
Candidate 5	0.10322	17-Nov-2022 23:35:58	222.09
Candidate 6	0.10278	17-Nov-2022 21:59:14	218.96
Candidate 7	0.099052	17-Nov-2022 22:47:49	204.48
Candidate 8	0.098964	18-Nov-2022 00:24:43	205.69

Table 5: H-2A DEB fragmentation: fragmentation epoch candidates according to FRED algorithm.

Figure 3 shows the gabbard diagram related to the CZ-6A fragmentation, at the epoch of the event estimated using PUZZLE.

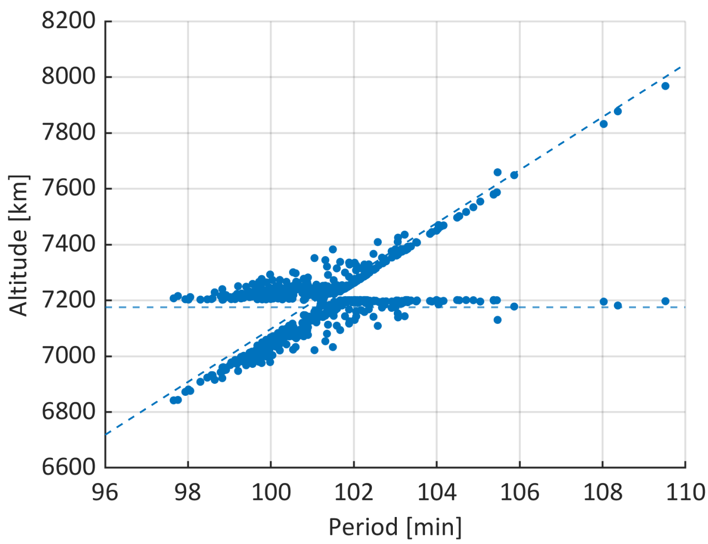

Figure 3: CZ-6A fragmentation: gabbard diagram of the fragments at the epoch estimated using PUZZLE.

3. H-2A DEB Fragmentation

For H-2A DEB fragmentation no fragments ephemerides were available. Thus, the fragmentation epoch can be estimated through FRED algorithm only, similarly to what shown in Sec. 2 about the CZ-6A fragmentation. In this case, the fragmentation event according to[3] took place on November 17th, around 23:36 UTC. Table 4 reports the orbital parameters of the last available ephemeris of the parent object before the event and the one published as soon as possible after it (both of them reported on[17]). As commented in Sec. 2, the latter can be considered as the fragment whose detected measurements resulted still correlated to the parent object transit prediction. For this fragmentation, FRED searches for the fragmentation epoch in an analysis time window ranging from the last available ephemeris to 03:00:00 UTC of November 18th.

Figure 4 shows the fragmentation epoch distribution computed by FRED algorithm in the plane time-MOID, and Tab. 5 reports the fragmentation epoch candidates computed by FRED algorithm, ranked according to their stochastic compliance. It is possible to notice that the candidate n. 5 is compliant with the fragmentation epoch reported in,[3] even if it is not the optimal one. However, the objective of FRED algorithm is to provide a set of candidate fragmentation

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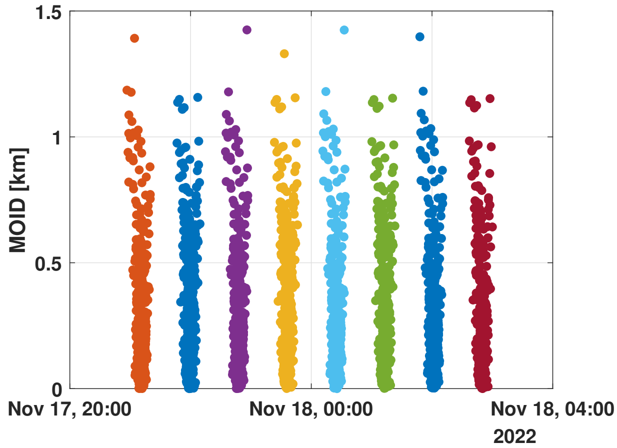

Figure 4: H-2A DEB fragmentation: distribution of the fragmentation epoch candidates in the plane time-MOID obtained through FRED algorithm.

epochs, which can be then refined through further considerations, which are carried out in Sec. 4.

4. Relationship between the two events

Given the temporal proximity of the two fragmentations, both a practical and a theoretical analysis is carried out to assess a possible relationship between the two events. Also, it is worth to point out that the H-2A DEB was a conical adapter (with no on-board energy source), and its explosion was supposed unlikely.

4.1 Geometrical analysis

To first assess the relationship between CZ-6A and H-2A DEB fragmentations, Fig. 5 shows the orbital geometries of the involved objects, together with the fragmentations inertial positions according to.[3] It is worth to notice that the H-2A DEB fragmentation occurs in proximity of one of the two orbital planes intersection, and this pushes to further analyses.

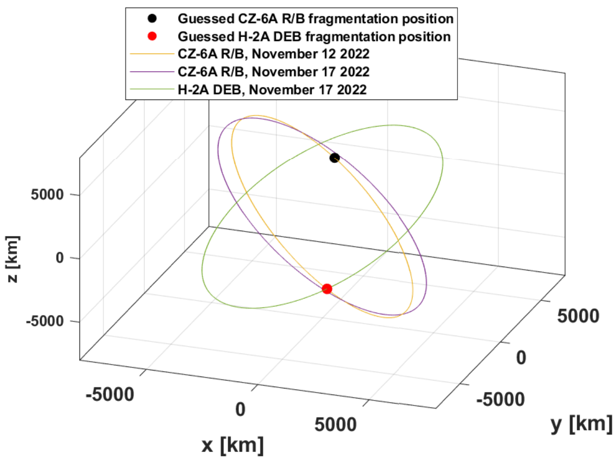

Figure 5: CZ-6A and H-2A DEB orbital geometries and the fragmentations inertial positions according to.[3]

As mentioned in Sec. 2, some real ephemerides of CZ-6A R/B fragments (though TLE format) were available, and they can be used to run FRED algorithm. In particular, the comparison is performed considering the H-2A DEB last available ephemeris before the event (parent data in Tab. 4) and all the CZ-6A R/B fragments ephemerides, which are provided of the uncertainty (which is defined according to[7]) and are processed one by one. For each couple parent-

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fragment, a set of fragmentation epoch candidates is returned, each one with a corresponding mean value of MOID and relative distance. All the values are shown in Fig. 6.

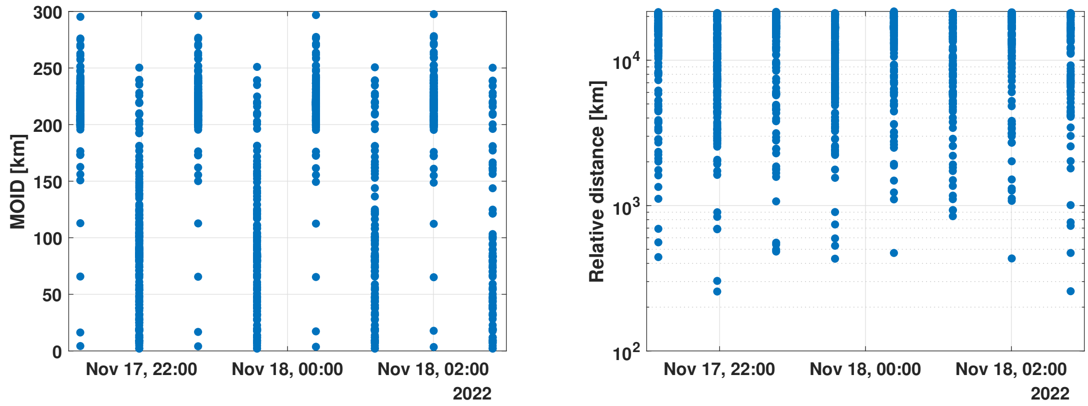

Figure 6: FRED results: distribution of the mean value of MOID (left) and relative distance (right), for all the fragmentation epoch candidates and for all the couples parent-fragment analysed. The parent is the H-2A DEB last available ephemeris before the break-up and the fragments are the CZ-6A ones.

Based on Fig. 6 it is possible to exclude some fragmentation epoch candidates, that is the n. 1, n. 2, n. 7, n. 8 of Tab. 5. Indeed, those candidates are less likely to have occurred, given that the MOID distribution gathers on large median values. On the contrary, the remaining epoch candidates (n. 3, n. 4, n. 5, n. 6 of Tab. 5) present a MOID distribution with small median values. None of the analysed CZ-6A R/B fragments can have impacted H-2A DEB, given the large relative distance at the fragmentation epoch candidates in Fig. 6. However, the MOID analysis suggests a possible impact of a not detected (or not correctly characterised) fragment.
This analysis can be further motivated by looking at the orbits of the CZ-6A R/B fragments with respect to the H-2A DEB, as represented in Fig. 7. In this case the fragmentations inertial positions are represented both according to[3] (left plot) and from FRED algorithm result (right plot). It is possible to notice that the H-2A DEB fragmentation inertial position (which is close to the intersection of the H-2A DEB and CZ-6A R/B orbital planes, as mentioned above) is located near the MOID inertial position with the larger envelope of the fragments cloud trajectories. This inertial point is crossed by the H-2A DEB parent object in those epochs corresponding to the low median MOID distributions in Fig. 6. This allows to shrunk the H-2A DEB fragmentation epoch candidates of Tab. 5 to those in Tab. 6. It is worth to highlight that the remaining fragmentation epoch candidates share a similar index, and it is not straightforward to identify the optimal one. Nevertheless, the candidate n. 5 is compliant with the H-2A DEB fragmentation epoch according to.[3]

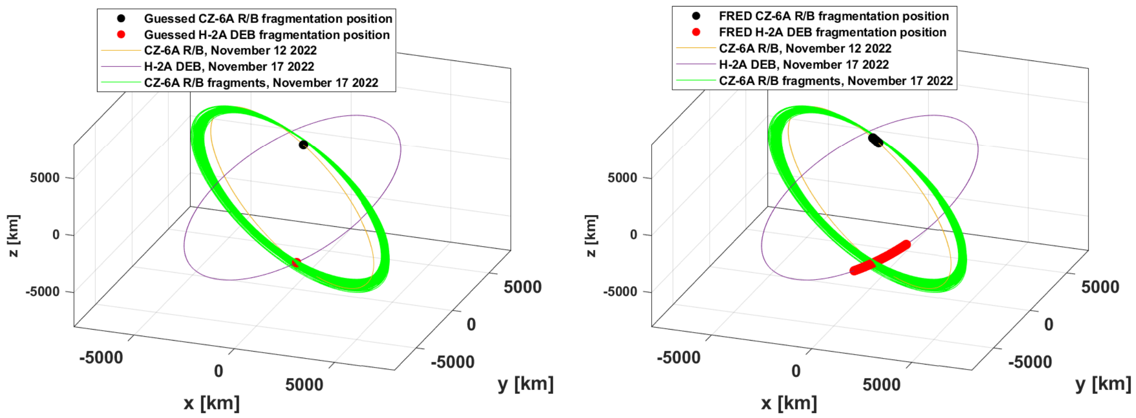

Figure 7: Orbits of the H-2A DEB, CZ-6A R/B and CZ-6A R/B fragments and the fragmentations inertial positions according to[3] (left) and resulting from FRED algorithm (right).

To recap, besides having shrunk the H-2A DEB fragmentation epoch candidates, this analysis first assesses a possible relationship between CZ-6A R/B and H-2A DEB.

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	Index	Fragmentation epoch [UTC]	Standard deviation [s]
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Candidate 4	0.10374	18-Nov-2022 01:12:44	226.31
Candidate 5	0.10322	17-Nov-2022 23:35:58	222.09
Candidate 6	0.10278	17-Nov-2022 21:59:14	218.96

Table 6: H-2A DEB fragmentation: shrunk set fragmentation epoch candidates according to FRED algorithm.

4.2 Collision probability analysis

The correlation between the two fragmentation events is here assessed from a probabilistic perspective, through the STARLING tool.[9,11] The model characterises the fragments ejected by a fragmentation event as a debris cloud, which is described through a Probability Density Function (PDF) in the 7D phase space of Keplerian elements and area-to-mass ratio. A probabilistic reformulation of the NASA Standard Breakup Model[8] is used for the estimation of the initial density distribution. The dynamical evolution of the cloud under the effect of the orbital perturbations is retrieved by numerically integrating the continuity equation through the method of characteristics.[10] The solution along the characteristics curves is eventually translated into a PDF over the considered 7D phase space through binning. The STARLING tool also allows for the evaluation of the collision probability between the debris cloud and an orbiting object. It is computed from the estimated number of impacts over the considered time range according to a Poisson distribution. The number of impacts η is evaluated through the time integration of the fragments flux against the target object cross-section A_c, as follows.

$$\eta = \int_{t_0}^{t_f} A_c \iiint_{\mathbb{R}^3} n_{\boldsymbol{r},\boldsymbol{v}}(\boldsymbol{r}_T(t), \boldsymbol{v})\, v_{\text{rel}}(t)\, \mathrm{d}\boldsymbol{v}\, \mathrm{d}t \tag{1}$$

where $n_{\boldsymbol{r},\boldsymbol{v}}$ is the evolving fragments spatial density, $\boldsymbol{r}_T$ is time-dependent target object position vector, and v_{rel} is the relative velocity between fragments and target object.

The STARLING tool is adopted for the modelling of the CZ-6A in-orbit explosion, and for the evaluation of the collision probability of the resulting fragments cloud with H-2A DEB, to determine the possible correlation between the two events. Figure 8 depicts the estimated fragments density distribution over the phase space of Keplerian elements at fragmentation epoch, and the related fragments cloud in the physical space. The H-2A DEB orbit and position is also shown.

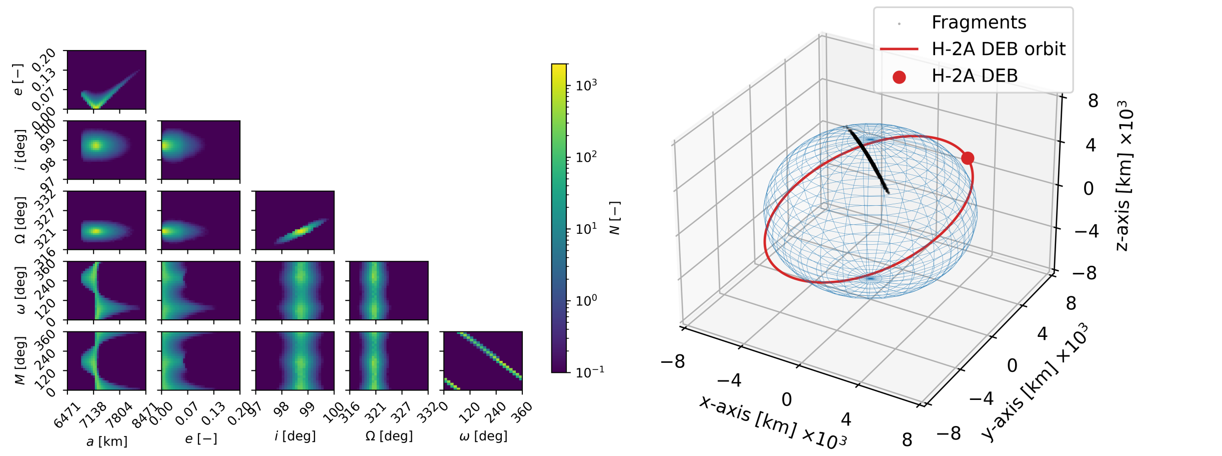

Figure 8: CZ-6A fragments distribution over the phase space of Keplerian elements and related fragments cloud at fragmentation epoch, as estimated by the STARLING tool.

The fragments density distribution is propagated in time until the 17/11/2022 at 23:36 (i.e., when the second fragmentation occurred), under the effect of atmospheric drag, J_2 and J_{22} perturbations, solar radiation pressure and luni-solar perturbation. Figure 9 shows the density distribution at the epoch of the second fragmentation event and the related fragments cloud.

As it can be observed, in such a short period of time, the main variation in the fragments distribution is monitored in mean anomaly M; indeed, because of the impulse received by the explosion event, the fragments are characterised by

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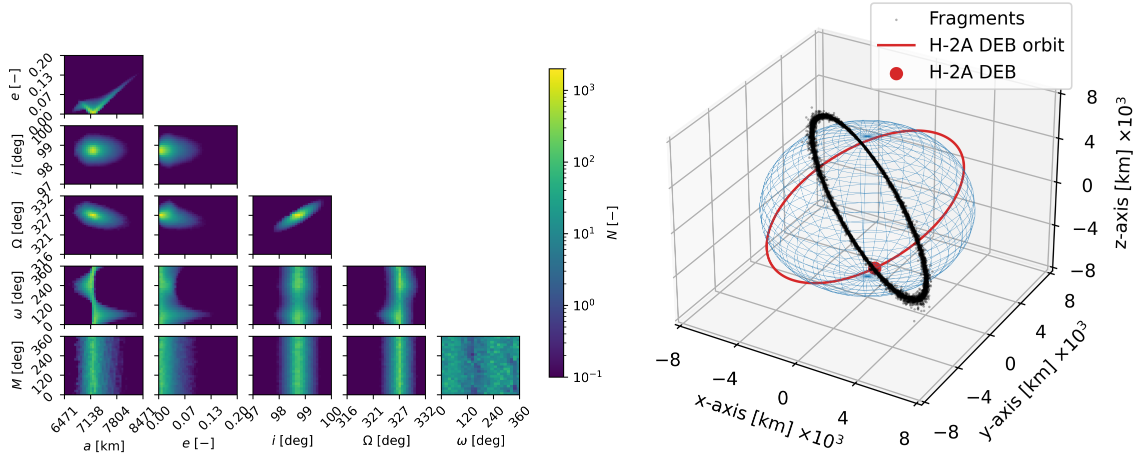

Figure 9: CZ-6A fragments distribution over the phase space of Keplerian elements and related fragments cloud on 17/11/2022 at 23:36, as estimated by the STARLING tool.

different semi-major axis values (i.e., different orbital period), which induce a randomisation over M and the formation of the fragments toroid around the Earth. The nodal precession caused by the J_2 perturbation is also clearly visible. By looking at the fragments cloud distribution over the physical space and the H-2A DEB position, one can evaluate how likely it is that a conjunction has occurred.

To further assess the correlation between the two events, the impact rate between the fragments cloud and H-2A DEB is computed from the CZ-6A explosion epoch until the H-2A DEB fragmentation epoch. The resulting profile is shown in Figure 10.

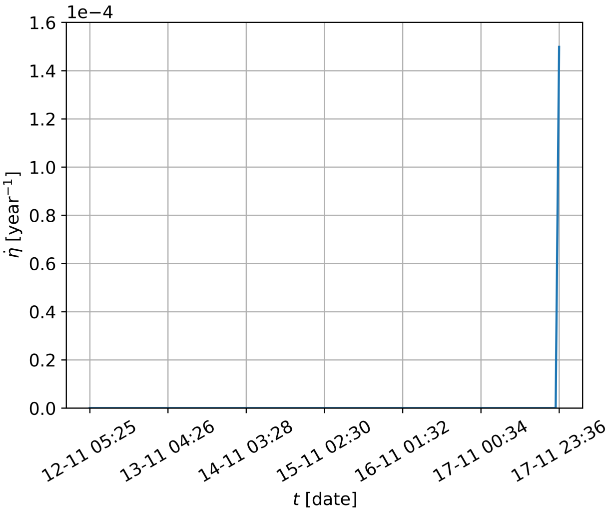

Figure 10: Impact rate between CZ-6A fragments cloud and H-2A DEB from 12/11/2022 05:25 until 17/11/2022 23:36, as estimated by the STARLING tool.

As it can be observed, over the entire time range between the two events, a unique non-null impact rate value is monitored at the epoch of the H-2A fragmentation event.

5. Conclusions

The work has described the analyses carried out by Politecnico di Milano and the ISOC-CSSA regarding the CZ-6A R/B and H-2A DEB fragmentations, which occurred on November 12th and November 17th, 2022, respectively. For both the events the fragmentation epoch has been characterised through FRED, PUZZLE and STARLING algorithms, resulting compliant with the official values published in.[3]

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Since these two events caught the attention of the SST operators because of their temporal proximity, also considering that H-2A DEB explosion was supposed unlikely, the relationship between the two events has been discussed based on real data and simulations, turning out a strong evidence of mutual implication between the two events.

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