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ORIGINAL ARTICLE

Simulation of In-Space Fragmentation Events

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Abstract

In the next years, the space debris population is expected to progressively grow due to in-space collisions and break-up events; in addition, anti-satellite tests can further affect the debris environment by generating large clouds of fragments. The simulation of these events allows identifying the main parameters affecting fragmentation and obtaining statistically accurate populations of generated debris, both above and below detection thresholds for ground-based observatories. Such information can be employed to improve current fragmentation models and to reproduce historical events to better understand their influence on the non-detectable space debris population. In addition, numerical simulation can also be used as input to identify the most critical objects to be removed to reduce the risk of irreversible orbit pollution. In this paper, the simulation of historical in-orbit fragmentation events is discussed and the generated debris populations are presented. The presented case-studies include the COSMOS-IRIDIUM collision, the COSMOS 1408 anti-satellite test, the 2022-151B CZ-6A in-orbit break-up, and a potential collision of ENVISAT with a spent rocket stage; for these events, results are presented in terms of cumulative fragments distributions and debris orbital distributions.

Keywords Space debris · Fragmentation · Break-up · Numerical simulations

1 Introduction

The increasing number of objects resident in Earth orbits due to large constellations deployment [1, 2] and a general growth in the number of launches [3, 4] is leading the debris environment dangerously close to the Kessler Syndrome, i.e. to a condition of self-sustained cascade impacts and break-ups that would strongly reduce the access and exploitation of near-Earth space [5]. In fact, experts are indicating that the current situation is already showing a growing trend in the number of in-orbit collisions and number of resident objects even for "no further launches" scenario [6, 7]. The sustainability of the space environment is, therefore, under scrutiny by the scientific community [8]: mitigation techniques [9–11] and strategies to reduce the hazard of space debris [12–14] are under evaluation by all the main stakeholders [15, 16]. In addition, it is still crucial to understand the physical processes involved in spacecraft collisions and fragmentations and how these events can affect the space environment [17] and other spacecraft [18]. Data on spacecraft breakup can be acquired by the observation of in-space fragmentation events [19–21], the execution of ground tests [22, 23], and the performing of numerical simulations [24, 25].

In this context, the University of Padova has developed the Collision Simulation Tool Solver (CSTS) to numerically evaluate in-space fragmentation events [26, 27]. In the tool (see Fig. 1), the colliding bodies are modelled with a mesh of Macroscopic Elements (MEs) that represent the main parts of the satellite; structural links connect them forming a system-level net. In the current version of CST four link models have been implemented to connect elements, featuring common structural joints (bolts, welds, and glued surfaces) as well as material continuity [26]. In case of collision, the involved MEs are subjected to fragmentation,

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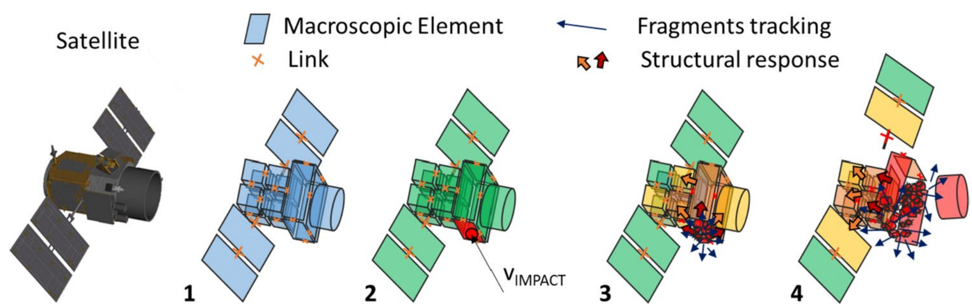

Fig. 1 CSTS modelling with MEs and links and simulation logic with cascade effect

addressed through the use of semi-empirical breakup models, that depends on impact point and elements geometry and material [26]. In parallel, structural damage can be transmitted through the links: the failure is addressed through a discrete-elements approach, which considers the momentum transferred to MEs and the energy dissipated inside them and through the links [26]. This approach can be propagated through a cascade effect representative of the object fragmentation, allowing the simulation of complex collision scenarios and producing statistically accurate results [28, 29].

In this work, the CSTS is employed to simulate four relevant fragmentation events; the debris distributions obtained by each case are discussed. First, three fragmentation events observed in orbit (the COSMOS-IRIDIUM collision, the COSMOS 1408 anti-satellite test, and the 2022-151B CZ-6A in-orbit fragmentation) are presented; last, the potential breakup of ENVISAT due to the collision with a spent rocket stage is introduced. The first three scenarios are employed to compare the tool outputs with real observation data and with the empirical NASA Standard Breakup Models (SBM) [30]. The last case, ENVISAT fragmentation, showcases the danger from this large and uncontrolled object and further suggests the importance of performing an Active Debris Removal mission before a hypothetical break-up would strongly contaminate the Low-Earth Orbit environment. For each case, a brief description of the model and the main simulation results are presented.

2 In-Space Fragmentation Case Studies

In this section, the four cases studied with the CSTS are presented and the main simulation results are discussed. Fragments distributions are compared with the NASA Standard Breakup Models (SBM), an empirical model developed from observational and test data to evaluate the distributions of fragments generated by orbital break-ups [30]. It shall be underlined that CSTS does not perform orbital propagation and therefore the simulations represent the fragments distributions right after the event. On the contrary, observation data often can date back to weeks or months after the fragmentation and in this timeframe their orbit could be partially affected by external disturbances. In particular, atmospheric drag can affect low-altitude debris by circularizing their orbit.

2.1 COSMOS-IRIDIUM Collision

On 10 February 2009, the 950 kg defunct satellite COSMOS 2251 and the 560 kg active IRIDIUM 33 collided at an altitude of about 790 km [20]; both spacecraft fragmented, generating two large clouds of debris [31]. This event was the first collision between two intact spacecraft; more than 1000 debris were detected with ground telescopes, with an expected orbital lifetime of several decades [32]. For this event, it is possible to calculate the kinetic energy to mass ratio (EMR); a value of 39,660 J/g, few orders of magnitude above the classic threshold of 40 J/g [30], suggests that the collision can be considered catastrophic (i.e. leading to the complete fragmentation of the involved bodies).

Iridium 33 was shaped as a 3.6 m long triangular prism main body, with two solar panels and three communication antennas [33]. COSMOS 2251 had a cylindrical shape of about 2 m diameter by 2 m length, and a gravity gradient boom as main appendage [33]. Only partial data are available on the COSMOS 2251 and IRIDIUM 33 collision parameters; in particular, a glancing impact (i.e. with only a fraction of the bodies mass directly involved in the collision, such as an impact on an appendage) has been hypothesized [33] but no direct evidence could be obtained from observations. To better understand the event and investigate the impact geometry, two simulations were therefore performed with CSTS, replicating a central and a glancing impact. The geometrical model developed in CSTS can be seen in Fig. 2. COSMOS 2251 model consists in an equivalent solid cylinder with density of 55 kg/m3 (an average value for satellites honeycomb sandwich panels) with a 6 m boom. IRIDIUM 33 has a main body in the shape of a triangular prism, populated by internal boxes, two panels, and three main flat antennas. The baseline choices for elements' material are aluminium alloy and carbon fibre-reinforced plastic (CFRP); the total mass fraction of CFRP in the models is 28%.

Figure 3 shows obtained results in terms of cumulative characteristic length distribution for both cases, compared

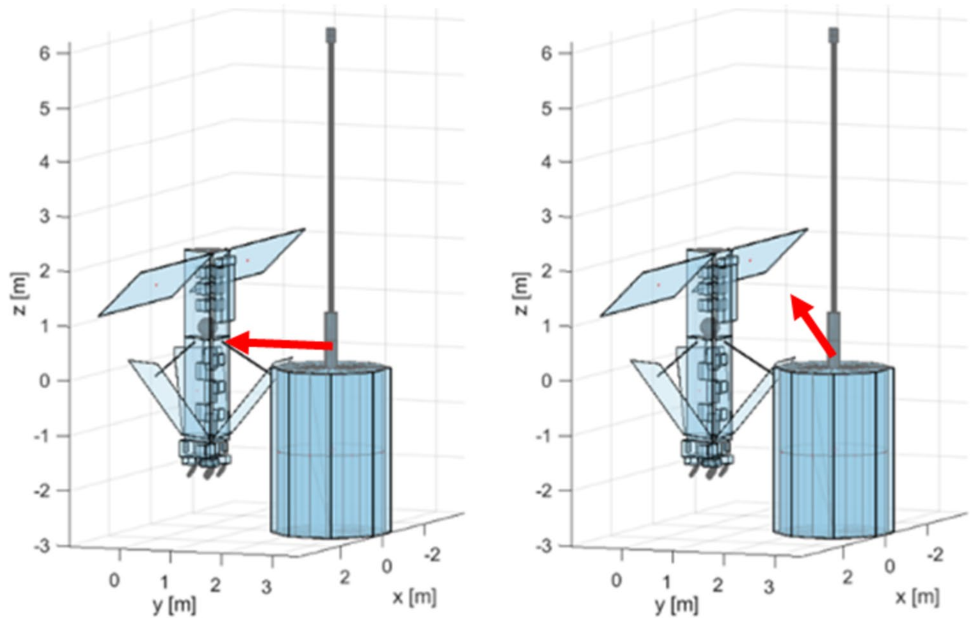

Fig. 2 COSMOS-IRIDIUM geometrical models for central (left) and glancing (right) impacts

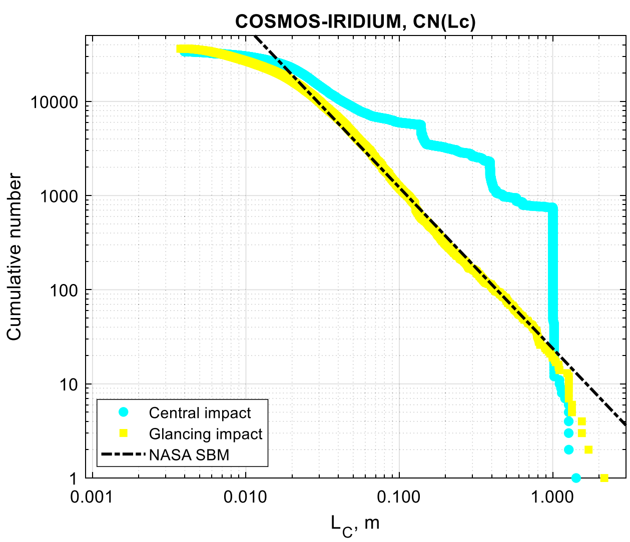

Fig. 3 COSMOS-IRIDIUM fragments cumulative distributions for central (blue) and glancing (yellow) impacts, compared to NASA SBM prediction (dashed line)

to the estimation from NASA SBM [30] for a catastrophic impact between the two satellites. The total number of fragments is comparable (33,900 for central impact, 36,308 for the collision on IRIDIUM appendage). However, the two distributions clearly differ, with a quasi-linear trend for the glancing impact (yellow markers) in the range from 2 mm to 1 m, clearly in accordance with the NASA SBM estimation; on the contrary, the central collision (in blue) shows a higher number of larger debris (at characteristic lengths of about 1 m) and, in general, a large deviation from the NASA SBM. The differences between simulations results also confirm that CSTS are capable to capture the effect of complex impact scenarios and the influence of parameters such as the impact point, that are not considered by the NASA SBM. The development and utilization of new, advanced models therefore enables evaluating the validity of NASA SBM predictions, that still represent a valid tool for a large fraction of break-ups. In fact, the accordance between glancing impact data and the NASA SBM confirms the hypothesis on this collision configuration.

The Gabbard diagram in Fig. 4 compares CSTS data for the glancing impact (green and pink circles) with the observed fragments for COSMOS 2251 [34]. It is possible to notice an accordance between numerical data and observations, further confirming that the COSMOS IRIDIUM event consisted in a glancing impact.

2.2 COSMOS 1408 Anti-Satellite Test

In November 2021, a Russian anti-satellite test led to the break-up of the defunct 1750 kg COSMOS 1408 satellite at an altitude of about 480 km, generating a cloud of fragments [35] comprising more than 1700 observed debris [36]. For this event, only partial information on the spacecraft and the kinetic impactor were available. The satellite belonged to the Tselina-D class [37], with two solar panels placed at about half of its body and four appendages hinged to its base, while the impactor is rumoured to be the last stage of an A-235 Nudol anti-ballistic missile [37]. A simplified model of the satellite was, therefore, designed in CSTS (see Fig. 5), with a central prismatic body populated by internal boxes, two solar panels, and four appendages; two internal spherical elements reproduce internal tanks. In a similar fashion,

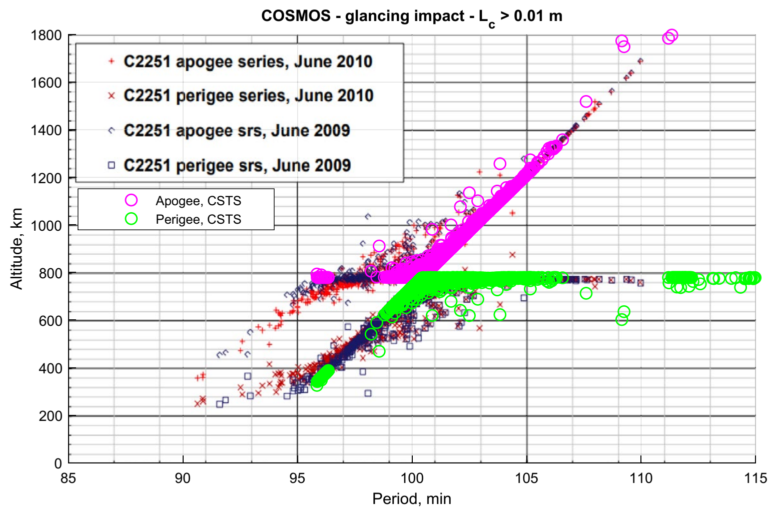

Fig. 4 Comparison of observed [34] and simulated fragments (glancing impact) on the Gabbard diagram for COSMOS 2251 debris cloud

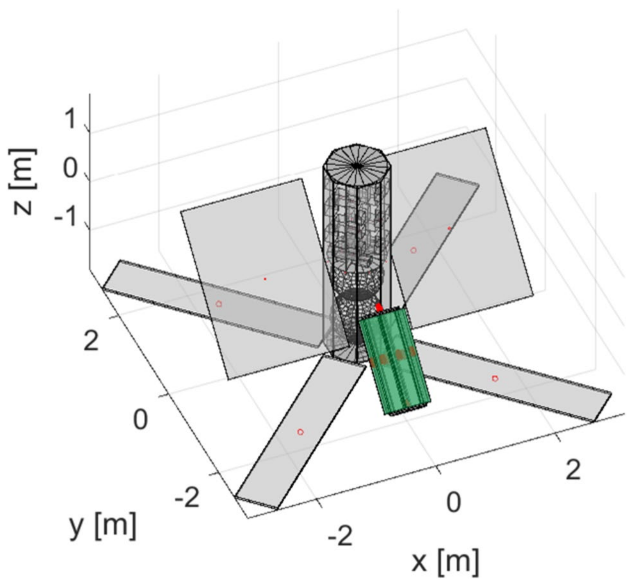

Fig. 5 Geometrical model of COSMOS 1408, in gray, with the kinetic impactor, green

the kinetic impactor is replicated with a cylindrical body. It shall be noted that the NASA SBM presents two formulations, for catastrophic and sub-catastrophic collisions [30], both linear in the logarithmic space and both depending on a parameter M; in the first case, M is the total mass of the involved bodies, and in the second case, it represents the impactor momentum. From observation data (Fig. 6, left, blue dashed line), a numerical value of $M = 1112 \pm 18$ was obtained; as the COSMOS 1408 mass is larger than M, this parameter shall represent the impactor momentum. On these considerations, assuming an impact velocity of 3 km/s for a ballistic launch (i.e. less than half the orbital velocity), it was possible to obtain an impactor mass of 370 kg. It shall be noted that the EMR of this collision is 951 J/g, above the catastrophic threshold; this contradiction already suggests that the NASA SBM could be not capable to represent the complexity of this collision event.

Figure 6 compares observed and simulated fragments in terms of cumulative distributions (left) and Gabbard diagram (right). Due to uncertainties in the geometrical model and in the impact conditions (among all, the impact point and the attitude of COSMOS 1408 at collision), the accuracy of the CSTS model was limited, leading to an underestimation of the fragments cumulative number (in red in Fig. 6, left) with respect to observations (blue line) and NASA SBM model (black lines). However, as visible in the Gabbard diagram (Fig. 6, right), the orbital distribution of generated fragments is still in accordance with observations [36], with the classical divergent "butterfly" shape, in particular for objects with apogee altitude higher than COSMOS 1408 original one. It shall be noted that the lower altitude objects were affected by atmospheric drag in the period between the event (November 2021) and the date of observation (January 2022), leading to a partial circularization of their orbit; for this reason, a larger deviation between CSTS results and observations can be observed for debris with perigee lower than COSMOS 1408 original one.

2.3 2022-151B CZ-6A In-Orbit Break-Up

In November 2022, the second stage of the Long March CZ-6A fragmented after releasing its payload [38]. The whole launcher vehicle is about 50 m high with a diameter of 3.5 m; both stages use kerosene and liquid oxygen as propellant and the launcher can lift up to 4 tons at a 670 km sun-synchronous orbit. After the 11 November 2022 launch and payload release, the second stage was subjected to an expected break-up, that might be related to a failure in one of the following operations: a venting procedure, a thruster re-activation for orbit lowering, or the stage deactivation [39].

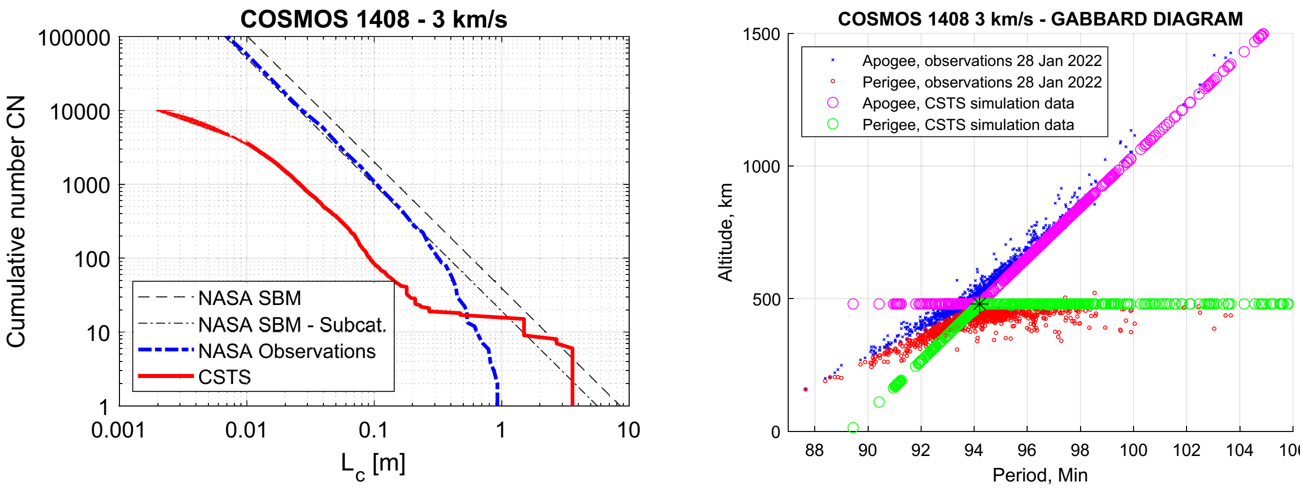

Fig. 6 COSMOS 1408: generated fragments cumulative distributions (left) and Gabbard diagram (right)

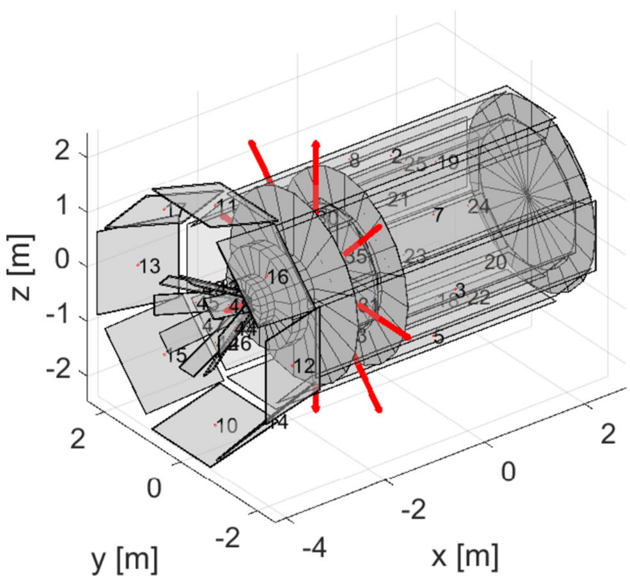

Fig. 7 CZ-6A geometrical model in CSTS

Only limited information is available on the geometry of the CZ-6A second stage. The CSTS model for the stage can be seen in Fig. 7 and consist in a single nozzle, two internal tanks, and an external metallic case. The explosion of one tank was simulated by applying a radial expansion velocity to its components (red arrows in Fig. 7); a value of 150 m/s, obtained from data in literature on tanks explosion [40], was applied.

A total of more than 500 fragments were obtained by the simulation; Fig. 8 shows the characteristic length distribution (left, compared to the NASA SBM curve for explosion event) and the fragments Gabbard diagram (right). In this case, no size distribution was available from observation data. With respect to the Gabbard diagram (Fig. 8, left), numerical data are compatible with the orbital distribution of observed fragments (31 December 2022) [41], suggesting that CSTS can be employed to replicate in-orbit explosion events.

2.4 Potential Collision of ENVISAT with a Spent Rocket Stage

ENVISAT is currently one of the largest debris (about 7 tons) in Low Earth Orbit and it resides in a highly populated zone (800 km sun-synchronous orbit) [42]. After its loss in 2012, probably due to a collision with an undetected debris, the scientific community has been worried of further potential impacts that can lead to the spacecraft breakup; for this reason, ENVISAT ranks among the first positions for future Active Debris Removal missions [43–45].

In this section, a potential collision scenario between ENVISAT and a 4 ton spent rocket stage is evaluated. The CSTS geometrical model and impact configuration can be seen in Fig. 9; two different velocities are simulated, respectively of 1 km/s (ballistic collision, EMR of 286 J/g) and 10 km/s (hypervelocity collision, EMR of 28,571 J/g); both are representative of potential impacts in low-Earth orbits. In both cases, the collision can be considered “central”, as the rocket stage impacts directly on ENVISAT main body and the majority of the masses are directly involved in the breakup (see Fig. 9). ENVISAT model features the same elements of the real spacecraft, with structural components, the solar array, and the scientific instrumentation. The baseline choice for elements’ material is aluminium alloy, since it features a ductile structural behaviour, while solar panels are CFRP to simulate a brittle fracture. The rocket stage model is based on the 4-ton second stage of the Long March CZ2C; again, the element’s material is aluminium alloy. Complex

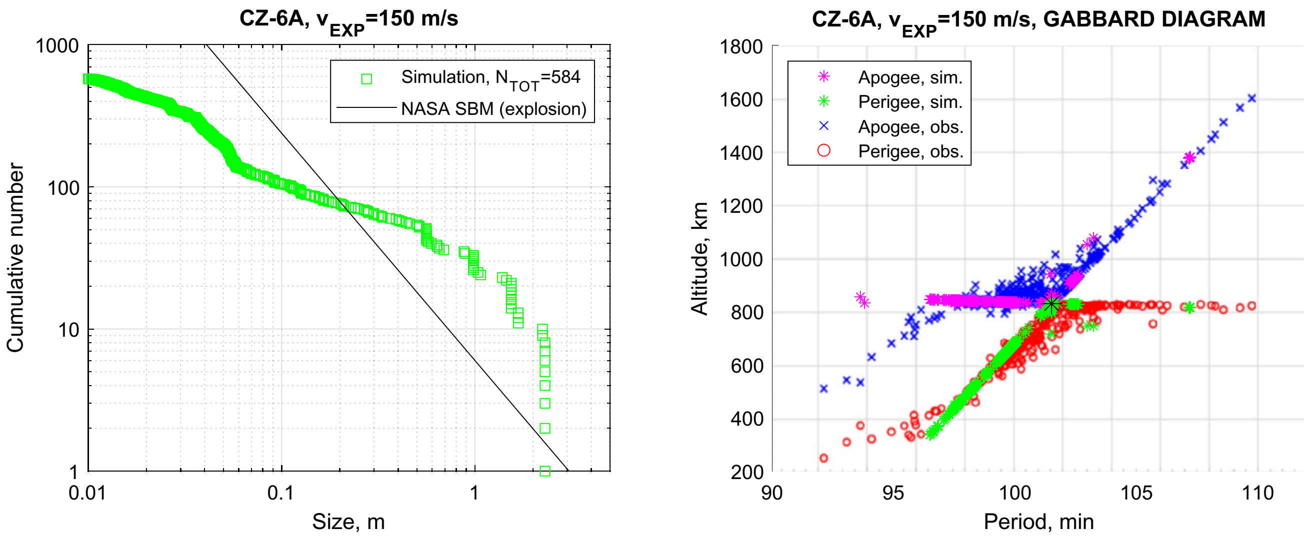

Fig. 8 CZ-6A generated fragments cumulative distributions (left, CSTS data and NASA SBM estimation), and comparison of observed and simulated fragments on the Gabbard diagram (right)

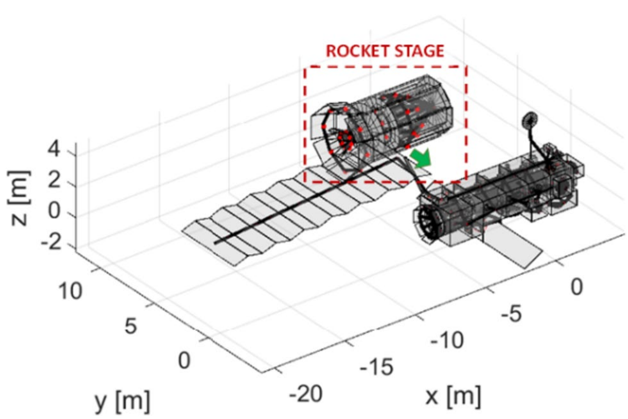

Fig. 9 ENVISAT Vs. rocket stage impact geometrical models in CSTS simulation

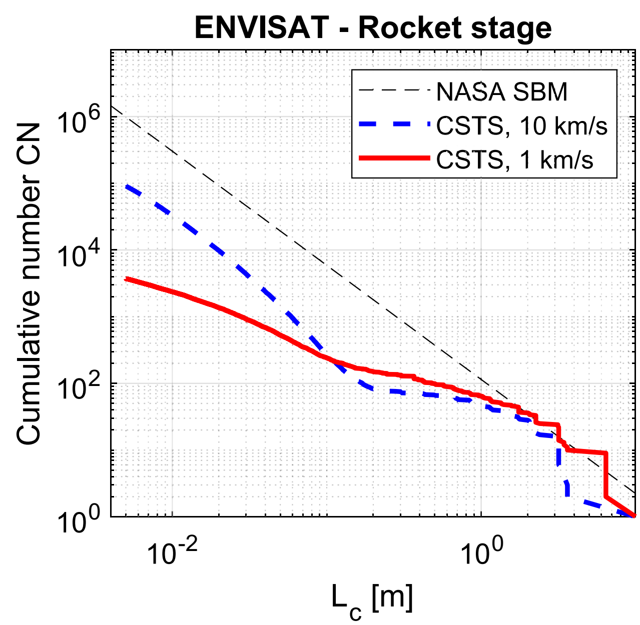

Fig. 10 ENVISAT Vs. rocket stage: the cumulative distributions of generated fragments for the two velocity cases are compared with the NASA SBM

features such as the nozzle are simplified with a series of radial plates.

For these two scenarios, the cumulative distributions reported in Fig. 10 were obtained. The results are compared with the NASA SBM estimation, that for catastrophic impacts (EMRs larger than 50 J/g) depend only on the total involved mass and not from the impact velocity; for this reason, only one curve, valid for bot simulation parameters, is represented for the model. As expected, the 10 km/s scenario generates more fragments due to the higher energy of the event, with about 100,000 fragments larger than 5 mm. The distribution is below the estimation of this event performed by the NASA SBM, suggesting that the complex geometry and high mass of the two involved bodies might influence the fragmentation mechanism; however, this breakup would strongly affect the already crowded 800 km sun-synchronous orbit currently occupied by ENVISAT. These results strongly suggest that ENVISAT should be selected among the first targets for Active Debris Removal, before any fragmentation event could involve this large, uncontrolled object.

3 Conclusions

This paper presented four simulation cases for in-space break-up events performed with the CSTS tool. First, the collision between COSMOS and IRIDIUM was evaluated, suggesting that a glancing impact might be representative of the event. Second, the anti-satellite test on COSMOS 1408 was replicated; while uncertainties in the geometrical model and in the impact conditions led to an underestimation of the number of generated fragments, CSTS was capable to simulate their orbital distribution. Third, the break-up of the second stage of the Long March CZ-6A was simulated, indicating that CSTS can be used to replicate explosion events. Last, the simulation a potential collision between ENVISAT and a spent rocket stage was performed; results suggest that thousands of fragments might contaminate ENVISAT 800 km sun-synchronous orbit in case of the satellite break-up.

In conclusion, it is shown that CSTS is capable to replicate complex fragmentation scenarios, providing statistically accurate results. These data can be employed to evaluate the effect of break-ups in the evolution of both observable and non-detectable debris population, providing a solid set of data to assess the risks and the consequences of fragmentation events. In the close future, further capabilities will be included in CSTS: new materials libraries are under development to better represent appendixes such solar arrays, while automatic procedures for fragments generation from tank explosion will be added to the code. In addition, in the next years, a set of ground experiments on complex targets will be performed to provide a solid reference for the code validation. These advances will lead to a reliable and accurate code capable to perform numerical simulations of known and future break-up events.

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Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Lorenzo Olivieri, Stefano Lopresti 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 authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The data supporting the findings of this study are available from the corresponding author, LO, upon reasonable request.

Declarations

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

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