ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (xxxx) xxx

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

# Attitude reconstruction of the second stage of the CZ-6A rocket at break-up based on fragmentation data

Antonio Nicolino [a], Lorenzo Olivieri [b]

[a] CISAS "G. Colombo, University of Padova, Via Venezia 1, 35131 Padova, Italy
[b] DII/CISAS, University of Padova, Via Venezia 1, 35131 Padova, Italy

Received 2 March 2026; received in revised form 8 June 2026; accepted 15 June 2026

**Abstract**

The increasing frequency of orbital launches and the associated proliferation of space debris have raised significant concerns within the aerospace community. Among the most notable recent events is the fragmentation of the second stage of the Chinese Long March 6A (CZ-6A) rocket, which occurred on August 6, 2024, after the deployment of the Yunhai-3 satellite. This incident, which generated a large population of new debris objects in low Earth orbit, underscores the need for further investigation into the physical mechanisms and dynamical characteristics of in-orbit fragmentation events. The main objective of this work is to estimate the pre-breakup orientation (attitude) of the CZ-6A second stage by analysing post-event data of the resulting debris cloud. The analysis entails acquiring and filtering Two-Line Element (TLEs) sets of the fragments followed by an inverse kinematic reconstruction to estimate the fragments' ΔV components in the radial, tangential and normal directions. By combining the reconstructed ΔV distribution with the known geometry of the stage and the location of its propellant tanks, a likely explosion direction was hypothesized enabling the inference of a plausible pre-breakup attitude. Additional outcomes of the analysis include the determination of the fragmentation epoch and the reconstruction of the parent body's orbital parameters.


*Keywords:* Space debris; Fragmentation; Delta-V; Attitude reconstruction

## 1. Introduction

In recent years, the increasing number of orbital launches has led to a significant growth in the population of space debris surrounding Earth (Johnson, 2010). This issue has become one of the main concerns for the space community (Murtaza et al., 2020), as the growing population of debris poses risks to the safety of operational satellites and the long-term sustainability of space activities (Adushkin et al., 2020). Fragmentation events represent a critical source of debris (Pardini and Anselmo, 2014), since they can release a large number of fragments in a short time and substantially alter the dynamics of the orbital environment, contributing to the risk of cascading collisions described by the Kessler syndrome (Kessler and Cour-Palais, 1978). Studying and reconstructing such events is therefore crucial for two main reasons. In the short term, understanding the characteristics of debris clouds supports collision avoidance strategies for operational satellites, reducing the risk of conjunctions (Frey and Colombo, 2021; Shu et al., 2023). In the long term, detailed reconstructions improve our knowledge of debris generation mechanisms and contribute to the prediction of the orbital environment's evolution (Anselmo et al., 1999, Yuan et al., 2025a, b), which is essential for sustainable space operations and future mission planning (Colombo et al., 2021).

*E-mail addresses:* antonio.nicolino@studenti.unipd.it (A. Nicolino), lorenzo.olivieri@unipd.it (L. Olivieri)

https://doi.org/10.1016/j.asr.2026.06.047
0273-1177/© 2026 The Author(s). Published by Elsevier B.V. on behalf of COSPAR.


Please cite this article as: A. Nicolino and L. Olivieri, Attitude reconstruction of the second stage of the CZ-6A rocket at break-up based on fragmentation data, Advances in Space Research, https://doi.org/10.1016/j.asr.2026.06.047

In-space fragmentation events have been observed for decades and can be classified as explosions (Rykhlova et al., 1997; Ravi et al., 2023), accidental collisions (Kelso, 2009), deliberate collisions (Kelso, 2007; Kosambe, 2019; Muciaccia et al., 2022) and unknown events (Mains et al., 2024). One of the most notable recent cases is the fragmentation of the second stage of the Chinese Long March 6A (CZ-6A) rocket, which occurred on August 6, 2024, after the deployment of the Yunhai-3 satellite. The event generated a large cloud of fragments and immediately drew the attention of researchers and monitoring agencies. Understanding such an event not only provides insights into the specific failure mechanisms involved but also contributes to the broader effort of improving debris modelling and mitigation strategies. Prior to August 6, 2024, other fragmentation events involving the CZ-6A upper stage had already been recorded, the most severe of which occurred on November 11, 2022. To date, the event has produced a total of 793 tracked fragments, ranking it as the fourth most severe fragmentation ever recorded and the most significant breakup of an upper stage to date (NASA, 2024).

The main objective of this work is to reconstruct the pre-breakup orientation of the CZ-6A second stage by analysing the orbital evolution of the debris produced by the explosion. To achieve this, publicly available Two-Line Element (TLE) data are collected, processed, and propagated backward in time in order to approximate the conditions at the moment of fragmentation. From these results, the velocity changes experienced by the fragments are estimated, and an inverse reconstruction approach is applied to infer the likely orientation of the parent body. This work links the kinematics of the fragments to the physical orientation of the parent body showing that the resulting debris population is strongly influenced by the attitude at the time of breakup. This aspect is often neglected in debris modelling; therefore, including the pre-fragmentation attitude can improve the accuracy of future debris cloud models and collision risk assessments.

The remainder of this paper is organised as follows. The next section introduces the rocket stage geometry and describes the fragmentation event. Section 3 presents the methodology adopted in this study, while Section 4 discusses the main results, including the reconstruction of the inferred stage attitude before fragmentation.

## 2. The CZ-6A stage fragmentation

The Long March 6A is a Chinese launch vehicle that was developed by the China Aerospace Science and Technology Corporation (CASC) and the Shanghai Academy of Spaceflight Technology (SAST) (W. Zhang et al., 2022). The first stage is equipped with two YF-100 engines capable of delivering a thrust of 2376 kN, with a specific impulse of 300 s at sea level and 335 s in vacuum. The engines use RP-1/LOX (kerosene and liquid oxygen) as propellant. The vehicle also features four solid rocket boosters, each 2 m in diameter and providing 1214 kN of thrust, marking the first use of this configuration on a Chinese launch vehicle. It has a total length of 50 m and a diameter of 3.35 m. The total mass is 530,000 kg, with a payload capacity of 4000 kg to Sun-Synchronous Orbit (SSO) (Krebs, 2025). The second (upper) stage is based on a cylindrical geometry, with the approximate dimensions of $8.5 \times 3.35$ m, and a mass of 5800 kg. It provides a maximum thrust of 180 kN and a specific impulse of 341.5 s in vacuum. Among the parameters listed above, only the cylindrical geometry of the upper stage is directly used in the subsequent analysis, as it supports the working hypothesis introduced in Section 4.4 regarding the preferential direction of the velocity perturbations. The remaining parameters are reported only as general context and are not used in the attitude reconstruction. The CZ-6A upper stage has been employed in several launches since its maiden flight in 2022, mostly targeting Sun-synchronous orbit. On 6 August 2024, the CZ-6A upper stage experienced an in-orbit fragmentation, leading to the generation of hundreds of debris fragments (Jones, 2024a; Jones, 2024b). This event represents one of several recorded fragmentation events involving a CZ-6A upper stage, highlighting a recurring issue associated with the long-term orbital behaviour of this launch vehicle class (Jones, 2022). Publicly available data from Space-Track.org and secondary reporting sources provide estimates of the fragmentation time and altitude. The breakup was detected at an altitude of approximately 800 km, with the first observations of debris reported around 8 August 2024. As of the time of writing (December 2025), the number of tracked debris associated with the event exceeds 700.

## 3. Methodology

This study aims to reconstruct the dynamical conditions of an in-orbit fragmentation event, with specific focus on the CZ-6A upper stage breakup of August 2024. The overall aim is to provide a consistent framework that links observable orbital data with the physical mechanisms underlying fragmentation.

The reconstruction of the attitude state was performed through a multi-step methodology. First, the orbital elements of both the fragments and the parent body were retrieved from publicly available sets (Spacetrack, 2025) and propagated backward in time using custom MATLAB routines (Mahooti, 2025a; Mahooti, 2025b) in order to estimate the orbital states at the fragmentation epoch. Second, the fragmentation epoch was reconstructed using two complementary approaches: the first method analyzed the relative distance between each fragment and the parent body, while the second examined the mutual distances among the fragments. Third, the pre-fragmentation orbit of the parent body was reconstructed from historical tracking data, enabling identification of the fragmentation point along the orbit. Based on the observed variations in orbital parameters, the velocity increments imparted to the fragments were estimated. Fourth, the resulting distribution of fragment orbital elements and $\Delta V$ components was analyzed to formulate hypotheses regarding preferential fragmentation directions. Finally, the attitude of the CZ-6A upper stage was estimated using the reconstructed fragment data.

The orbital data used in this study were retrieved from the public catalogue available on Space-Track.org through a dedicated MATLAB routine that queries the catalogue via its REST API. Since the August 2024 event was not the first explosion involving the CZ-6A upper stage, an initial screening of the available TLEs was performed to retain only the objects associated with the breakup of interest. The screening was based on the International Designator (INTLDES) of the fragments. Only objects sharing the designator 2024–140, corresponding to the launch that placed the Yunhai-3 satellite into orbit, were retained. For each retained fragment, the earliest available TLE was downloaded, so that the initial state used for the backward propagation was as close as possible to the fragmentation epoch and the length of the backward integration interval was minimized.

The backward propagation of the fragments to the fragmentation epoch was performed by combining two complementary tools: SGP4 was used to parse each TLE and recover the corresponding state vector at the TLE epoch of validity, while a High Precision Orbit Propagator (HPOP) was used to perform the actual backward integration of the equations of motion. Performing the entire backward analysis within the SGP4 framework was considered but discarded, because the accuracy of SGP4 is known to degrade rapidly with the propagation interval, with position errors that may grow to several kilometers within only a few days from the TLE epoch (Boyce, 2004). Since the backward propagation of the fragments spans several days, a higher-fidelity numerical integrator is preferable to limit the accumulation of dynamical errors. The combined use of the two tools is justified by the fact that SGP4 is invoked only at the TLE epoch, where its representation of the orbit is most accurate, so that the inconsistency with the numerical integration is minimized. From that epoch onward, the propagation is governed exclusively by the HPOP dynamical model. The residual systematic inconsistency introduced by the combined workflow is further mitigated by the large sample size: by analyzing hundreds of fragments simultaneously, individual stochastic errors tend to average out, as later confirmed by the agreement between the reconstructed fragmentation epoch and the values independently reported by other agencies (Section 4.1).

Operationally, SGP4 is used to convert each TLE into a state vector in the True Equator Mean Equinox (TEME) frame, which is then rotated to the Earth-Centered Earth Fixed (ECEF) frame and provided as input to HPOP. The equations of motion are then integrated with a negative time step in the inertial frame, sampling the propagated state every 30 s along the backward trajectory. The main settings of the HPOP dynamical model and of the numerical integrator are summarized in Table 1.

## 4. Results

This section presents the main results of the CZ-6A fragmentation analysis. To provide an initial overview of the generated debris cloud, a Gabbard diagram of the propagated fragments is introduced in Fig. 1.

### 4.1. Reconstruction of the fragmentation epoch

The epoch of the fragmentation event was estimated by evaluating the mutual distances between fragments. The temporal evolution of these distances was then examined for each time step of 6 August 2024, in order to identify the instant at which the debris cloud was most spatially concentrated. This analysis indicated that the minimum mean mutual distance between the fragments occurred at 20:19 UTC (Fig. 2), so it was adopted as the nominal breakup time for subsequent analyses.

This result is further supported by an additional analysis based on the distances between the debris and the parent body, which shows consistent behaviour around the identified epoch.

The estimated fragmentation epoch is consistent with values reported in the literature (LeoLabs, 2024; NASA, 2024; Wacker et al., 2025), as shown in Table 2. The differences in the reported fragmentation epochs may be due to different input data (TLE selection and freeze date), different propagation tools or different criteria used to identify the breakup epoch from the fragment trajectories. It should also be noted that LeoLabs derived the fragmentation epoch directly from radar observations of the event and was the first to publicly report it, only a few days after the fragmentation.

### 4.2. Reference orbit definition

The pre-fragmentation orbit of the parent body was reconstructed using the orbital data obtained from the backward propagation. At the fragmentation epoch, the state vector of the parent body was converted into classical orbital elements. The resulting values are reported in Table 3.

### 4.3. Delta-V evaluation

Velocity perturbation analysis has been widely applied to investigate historical fragmentation events. Recent case-specific applications include the NOAA-3, USA-193, and Landsat-1 breakups (Tan et al., 2017a, b; Tan and Reynolds, 2021; Tan, 2025a, b). The velocity perturbations imparted to the fragments at the time of breakup were estimated using classical astrodynamical relations linking variations in orbital elements to impulsive velocity changes.

Table 1
Main settings of the HPOP backward propagation.

| Component | Settings |
|---|---|
| Earth gravitational field | GGM03C, 70 × 70 |
| Atmospheric model | NRLMSISE-00 |
| Other perturbations | Third-body (Sun, Moon, planets, JPL DE440), solar radiation pressure, tides, relativity |
| Numerical integrator | MATLAB ode113, adaptive step |
| Integration tolerances | RelTol = $1{\cdot}10^{-10}$, AbsTol = $1{\cdot}10^{-12}$ |

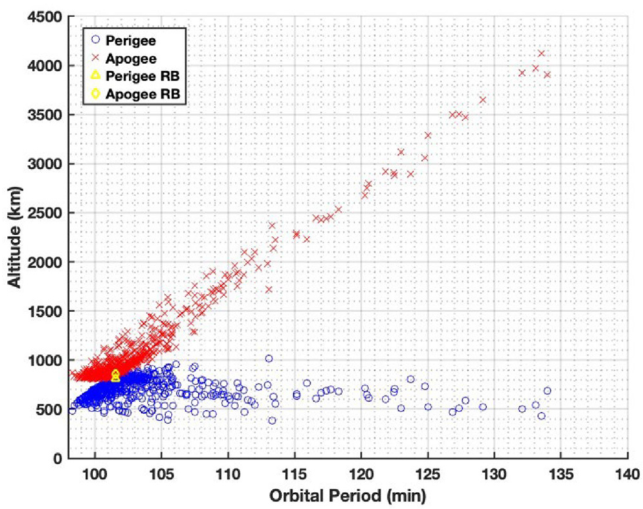


Fig. 1. Gabbard diagram of the propagated debris.

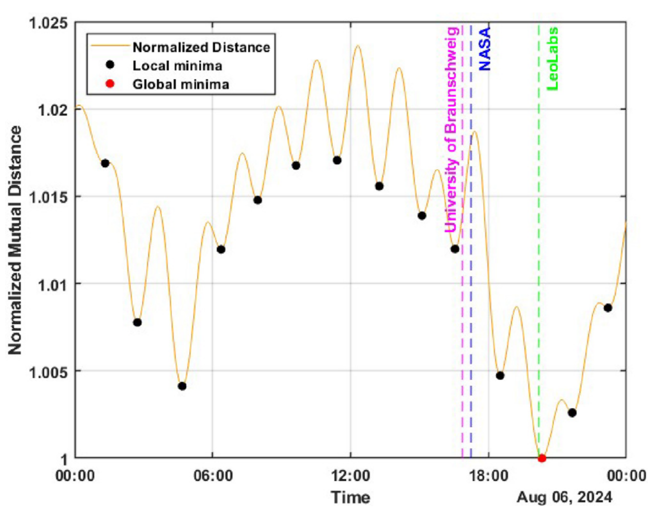


Fig. 2. Temporal evolution of the normalized mean mutual distance between fragments on 6 August 2024. The red dot identifies the nominal fragmentation epoch at 20:19 UTC.

This approach allows the mapping of small variations in orbital elements into equivalent velocity changes in the radial "r", along-track "t", and cross-track "n" directions (Tan, 1989; Badhwar et al., 1990).

The following equations are the starting point from which is possible to obtain the three components of DV of the fragments:

Table 2
Estimated fragmentation epochs reported by different sources.

| Source | Estimated Epoch [UTC] |
|---|---|
| University of Braunschweig | 16:52 |
| NASA | 17:15 |
| LeoLabs | ≈ 20:10 |

Table 3
Main orbital parameters of the parent body.

| Parameters | Values |
|---|---|
| Semi-Major Axis | 7211.1 km |
| Eccentricity | 0.003 |
| Inclination | 88.998° |

$$v = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)} \tag{1}$$

$$v_t = \frac{1}{r}\sqrt{\mu a(1 - e^2)} \tag{2}$$

$$v_r = \pm\sqrt{v^2 - v_t^2} \tag{3}$$

where the classical orbital elements, defined as $a$ and $e$, correspond to the semi-major axis and the eccentricity of the parent object, $r$ is the radial distance to the breakup point and $\mu$ is the gravitational parameter.

Due to the breakup, fragments suffer changes in energy, angular momentum and orbital inclination. By calculating these values and manipulating their equations it is possible to obtain the following:

$$dv_r = \pm\sqrt{\mu\left(\frac{2}{r} - \frac{1}{a'}\right) - \frac{\mu a'}{r^2}\left(1 - e'^2\right)} \mp \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right) - \frac{\mu a}{r^2}(1 - e^2)} \tag{4}$$

$$dv_t = \frac{\cos\zeta}{r}\sqrt{\mu a'\left(1 - e'^2\right)} - \frac{1}{r}\sqrt{\mu a(1 - e^2)} \tag{5}$$

$$dv_n = \frac{\sin\zeta}{r}\sqrt{\mu a'\left(1 - e'^2\right)} \tag{6}$$

where $a'$ is the semi major axis and $e'$ the eccentricity of the fragment's orbit. $\zeta$ is the plane-change angle of the fragment's orbit and can be expressed as a function of the inclinations $i$ and $i$ of the parent's and the fragment's orbits, respectively, and $\lambda$, the latitude of the breakup point.

$$\zeta = \pm\cos^{-1} \times \frac{\cos i \cos i' + \sqrt{\left(\cos\lambda^2 - \cos i^2\right)\left(\cos\lambda^2 - \cos i'^2\right)}}{\cos\lambda^2} \quad (7)$$

In this last equation the positive sign applies when $i' > i$ and the negative one when $i' < i$. The true anomaly $\nu'$ of the fragment at the time of the breakup, which dictates the sign of $dv_r$, the plus sign corresponds to the ascending mode of the fragment orbit ($v' < 180°$), whereas the minus sign corresponds to the descending mode ($v' > 180°$). The radial distance $r$ used in Eqs. (1), (4), (5), and (6), and the latitude $\lambda$ used in Eq. (7), are both obtained directly from the position vector of the parent body at the fragmentation epoch.

The distributions of $dv_t$, $dv_n$ and $dv_r$, shown in Figs. 3 and 4, exhibit an approximately Gaussian profile, whereas the Total ΔV exhibits a nearly exponential behaviour. Another noticeable feature is the presence of some fragments that exhibit significantly higher ΔV values compared to the bulk of the debris population of the debris population. This anomalous behaviour may correspond to fragments with an atypical orbital evolution or to residual identification or tracking errors.

The fragments with the highest ΔV values were retained in the analysis. Their number is small (of the order of ten) compared to the total population of about 700 fragments, and the inspection of the histograms in Fig. 3 shows that these outliers are mostly aligned with the radial direction and are distributed symmetrically around zero.

### 4.4. Attitude estimation

The pre-breakup attitude of the CZ-6A upper stage was estimated directly from the reconstructed fragment data using custom MATLAB scripts. The methodology relies on the working assumption that the anisotropy in the velocity distribution is caused by the breakup geometry. This assumption is supported by recent numerical investigations on fragmentation dynamics (Francesconi et al.,

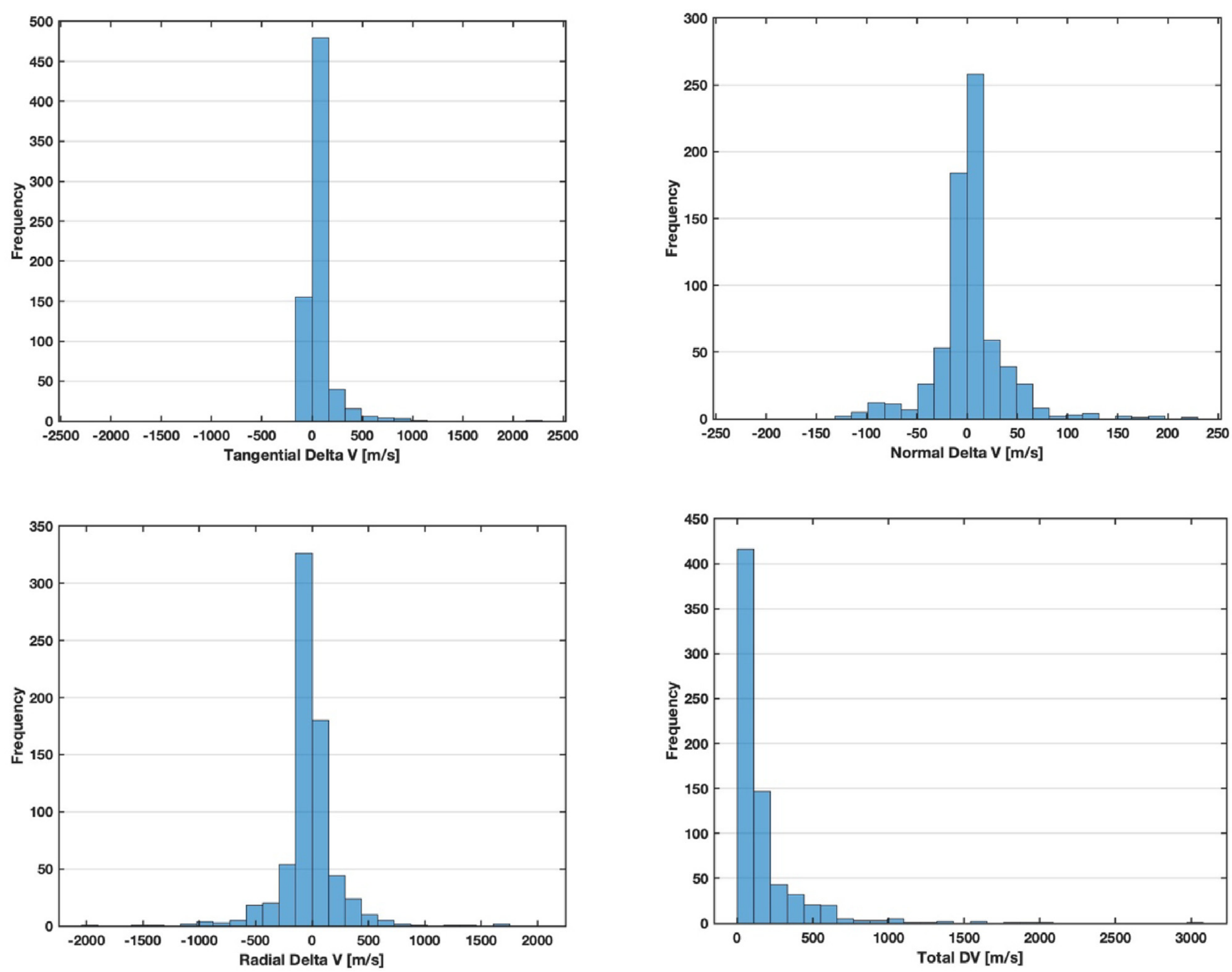


Fig. 3. Frequency distributions of $dv_t$, $dv_n$, $dv_r$ and Total DV of the fragments, arranged from left to right and top to bottom.

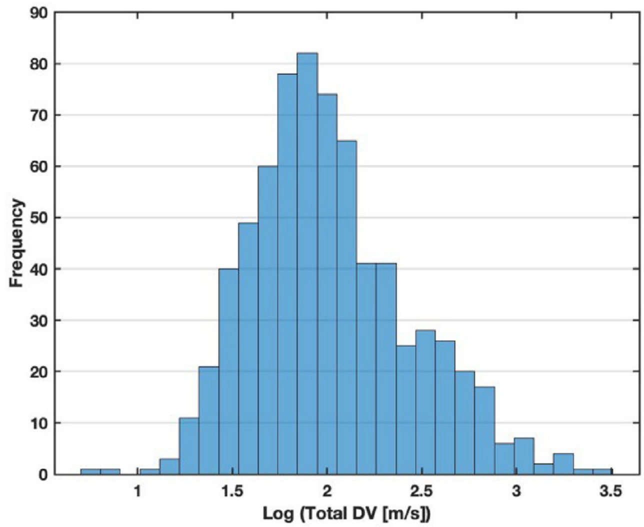


Fig. 4. Histogram of $\log_{10}(\Delta V_{tot})$ for the fragment population.

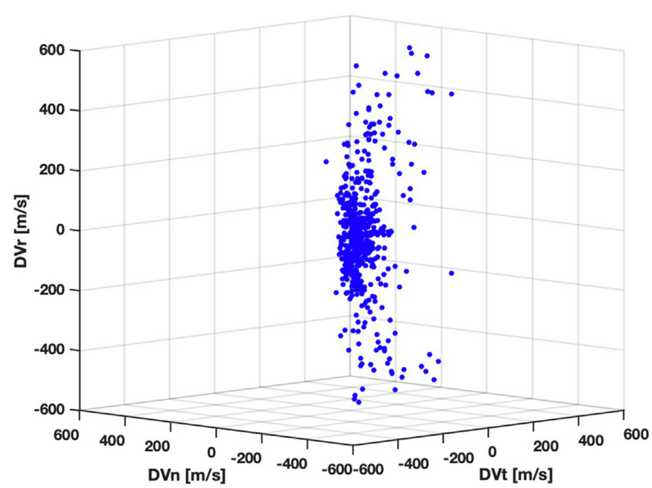


Fig. 5. Three-dimensional scatterplot of the velocity perturbation components of the CZ-6A fragments.

2019; Olivieri et al., 2024), which demonstrate that the spatial distribution of a debris cloud is strongly sensitive to the spacecraft's internal geometry and its attitude at the moment of break-up. Specifically, simulations of explosions occurring near the structural extremities of a satellite suggest that the resulting velocity perturbations (ΔV) exhibit a marked directionality, with the highest velocities aligned with the longitudinal axis of the vehicle [37]. Given the cylindrical geometry of the CZ-6A stage, fragments located near the extremities would be more exposed to the release of pressurized energy and thus acquire a larger velocity along the cylinder axis. As a result, the direction of the dominant ΔV component can be interpreted as coinciding with the stage's longitudinal axis. By analysing the orientation of the ΔV vectors in the radial, tangential, and normal directions, it is therefore possible to infer the most likely attitude of the stage at the epoch of fragmentation. Two methods were used to infer the preferred explosion

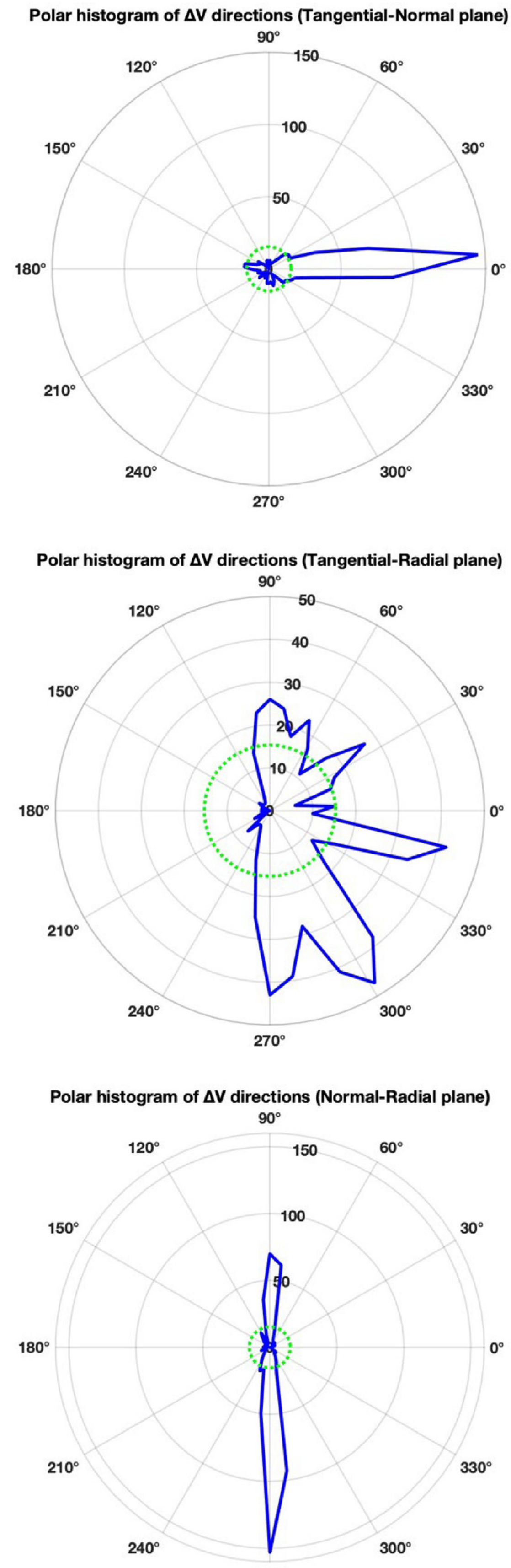


Fig. 6. Polar histogram of ΔV directions in the different planes. The green dotted line represents the possible isotropic explosion.

axis, which for a cylindrical stage is expected to coincide with the stage longitudinal axis.

- **Method A:** For each fragment, the three ΔV components (Fig. 5) were arranged into a dataset, and the covariance matrix of the ΔV vectors was computed. The principal eigenvector of this covariance matrix corresponds to the dominant direction of the velocity perturbations and thus provides a direct estimate of the stage axis orientation.This method yields explicit angular values between the stage axis and the three orbital directions:
  - Tangential: 98.27°
  - Normal: 90.66°
  - Radial: 8.29°
- **Method B:** In this method, each fragment ΔV was projected onto the three orbital planes (tangential–normal, normal–radial, and tangential–radial). The dominant direction within each plane was then identified, providing an indication of the preferential ΔV orientation (Fig. 6). Method B does not represent an independent attitude reconstruction technique, but rather provides a qualitative consistency check of the dominant ΔV direction inferred from Method A.

A direct comparison (Table 4) shows that the orientations obtained with Method B are consistent with the corresponding plane projections from Method A, with a maximum angular deviation of 3.12° observed in the Tangential-Radial plane.

Both methods converge to indicate that the stage axis was preferentially aligned in the radial direction, pointing approximately toward the Earth. This result can be physically interpreted in terms of the gravity gradient effect. For an extended body in orbit, the Earth's non-uniform gravitational field exerts a torque that tends to align the body's principal axis of minimum moment of inertia with the local radial direction. Since the CZ-6A upper stage is a nearly cylindrical structure, its longitudinal axis corresponds to the minimum inertia axis, and thus the gravity gradient naturally stabilizes it along the radial direction. An independent observational confirmation comes from imagery acquired by HEO Robotics with the Continuum-1 satellite (HEO, 2026), which captured an in-orbit image of the CZ-6A upper stage from the launch of October 31, 2023, and reported it as largely intact and gravity-gradient stabilized. Although the image refers to a different mission, it supports the attitude state inferred in this work for the August 2024 stage prior to its breakup.

Table 4
Comparison between projection obtained using Method A and Method B.

| Plane | Method A | Method B |
|---|---|---|
| Tangential–Normal | 4.58° | 2.49° |
| Normal–Radial | 90.67° | 89.75° |
| Tangential–Radial | 98.27° | 101.39° |

## 5. Conclusions

This work presented a methodology for reconstructing the fragmentation conditions of an upper stage that experienced an in-orbit explosion. The case study of the CZ-6A upper stage demonstrated the feasibility of combining orbital data analysis, high-precision orbit propagation, and rigid-body dynamics to infer both the temporal and spatial characteristics of the event. The main findings of the study are:

- The fragmentation epoch was estimated at 20:19 UTC on 6 August 2024, in close agreement with independent estimates reported in the literature.
- The pre-fragmentation orbital parameters of the parent body were reconstructed yielding an approximate reference orbit for subsequent comparisons.
- The ΔV distribution of the fragments was derived, allowing the relative contribution of the radial, tangential and normal components to be analysed.
- The attitude of the stage was reconstructed using a statistical analysis of the fragment ΔV distribution, supported by a complementary projection-based consistency check. Both approaches indicate that the stage axis was preferentially aligned along the radial direction, consistent with the expected passive stabilization due to the gravity gradient effect.

These results provide a coherent physical interpretation of the fragmentation event and represent a contribution to the broader effort of understanding breakup dynamics in Earth orbit. In particular, the reconstruction of the stage orientation at the time of the explosion offers new insights into the underlying mechanisms and supports the use of attitude-sensitive approaches in debris analysis.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

Adushkin, V.V., Aksenov, O.Y., Veniaminov, S.S., Kozlov, S.I., Tyurenkova, V.V., 2020. The small orbital debris population and its impact on space activities and ecological safety. Acta Astronaut. 176, 591–597. https://doi.org/10.1016/j.actaastro.2020.01.015.

Anselmo, L., Rossi, A., Pardini, C., 1999. Updated results on the long-term evolution of the space debris environment. Adv. Space Res. 23 (1), 201–211. https://doi.org/10.1016/S0273-1177(99)00005-8.

Boyce, W.H., 2004. Examination of NORAD TLE Accuracy using the Iridium Constellation. Presented at the AAS/AIAA Spaceflight Mechanics Meeting, Maui, HI, Feb. 2004, Paper AAS 04-240.

Badhwar, G.D., Tan, A., Reynolds, R.C., 1990. Velocity perturbations distributions in the breakup of artificial satellites. J. Spacecr. Rocket. 27, 299–305.

Colombo, C. et al., 2021. Assessing the impact of a space mission on the sustainability of the space environment. Int. Astronaut. Congr.: IAC Proc., 1–10

Francesconi, A. et al., 2019. CST: a new semi-empirical tool for simulating spacecraft collisions in orbit. Acta Astronaut. 160, 195–205. https://doi.org/10.1016/j.actaastro.2019.04.035.

Frey, S., Colombo, C., 2021. Transformation of satellite breakup distribution for probabilistic orbital collision hazard analysis. J. Guid. Control Dynam. 44 (1), 88–105. https://doi.org/10.2514/1.G004939.

HEO, 2026. Continuum-1 imagery of a CZ-6A upper stage in orbit. Linkedin [online]. Available at: https://www.linkedin.com/posts/when-heo-acquired-continuum-1-we-committed-share-7463481264268808193-lsVU/ [Accessed 26 May 2026].

Johnson, N.L., 2010. Orbital debris: the growing threat to space operations. In: 33rd Annual Guidance and Control Conference, Paper AAS 10-011, pp. 10–011.

Jones, A., 2022. Chinese rocket body breaks up in orbit after successful satellite launch. Space.com [online]. Available at: https://www.space.com/ [Accessed 15 December 2025].

Jones, A., 2024a. China's Long March 6A rocket appears to have an orbital debris problem. SpaceNews [online]. Available at: https://spacenews.com/ [Accessed 15 December 2025].

Jones, A., 2024b. Chinese rocket stage breaks up into cloud of more than 700 pieces of space debris. SpaceNews [online]. Available at: https://spacenews.com/ [Accessed 15 December 2025].

Kelso, T.S., 2007. Analysis of the 2007 Chinese ASAT test and the impact of its debris on the space environment. In: 8th Advanced Maui Optical and Space Surveillance Technologies Conference, Maui, HI, vol. 7.

Kelso, T.S., 2009. Analysis of the Iridium 33–Cosmos 2251 collision. Adv. Astronaut. Sci. 135 (2), 1099–1112.

Kessler, D.J., Cour-Palais, B.G., 1978. Collision frequency of artificial satellites: the creation of a debris belt. J. Geophys. Res. Space Phys. 83, 2637–2646. https://doi.org/10.1029/JA083iA06p02637.

Kosambe, S., 2019. Mission shakti aka project XSV-1: India's first anti-satellite test (ASAT). J. Aircraft Spacecraft Technol. 3, 172–182. https://doi.org/10.3844/jastsp.2019.172.182.

Krebs, G.D., 2025. CZ-6A (Chang Zheng-6A). Gunter's Space Page [online]. Available at: https://space.skyrocket.de/doc_lau_det/cz-6a.htm [Accessed 15 December 2025].

LeoLabs (@LeoLabs_Space), 2024. CZ-6A fragmentation updates. X (formerly Twitter) [online]. Available at: https://x.com/LeoLabs_Space/status/1821674976245670386 [Accessed 15 December 2025].

Mahooti, M., 2025a. SGP4 [software]. MATLAB Central File Exchange. Available at: https://it.mathworks.com/matlabcentral/fileexchange/62013-sgp4 [Accessed 15 December 2025].

Mahooti, M., 2025b. High Precision Orbit Propagator [software]. University of Tehran, ResearchGate.

Mains, D.L., Peterson, G.E., McVey, J.P., Maldonado, J.C., Sorge, M.E., 2024. Forensic analysis of recent debris-generating events. J. Space Safety Eng. 11 (3), 388–394. https://doi.org/10.1016/j.jsse.2024.06.006.

Muciaccia, A. et al., 2022. Observation and analysis of Cosmos 1408 fragmentation. Int. Astronaut. Congr.: IAC Proc., 1–7

Murtaza, A., Pirzada, S.J.H.P., Xu, T., Li, J., 2020. Orbital debris threat for space sustainability and way forward. IEEE Access 8, 61000–61019. https://doi.org/10.1109/ACCESS.2020.2979505.

NASA, 2024. Orbital Debris Quarterly News 28 (4).

Olivieri, L., Giacomuzzo, C., Francesconi, A., 2024. Numerical simulation of COSMOS 2499 fragmentation. CEAS Space J. 16, 659–665. https://doi.org/10.1007/s12567-024-00545-z.

Pardini, C., Anselmo, L., 2014. Review of past on-orbit collisions among catalogued objects and examination of the catastrophic fragmentation concept. Acta Astronaut. 100, 30–39. https://doi.org/10.1016/j.actaastro.2014.03.013.

Ravi, P., Black, A., Frueh, C., 2023. Investigation of Atlas V Centaur upper stage fragmentation events. J. Astronaut. Sci. 70 (3), 12. https://doi.org/10.1007/s40295-023-00377-9.

Rykhlova, L.V., Kasimenko, T.V., Mikisha, A.M., Smirnov, M.A., 1997. Explosions in the geostationary orbit. Adv. Space Res. 19 (2), 313–319.

Shu, P., Yang, Z., Luo, Y., 2023. Impact risk of a debris cloud to spacecraft. J. Guid. Control Dynam. 46 (5), 989–997. https://doi.org/10.2514/1.G007056.

Spacetrack, 2025. Spacetrack webpage [online]. Available at: https://www.space-track.org/ [Accessed 15 December 2025].

Tan, A., 1989. Estimation of velocity perturbations in satellite fragmentation events. NASA/ASEE Summer Faculty Fellowship Program, Johnson Space Center, Houston, TX, Final Report.

Tan, A., 2025a. Investigating Russia's direct-ascent anti-satellite test. J. Aeros. Sci. Appl. 10 (1), 41–53.

Tan, A., 2025b. Investigating the YunHai 1-02 satellite fragmentation using theory and velocity perturbations analysis of its fragments. J. Aerospace Sci. Appl. 10 (1), 31–40.

Tan, A., Alomari, A., Schamschula, M., 2017a. Analysis of the NOAA-3 rocket fragmentation in orbit using theory and computations. Adv. Aeros. Sci. Appl. 7 (1), 1–13.

Tan, A., Alomari, A., Schamschula, M., 2017b. Analysis of the Landsat-1 rocket fragmentation in orbit using theory and computations. Adv. Aeros. Sci. Appl. 7 (1), 15–24.

Tan, A., Reynolds, R.C., 2021. Velocity perturbations analysis of the fragmentation of USA-193 satellite in orbit. Adv. Aeros. Sci. Appl. 11 (1), 1–10.

Wacker, D.R., Klinner-Teo, T., Ly, J., Wiedemann, C., Metz, M., Silvestri, S., 2025. Analysis of recent CZ-6A rocket upper stage fragmentations. Proceedings of the 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025. ESA Space Debris Office.

Yuan, Y.R., Yang, K.Y., Zhang, J.R., et al., 2025a. Integrated macroscopic model of debris environment evolution and collision risk assessment. J. Guid., Contr., Dynam. 48 (8). https://doi.org/10.2514/1.G008581.

Yuan, Y.R., Zhang, J.R., Yang, K.Y., et al., 2025b. Collision risk assessment of constellation satellites based on a space debris environment topological network model. Chin. J. Aeronaut. 39 (2). https://doi.org/10.1016/j.cja.2025.103762.

Zhang, W., Fan, Y., Wu, J., Zhou, C., Shen, Z., Chang, D., 2022. Long March 6A and its technical characteristics. China Spaceflight (English Edition) 23 (2), 3–8.