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ORIGINAL PAPER

# Numerical simulation of COSMOS 2499 fragmentation

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**Abstract**
In-space satellites fragmentation events contribute to the continuous growth of man-made debris. Observations of these events can provide limited information on the number and characteristics of the generated fragments, as only the largest ones can be detected with ground instrumentation. Numerical simulations replicating in-orbit fragmentation can integrate the missing information regarding fragments number, shape, and orbital distribution. In this context, this paper presents the numerical reconstruction of COSMOS 2499 break-up of January 4th, 2023. First, a digital twin of the satellite is modeled with the Collision Simulation Tool Solver, a custom semi-empirical simulation code, to replicate the explosion of an internal tank; different expansion velocities for the exploding elements are examined and the resulting fragments size and shape distributions are presented. In a second part, the effect of the attitude at the moment of the break-up on the generated debris orbital distribution is discussed. Finally, the numerical results are compared with the available data from ground observations, showing a good accordance with them.

**Keywords** Space debris · Satellite break-up · Fragmentation

## 1 Introduction

The last decade showed a consistent increase in near-Earth orbits launches [1, 2], further increasing the risk of collision and fragmentation events that may hinder the access and exploitation of such orbits [3–5]. In fact, it has been observed that in-orbit accidental [6] and intentional [7, 8] collisions or explosions [9] can create large fragments clouds and can strongly increase the space debris population.

Space Surveillance and Tracking (SST) [10] and Space Situational Awareness (SSA) [11] activities allow the continuous identification, cataloging, and tracking of space debris [12], mostly from ground facilities [13–15], and the consequent evaluation of fragmentation events [16] and re-entry forecast [17]; in addition, for trackable objects, avoidance manoeuvers can be defined to reduce the probability of collisions [18, 19]. To further lessen the risk to operational spacecraft and to propose mitigation techniques, the scientific community is therefore working to better understand the fragmentation process, predict the event epoch and the cloud time evolution [20, 21], and define how it may affect the environment, including the smaller debris not observable from ground facilities. The most popular tool to date for simulating such occurrences and statistically determining fragment distributions is the NASA Standard Break-up Model (SBM) [22]; it consists in a set of empirical equations that describe the velocity, area-to-mass ratio, and characteristic length cumulative distribution of the generated debris. However, the reliability of this model is partially limited by the inability to discern between central and glancing impacts; the NASA SBM was also created using an outdated set of spacecraft configurations that did not take into account the most recent developments in manufacturing techniques or the application of innovative composite materials. For these reasons, numerical models have been created in an effort to overcome NASA SBM's limitations by taking into account more complicated spacecraft and impact configurations. These models include FASTT [23, 24], IMPACT [25, 26], and the more recent IMPETUS [27] and PHILOS-SOPHIA [28].

In this context, the Collision Simulation Tool Solver (CSTS) has been developed within the framework of the University of Padova's research activity on space debris [29] to simulate complex collision scenarios with detailed

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geometrical models of the involved bodies [16]. The tool employs a semi-empirical approach, discretizing the objects as a mesh of Macroscopic Elements (MEs), representative of their main subsystems and components, connected by structural links capable to transmit loads and deformations. MEs' break-up is governed by semi-empirical relations; the generated fragments are propagated and can cause further damage to other MEs in a cascade effect. This approach, partially based on computer graphic algorithm, allows the simulation of a wide range of collision and fragmentation scenarios [31, 32], producing statistically accurate results [30].

In an effort to evaluate the capability of CSTS to replicate explosion events, the break-up of COSMOS 2499 has been recently simulated. This satellite (U.S. Satellite Catalog Number 39765) was in an 82.45 deg inclined orbit with apogee of 1537 km and perigee of 1163 km; on January 4, 2023, it was subjected to its second known break-up event (after a minor fragmentation on October 23, 2021) [33]. While literature data are not available on this spacecraft configuration, it has been inferred that the satellite is equipped with energy storage elements and a thruster with on-board propellant/pressurization systems [34], that could have caused the January 2023 explosion. Ground observations tracked between 20 [33] and 36 [35] fragments generated by the event.

The remainder of this paper is organized as follows. The next section presents the digital model of COSMOS 2499, defines three different explosion conditions implemented in CSTS, and introduces the resulting fragments distributions. Section 3 discusses the effect of the spacecraft attitude on the orbital distribution of the generated fragments. Finally, the numerical data are compared with ground observations.

## 2 Break-up simulations

To simulate COSMOS 2499 break-up, the digital twin of the satellite was modeled with CSTS (see Fig. 1). Given that COSMOS 2499's size and shape have been compared to those of the 50 kg–1 m-long prismatic Yubileyniy satellite [36], this spacecraft served as the basis for the numerical model with the addition of a tank and a single nozzle placed in the lower part of the satellite. The model consists of 59 MEs, representing the main spacecraft subsystems and components, mainly structural elements and boxes representing instrumentation and electronics, whose density has been adjusted to obtain the total mass of 50 kg. The explosion is modeled by imposing an initial radial velocity to the MEs discretizing the internal tank (red arrows in Fig. 1). Three different radial velocities have been considered, respectively, 50 m/s, 150 m/s, and 1150 m/s, to represent different internal energies of the propellant tank; the first two values are typical of exploding vessels from literature [37], while the third one is in line with the fragments velocities elaborated from the 2009-047B explosion event analysis [9]

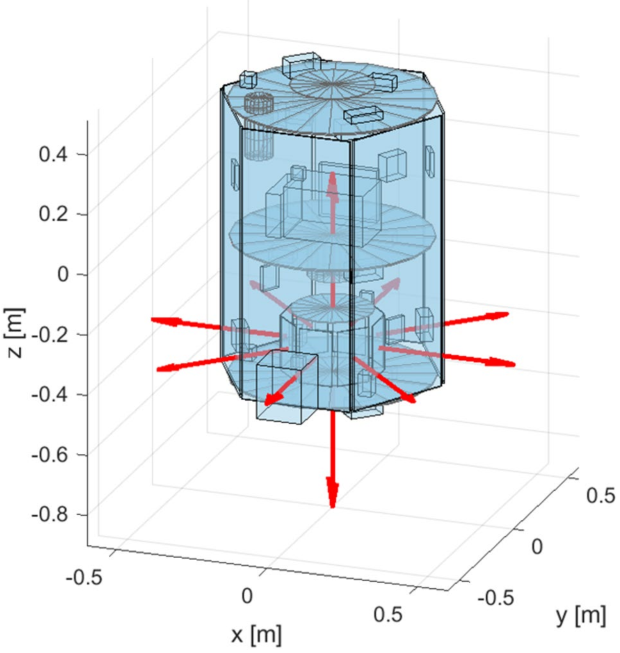

**Fig. 1** COSMOS 2499 model in CSTS. In red, the exploding tank elements' velocity vectors at simulation start

The numerical simulations performed with CSTS allow determining the number and main parameters generated by the event. For the three explosion velocities, break-up simulation results can be seen in Fig. 2 and include cumulative number distributions (i.e., the number of objects with size larger than the value reported in *x*-axis) for the fragments characteristic length and area-to-mass distributions.

It can be observed that the number of generated fragments increases with the explosion velocity. For the lower value (50 m/s), only 52 objects are generated; they mainly consist of large parts of the satellite, separated due to the failure of the structural joint. In this case, the explosion velocity is not high enough to cause a noteworthy fragmentation of the MEs of COSMOS 2499 model.

For the intermediate explosion velocity (150 m/s), a larger number of objects (88) is generated, due to the fragmentation of part of the components of the satellite; the cumulative number distribution suggests that the additional objects have a small characteristic length (below 5 cm). Comparing the area-to-mass histogram to the previous case, it can be noted that the additional fragments lie around $\log_{10}(A/m) = -1$ (i.e., an area-to*-mass ratio of about 0.10 $m^2/kg$). This result suggests that only a few MEs, with comparable densities, are subjected to the fragmentation.

Finally, for the most energetic case (1150 m/s), a finer fragmentation of COSMOS 2499 can be observed, with a total of 328 debris larger than 1 cm. The majority of these

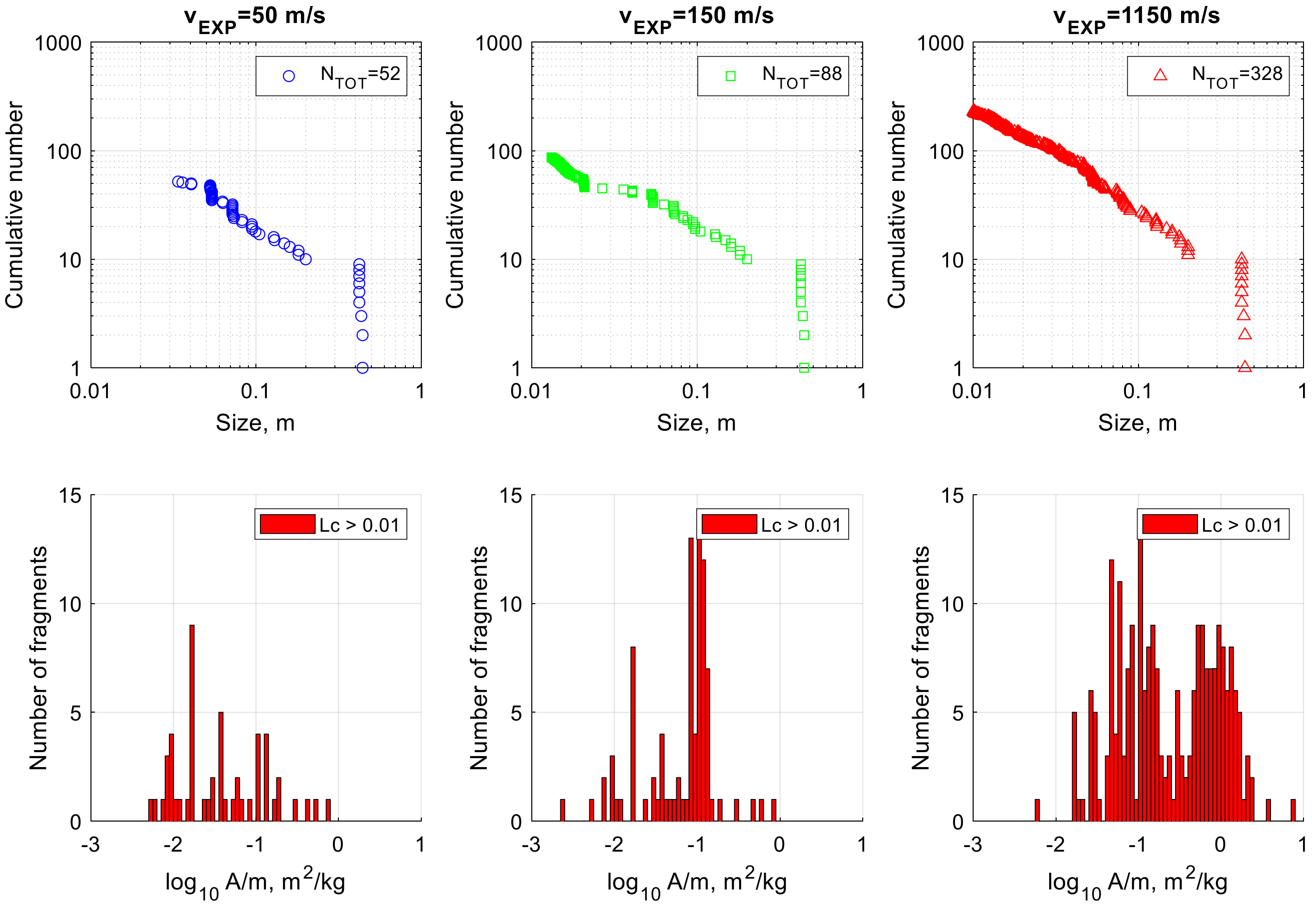

**Fig. 2** CSTS simulations results for the three investigated explosion velocities. On the top, cumulative number distributions of the generated fragments; on the bottom, area-to-mass ratio distributions

objects lie in the size class between 1 and 10 cm; in this case, their area-to mass ratio presents two major peaks, the first one between -1.5 and -1 (from 0.03 to 0.10 $m^2$/kg) and the second one between -0.5 and 0.5 (from 0.32 to 3.16 $m^2$/kg). These results suggest that, due to the high energy of this event, a larger number of MEs with different densities are fragmented by the explosion.

Ground observations from space-track.org (United Space Surveillance Network) cataloged 36 fragments from COSMOS 2499 break-up [36]. This value is compatible with numerical results: assuming a resolution of about 5 cm, it can be noted that all simulations generate between 40 and 60 fragments larger than this size.

## 3 Effect of spacecraft attitude on orbital distributions

Results generated by the three CSTS simulations include information on the generated fragments velocity with respect to an initial reference frame fixed on COSMOS 2499. The orbital propagation of these fragments is therefore related to the definition of the spacecraft attitude, i.e., the orientation of the COSMOS 2499 body-fixed reference frame with respect to the orbital reference frame (e.g., local vertical–local horizontal reference frame). It shall be underlined that a few orbital parameters (the semi-major axis and the eccentricity) of COSMOS 2499 can be directly extrapolated from the last observations of this object before the event; a precise knowledge of all parameters would require the knowledge of the fragmentation epoch.

To date, literature data on fragmentation events observation do not include information on the body attitude at the instant of the event; in fact, this information is usually not available and debris cloud data are presented in the form of Gabbard diagrams. In fact, the position of the exploding tank, close to one base of COSMOS 2499, suggests that velocity propagation of the generated fragments can be strongly directional: debris from the nozzle area would probably be directly ejected in space with a high velocity, while fragments closer to the satellite center would impact and interact with other elements, resulting in lower propagation velocities.

An assessment of the influence of the spacecraft attitude on the debris cloud orbital distribution can be seen in Fig. 3: for each explosion velocity, the fragments Gabbard diagrams were elaborated considering three different attitudes:

1. First, a nadir-pointing satellite was considered, with the nozzle aligned to the Earth direction. In this case, the majority of the generated fragments lie in the proximity of the COSMOS 2499 original position (green squares in the plots) or below it. Only the most energetic event (explosion velocity of 1150 km/s) generates debris with apogee above the spacecraft one. A symmetric condition (nozzle pointing to the zenith, not reported in the figure) would have generated fragments mostly in the proximity of the spacecraft and above it.
2. In case of an explosion with the spacecraft nozzle oriented "out of plane", i.e., aligned with orbit angular momentum direction, results on the Gabbard diagram are closer to the previous case, in particular for the lower explosion velocity cases. In fact, this representation lacks information on the debris orbital inclination, that can be affected by this attitude. In this case, a symmetric condition (nozzle oriented in the negative angular momentum direction) would have generated similar Gabbard diagrams, with minor differences due to the non-homogenous distribution of internal components surrounding the exploding tank.
3. Finally, for the satellite aligned with the velocity vector (nozzle aligned with the negative velocity direction), different orbital distributions can be observed with respect to the previous cases. For the lower velocity, fragments do not cluster symmetrically around the initial orbital parameters, but present a more scattered distribution, with a majority of them with apogee below the spacecraft one. For the more energetic impacts, the scattering is still evident and a few debris present an apogee higher than the COSMOS 2499 one. For a symmetric condition (nozzle aligned with the negative velocity direction), distributions would present a similar scattered distribution, but with the majority of fragments with perigee above the COSMOS 2499 one.

The knowledge of the spacecraft attitude at break-up is therefore an important parameter, as the fragments orbital distributions can be strongly affected by the satellite orientation before the explosion. More detailed simulations and larger set of orbital data should be investigated to assess if information on the debris cloud inclination asymmetries might be useful to reconstruct the spacecraft attitude at break-up.

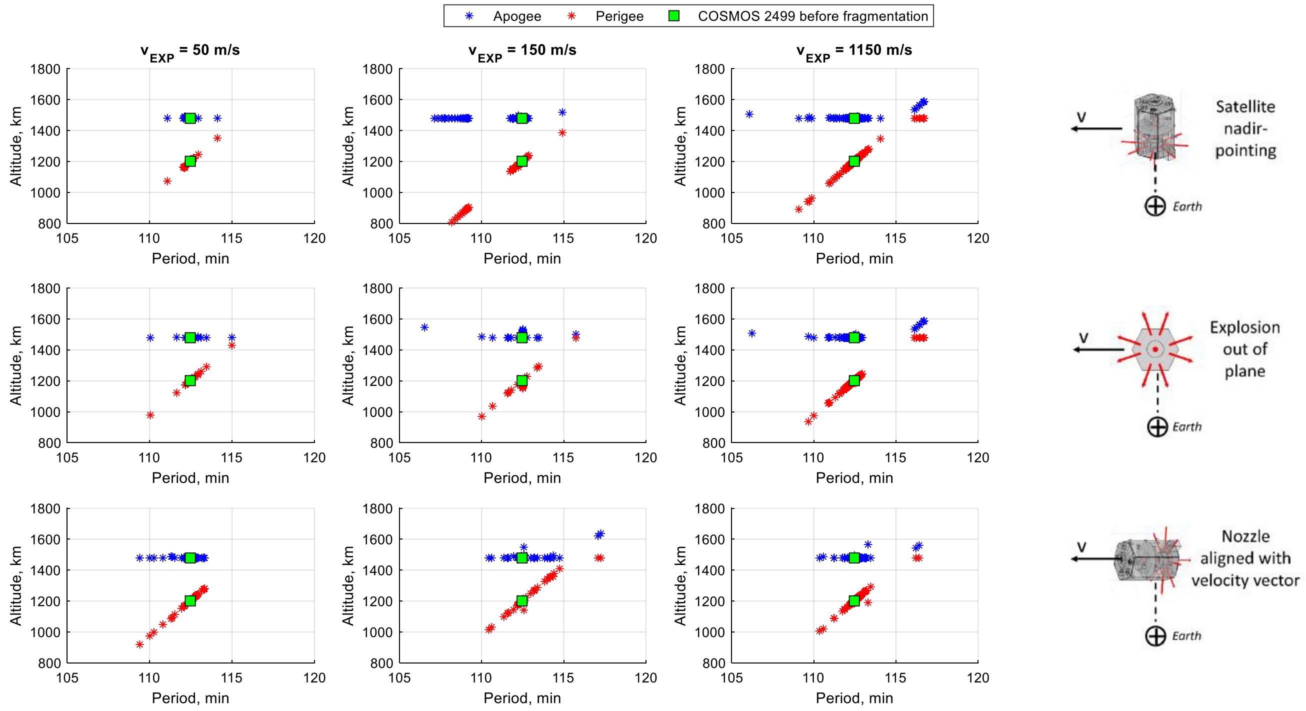

**Fig. 3** Comparison of Gabbard diagrams of the fragments generated by the three CSTS simulations (explosion velocity, respectively, of 50 m/s, 150 m/s, and 1150 m/s) for three different attitudes of COSMOS 2499. Green squares indicate COSMOS 2499 orbital parameters before the fragmentation

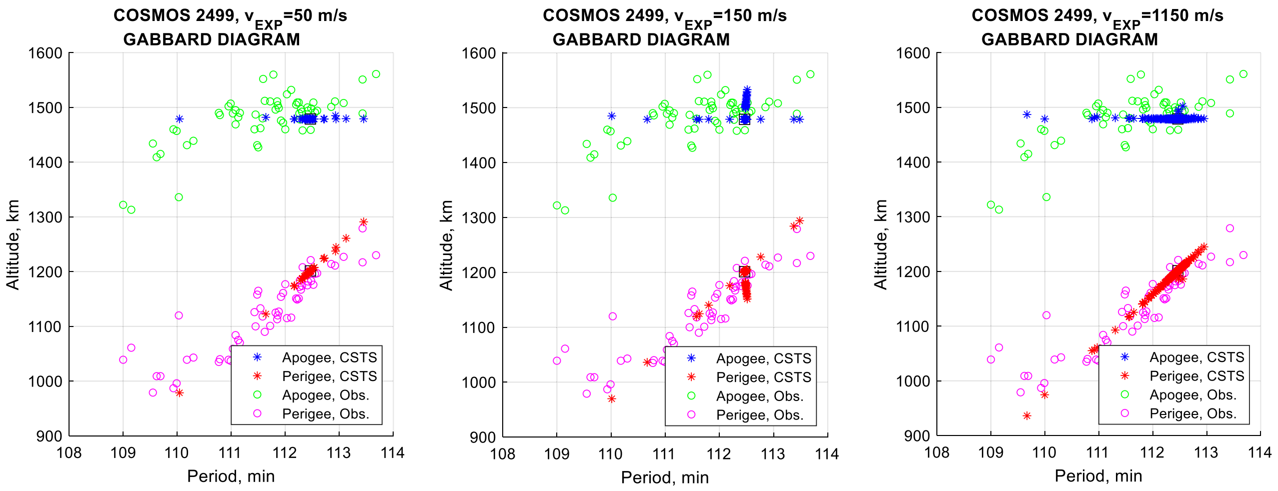

**Fig. 4** Comparison of the orbital parameter of observed debris (green and magenta) and fragments generated by CSTS simulations (blue and red)

## 4 Comparison with observation data

In this section, the simulation results are compared with data from objects tracked by the US Combined Force Space Component Command through the space-track.org website. Out of the COSMOS 2499 debris that are included in the online catalog in June 2023, 36 objects have their first observation dated after January 4, 2023 [35]. Figure 4 compares their orbital parameters with CSTS fragments data for the case of COSMOS 2499 out of plane, that among the selected cases was qualitatively the one most fitting the observation data; in fact, for all three simulations, numerical results are in accordance with observations. In particular, for the most energetic scenario (explosion velocity of 1150 m/s), the largest fraction of fragments is clustered at the same apogees and perigees of the observed debris: for this case, only 3% of all fragments generated by CSTS and only 4% of the fragments larger than 5 cm are at altitudes above or below the observed objects. These results indicate that CSTS can be employed to investigate explosion break-ups; while the number of fragments is strongly related to the explosion velocity, orbital distributions seem more affected by the spacecraft initial attitude.

## 5 Conclusions

In this paper, the COSMOS 2499 fragmentation of 4 January 2023 was replicated with a digital twin generated by the CSTS code and based on the limited information available on the spacecraft geometry. The break-up was modeled by applying an initial expansion velocity to the elements discretizing satellite tank to simulate the satellite explosion. The variation of this parameter affects the number of generated fragments and their area-to-mass ratio distribution; however, the number of fragments larger than 5 cm (between 40 and 60) is comparable with ground observations (38 debris).

The spacecraft attitude at break-up can strongly influence the orbital distribution of the debris cloud; for each simulation, three different attitudes were taken into account and the resulting Gabbard diagrams were obtained. It was observed that an explosion with COSMOS 2499 oriented in the direction of the orbital velocity can generate non-symmetrical debris clouds; further analysis should assess if information on the fragments distribution inclination asymmetries might also be helpful in reconstructing the spacecraft attitude at break-up.

Finally, the comparison of numerical data with the orbital parameters of the tracked debris suggests a good accordance between simulations and observations for at least an attitude configuration and an explosion velocity; this result suggests that CSTS can be an useful tool to investigate in-orbit fragmentation events and can help reconstructing the attitude of an object at the epoch of a break-up event. Future studies should focus on the explosion model, as the imposed velocity seems to be strongly related to the fragments number, and on a more detailed investigation of the effect of the spacecraft attitude on fragments orbital parameters.

**Author contributions** All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Lorenzo Olivieri and Cinzia Giacomuzzo. Funding and resources acquisition were performed by Alessandro Francesconi. The first draft of the manuscript was written by Lorenzo Olivieri and all

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**Data availability** Data sets generated during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

## References

1. Olivieri, L., Francesconi, A.: Large constellations assessment and optimization in LEO space debris environment. Adv. Space Res. **65**, 351–363 (2020)
2. Letizia, F., Virgili, B.B., Lemmens, S.: Assessment of orbital capacity thresholds through long-term simulations of the debris environment. Adv. Space Res. (2022). https://doi.org/10.1016/j.asr.2022.06.010
3. Kessler, D.J., Cour-Palais, B.G.: Collision frequency of artificial satellites: the creation of a debris belt. J. Geophys. Res. Space Phys. **83**, 2637–2646 (1978)
4. Pardini, C., Anselmo, L.: Using the space debris flux to assess the criticality of the environment in low Earth orbit. Acta Astronaut. **198**, 756–760 (2022)
5. Montaruli, M. F., Bonaccorsi, S., Muciaccia, A., Giudici, L., Di Lizia, P., & Colombo, C. (2023). Assessment of the CZ-6A R/B and the H-2A DEB fragmentation events. In: *Aerospace Europe Conference 2023-Joint 10th EUCASS-9th CEAS Conference* (pp. 1–10).
6. Kelso, T.S.: Analysis of the Iridium 33 Cosmos 2251 Collision. NTRA, Washington (2009)
7. Johnson, N.L., Stansbery, E., Liou, J.C., Horstman, M., Stokely, C., Whitlock, D.: The characteristics and consequences of the break-up of the Fengyun-1C spacecraft. Acta Astronaut. **63**(1–4), 128–135 (2008)
8. Muciaccia, A., Facchini, L., Montaruli, M. F., Purpura, G., Detomaso, R., Colombo, C., ... & Bianchi, G. (2022). Observation and Analysis of Cosmos 1408 Fragmentation. In *INTERNATIONAL ASTRONAUTICAL CONGRESS: IAC PROCEEDINGS* (pp. 1–7).
9. Ravi, P., Frueh, C., & Schildknecht, T. (2021). Investigation of three recent Atlas V Centaur upper stage fragmentation events. In 8th European Conference on Space Debris (Vol. 8).
10. Sridharan, R., & Pensa, A. F. (1998). Us space surveillance network capabilities. In *Image Intensifiers and Applications; and Characteristics and Consequences of Space Debris and Near-Earth Objects* (Vol. 3434, pp. 88–100). SPIE.
11. Kennewell, J. A., & Vo, B. N. (2013). An overview of space situational awareness. In *Proceedings of the 16th International Conference on Information Fusion* (pp. 1029–1036). IEEE.
12. Gao J. et al. "A space debris detection and tracking method for wide-field surveillance." Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. Vol. 12617. 2023.
13. Montaruli, M.F., et al.: Adaptive track estimation on a radar array system for space surveillance. Acta Astronaut. (2022). https://doi.org/10.1016/j.actaastro.2022.05.051
14. Karamanavis, V., et al.: Characterization of deorbiting satellites and space debris with radar. Adv. Space Res. **72**, 3269–3281 (2023)
15. Bianchi, G., et al.: A new concept of bi-static radar for space debris detection and monitoring. ICECCME (2021). https://doi.org/10.1109/ICECCME52200.2021.9590991
16. Gogoi, B.B., Rajarajan, D., Kumari, A., Chandrasekhar, M.V., Nirmala, S., Kartik, A.: Fragmentation analysis of a break-up event in low earth orbit. J. Space Safety Eng. **9**(1), 114–123 (2022)
17. Bianchi, G., et al.: A new concept of transmitting antenna on bi-static radar for space debris monitoring. ICECCME (2022). https://doi.org/10.1109/ICECCME55909.2022.9988566
18. Armellin, R.: Collision avoidance maneuver optimization with a multiple-impulse convex formulation. Acta Astronaut. **186**, 347–362 (2021)
19. Bombardelli, C., Hernando-Ayuso, J., García-Pelayo, R.: Collision avoidance maneuver optimization. Adv. Astronaut. Sci. **152**(7402), 1857–1870 (2014)
20. M. Romano, et al., Characterising in-orbit fragmentations with the PUZZLE software, ICATT 2021
21. Montaruli, M.F., et al.: A stochastic approach to detect fragmentation epoch from a single fragment orbit determination. Adv. Space Res. (2023). https://doi.org/10.1016/j.asr.2023.08.031
22. Johnson, N.L., Krisko, P.H., Liou, J.-C., Anz-Meador, P.D.: NASA's new breakup model of EVOLVE 4.0. Adv. Space Res. **28**, 1377–1384 (2001)
23. McKnight, D., Maher, R., Nagl, L.: Fragmentation algorithms for strategic and theater targets (FASTT) empirical breakup model, Ver 3.0. Int. J. Impact Eng **17**, 547–558 (1994)
24. McKnight, D., Maher, R., Nagl, L.: Refined algorithms for structural breakup due to hypervelocity impact. Int. J. Impact Eng **17**, 547–558 (1995)
25. Sorge, M.E. Satellite fragmentation modeling with IMPACT. In Proceedings of the AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Honolulu, HI, USA, 18–21 August 2008.
26. Sorge, M.E., Mains, D.L.: IMPACT fragmentation model developments. Acta Astronaut. **126**, 40–46 (2016)
27. Abdulhamid, H.; Bouat, D.; Colle, A.; Lafite, J.; Limido, J.; Midani, I.; Omaly, P. On-ground HVI on a nanosatellite. impact test, fragments recovery and characterization, impact simulations. In: Proceedings of the 8th ESA Space Debris Conference, Darmstadt, Germany, 20 April 2021.
28. Schimmerohn, M., Matura, P., Watson, E., Durr, N., Altes, A., Cardone, T., Schaefer, F., et al.: Numerical investigation on the standard catastrophic breakup criteria. Acta Astronaut. **178**, 265–271 (2021)
29. Olivieri, L., Giacomuzzo, C., Lopresti, S., Francesconi, A.: Research at the University of Padova in the Field of Space

Debris Impacts against Satellites: An Overview of Activities in the Last 10 Years. Appl. Sci. **13**(6), 3874 (2023)

30. Francesconi, A., Giacomuzzo, C., Olivieri, L., Sarego, G., Duzzi, M., Feltrin, F., Valmorbida, A., Bunte, K.D., Deshmukh, M., Farahvashi, E., et al.: CST: A new semi-empirical tool for simulating spacecraft collisions in orbit. Acta Astronaut. **160**, 195–205 (2019)
31. Francesconi, A., Giacomuzzo, C., Olivieri, L., Sarego, G., Valmorbida, A., Duzzi, M., Bunte, K.D., Farahvashi, E., Cardone, T., de Wilde, D.: Numerical simulations of hypervelocity collisions scenarios against a large satellite. Int. J. Impact Eng **162**, 104130 (2022)
32. Olivieri, L., Giacomuzzo, C., Francesconi, A.: Simulations of satellites mock-up fragmentation. Acta Astronaut. **206**, 233–242 (2023)
33. Orbital Debris Quarterly News, June 2023 | Volume 27 - Issue 2
34. Orbital Debris Quarterly News, February 2020| Volume 24 - Issue 1
35. Data downloaded on June 06, 2023 from space-track.org
36. https://space.skyrocket.de/doc_sdat/kosmos-2491.htm. Accessed 08 Jun 2023.
37. Baker, W. E., Kulesz, J. J., Ricker, R. E., Bessey, R. L., Westine, P. S., Parr, V. B., & Oldham, G. A. (1975). Workbook for predicting pressure wave and fragment effects of exploding propellant tanks and gas storage vessels (No. NASA-CR-134906).