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 generating 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 employed to identify the most critical object 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.

Introduction

The increasing number of objects resident in Earth orbits 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 [1]. Mitigation techniques and strategies to reduce the hazard of space debris are under evaluation by the scientific community and the main stakeholders [2]; however, it is still crucial to understand the physical processes involved in spacecraft collisions and fragmentations. Data on spacecraft breakup can be acquired by the observation of in-space fragmentation events [3-4], the execution of ground tests [5-6], and the performing of numerical simulations [7-8].

In this context, the University of Padova has developed the Collision Simulation Tool Solver (CSTS) to numerically evaluate in-space fragmentation events [9-10]. 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 case of collision, the involved MEs are subjected to fragmentation, while structural damage can be transmitted through the links; 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.

In this work, the CSTS is employed to replicate three fragmentation events observed in orbit and the potential breakup of ENVISAT due to the collision with a spent rocket stage. For each case, a brief description of the model and the main simulation results are presented.

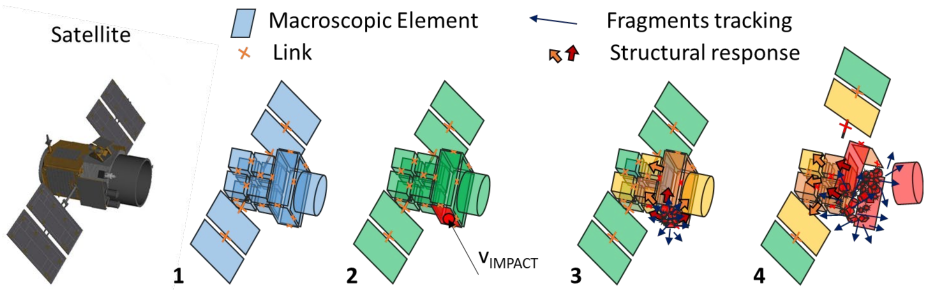

Fig. 1: CSTS modelling with MEs and links and simulation logic with cascade effect

In-space fragmentation case studies

1. COSMOS-IRIDIUM collision

This event, dating back to 2009, was the first collision between two intact spacecraft, the active IRIDIUM 33 and the defunct COSMOS 2251. In CSTS, two simulations replicating a central and a glancing impact have been performed. Fig. 2 shows the geometrical models for both cases and the obtained results in terms of cumulative characteristic length distribution; the glancing impact data (yellow) is clearly in accordance with the NASA SBM model.

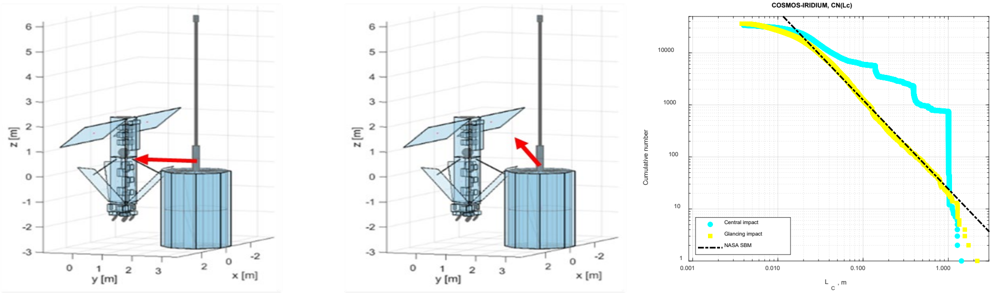

Fig. 2: COSMOS-IRIDIUM geometrical models for central (left) and glancing (centre) impacts and generated fragments cumulative distributions (right)

The Gabbard diagram in Fig. 3 compare CSTS data with the observed fragments for COSMOS 2251. Again, it is possible to notice an accordance between numerical data and observations.

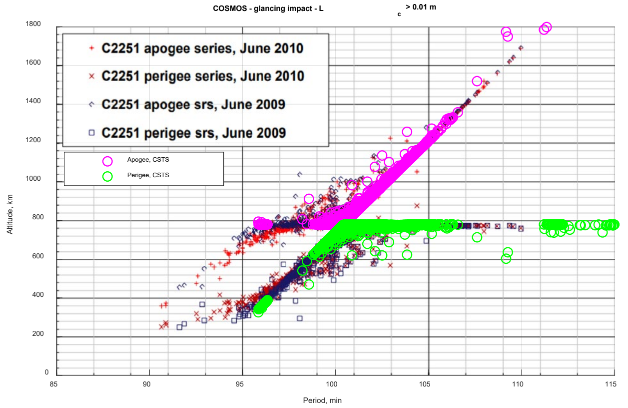

Fig. 3: Comparison of observed and simulated fragments (glancing impact) on the Gabbard diagram for COSMOS 2251 debris cloud

2. COSMOS 1408 anti-satellite test

In November 2021 a Russian anti-satellite test led to the break-up of the defunct COSMOS 1408 satellite. For this case, only partial information on the spacecraft and the kinetic impactor were available; the accuracy of CSTS model (see Fig. 4, left) is therefore limited, leading to an underestimation of the fragments cumulative number (in red in Fig. 4, center) with respect to observations (blue line) and NASA SBM model (black lines). However, as visible in the Gabbard diagram (Fig. 4, right), the orbital distribution of generated fragments is still in accordance with observations.

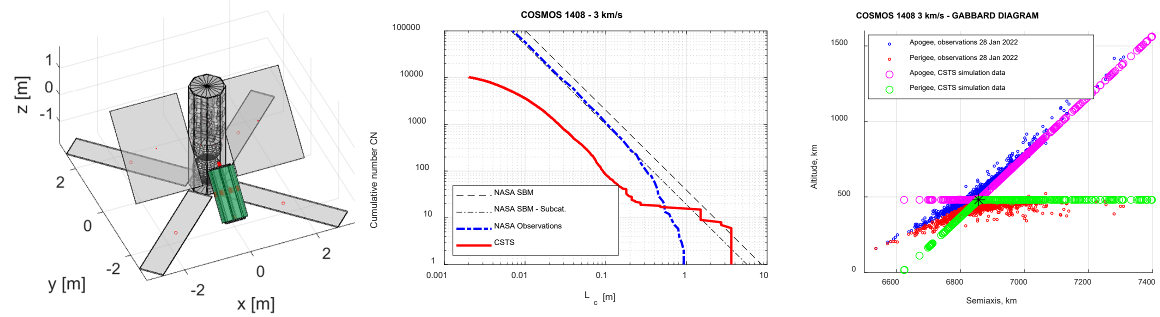

Fig. 4: geometrical model of COSMOS 1408, in gray, and the kinetic impactor, green (left); generated fragments cumulative distributions (center) and Gabbard diagram (left)

3. 2022-151B CZ-6A in-orbit break-up

In November 2022, the second stage of the CZ-6A fragmented after releasing its payload. This event was replicated with a dedicated CSTS simulation (Fig. 5), estimating the explosion of a tank. A total of more than 500 fragments were obtained by the simulation; numerical data are still compatible with the orbital distribution of observed fragments (Fig. 5).

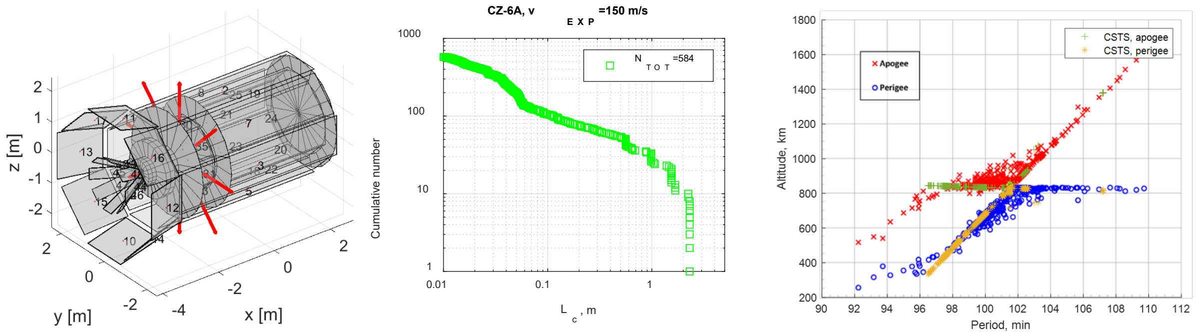

Fig. 5: CZ-6A geometrical model (left), generated fragments cumulative distributions (centre), and comparison of observed and simulated fragments on the Gabbard diagram (right)

4. Potential collision of ENVISAT with a spent rocket stage

Last, this potential collision scenario evaluated an impact of ENVISAT with a spent rocket stage (Fig. 6, left) at two different velocities, respectively of 1 km/s and 10 km/s. With CSTS it is possible to obtain the cumulative distributions reported in Fig. 6, right. 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 obtained distribution is below the estimation of this event performed by the NASA SBM; however, this breakup would strongly affect the already crowded 800 km sun-synchronous orbit currently occupied by ENVISAT.

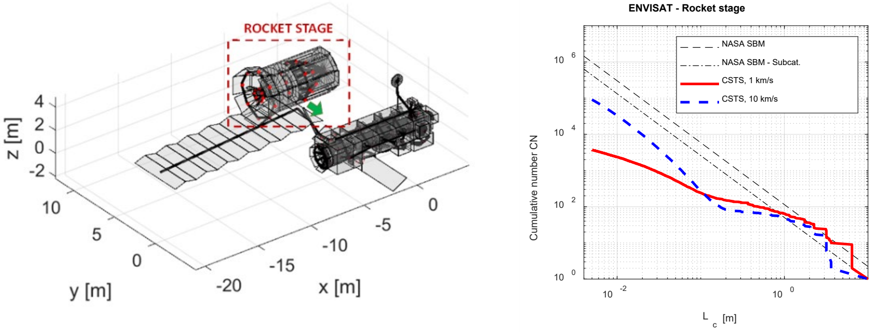

Fig. 6: ENVISAT Vs. rocket stage impact geometrical models (left) and generated fragments cumulative distributions (right)

Conclusions

This paper presented four simulation cases for in-space break-up events. It is shown that CSTS is capable to replicate complex fragmentation scenarios, providing statistically accurate results. These data will be employed to evaluate the effect of break-ups in the evolution of the non-detectable debris population and to assess the correlated risks.

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