POLITECNICO MILANO 1863 | DEPARTMENT OF AEROSPACE SCIENCE AND TECHNOLOGY

COMPASS

2nd Space Capacity Allocation For The Sustainability of Space Activities Workshop

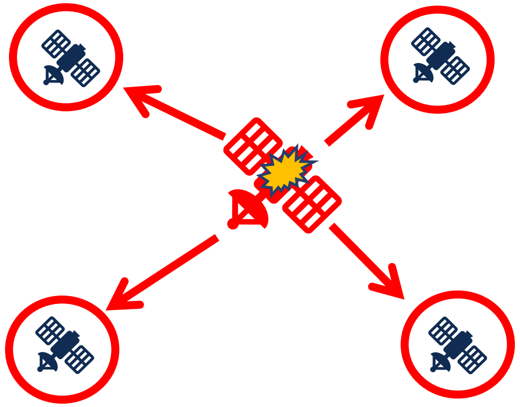
Estimation of the Avoidance Manoeuvre Operational Burden Caused by In-Orbit Fragmentation Events

04.06.2026 I **Juan Felipe Cabrera**, Daniel Lück, Achraf Mizmizi, Emma Stevenson, Francisco Simarro, Eduardo Arias, Sean Hannon, and Camilla Colombo

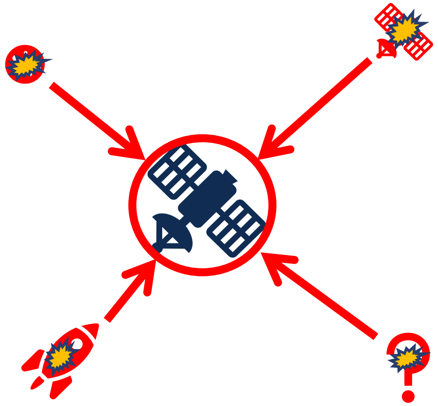
Fragmentation Consequences

- The congested space environment requires methods for the estimation of the consequences that a fragmentation can create.

Consequences created **by** you



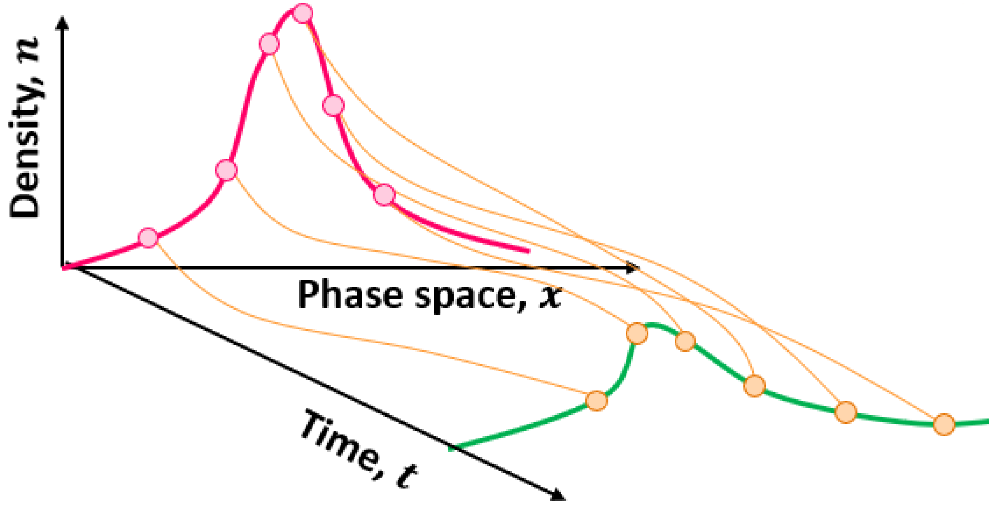
Consequences created **on** you



- The **aim** of this work is to present a more tangible way to measure consequences in an operational context
  - In addition to the known methods to estimate the **No. of collisions with debris**
  - We seek to estimate the **operational burden** in terms of No. of conjunctions to be assessed and potential **CAMs to be performed on debris**.

Continuum approach for debris modelling

- The fundamental aspect is the use of the Method of Characteristics (MOC) for solving the system of partial differential equations, where the phase state is in orbital elements.
- Probability density functions can be rebuilt after propagation by marginalising any combination of orbital elements.
- The initial distribution for a fragmentation is obtained from the NASA SBM.
- Cumulative Probability of Collision (PoC) between the debris and other targets can be estimated using the kinetic gas analogy.



$$\begin{cases} \dfrac{\mathrm{d}\boldsymbol{y}}{\mathrm{d}t} = \boldsymbol{F} \\ \dfrac{\mathrm{d}n}{\mathrm{d}t} = -n\nabla_{\boldsymbol{y}} \cdot \boldsymbol{F} \end{cases}$$

$$P_c(t) = 1 - \exp\left(-\eta(t)\right)$$

Giudici, Lorenzo. (2024). Space debris environment analysis with continuum mechanics. *PhD Thesis. Politecnico di Milano.*

Impact rate between fragments and target

- From kinetic gas theory, the impact rate $\dot{\eta}$ depends on the target's cross-sectional area A_c, the fragment density in the path of the target $n(\boldsymbol{r})$ and the relative velocity v_{rel}.

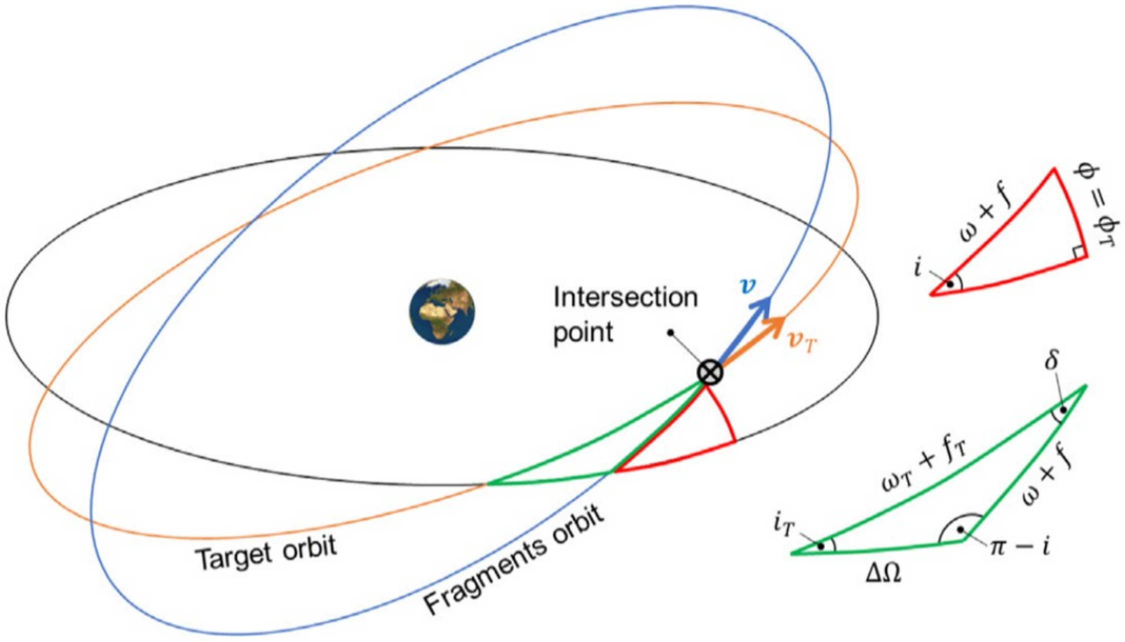
$$\dot{\eta} = A_c n(\boldsymbol{r}) v_{rel}$$

- Relative velocity depends on the impact geometry, specifically the collision angle δ for circular orbits:

$$v_{\mathrm{rel}} = \sqrt{v_T^2 + v^2 - 2 v_T v \cos\delta}$$

- From the Keplerian elements assuming circular orbit for fragment and target:

$$\cos\delta = \sin i_T \sin i \cos\Delta\Omega + \cos i_T \cos i$$

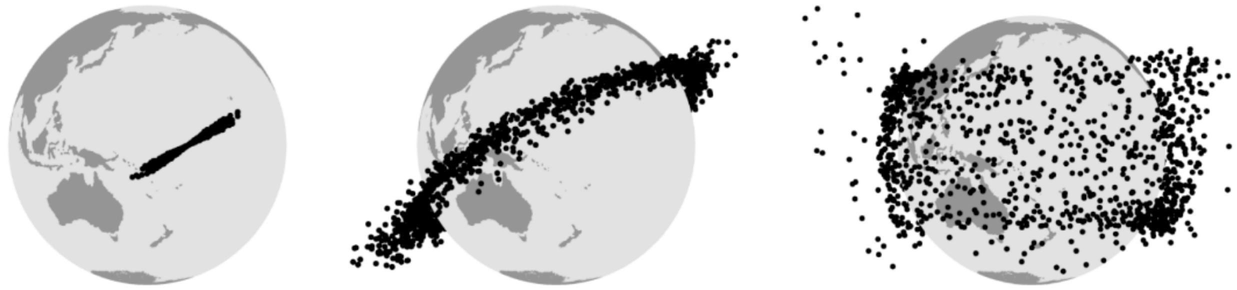


- **For any inclination, v_{rel} is maximized when:**
  - **i and i_t are opposite i.e. $i = 180° - i_t$**
  - **$\Delta\Omega = 180°$**

Giudici, Lorenzo, Juan Luis Gonzalo, and Camilla Colombo. "Density-based in-orbit collision risk model valid for any impact geometry." *Acta Astronautica* 219 (2024): 785-803.

Debris cloud evolution stages

- In LEO, debris clouds evolve throughout 3 different stages.
  - **Ellipsoid** (for the first few days); transition driven by δa until mean anomaly randomizes.
  - **Toroid** (for months and a few years); transition driven by J2 perturbation until RAAN and argument of perigee randomize.
  - **Band** (until fragments decay due to atmospheric drag)



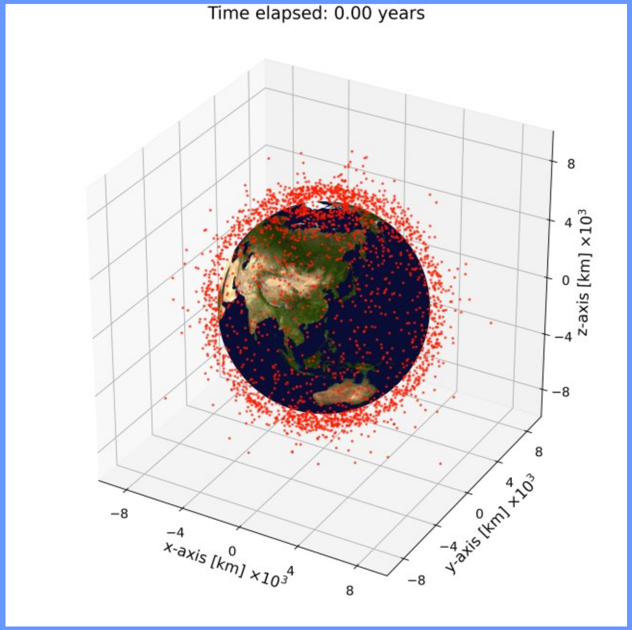
a) Ellipsoid b) Toroid c) Band

Letizia, Francesca, Camilla Colombo, and Hugh G. Lewis. "Analytical model for the propagation of small-debris-object clouds after fragmentations." *Journal of Guidance, Control, and Dynamics* 38.8 (2015): 1478-1491.

Impacts computation methods

3D Method

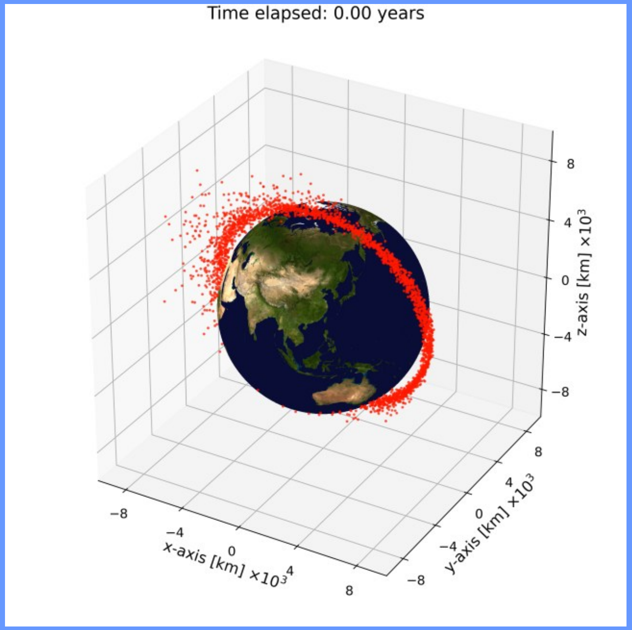
- Density interpolated on **SMA, Eccentricity** and **Inclination**
- Makes physical sense from **band** stage
- Requires **only Drag**



- **Less** computationally expensive

5D Method

- Density interpolated on **SMA, Eccentricity, Inclination, RAAN,** and **Argument of perigee**
- Makes physical sense from **toroid** stage
- Requires **Drag** and **J2**



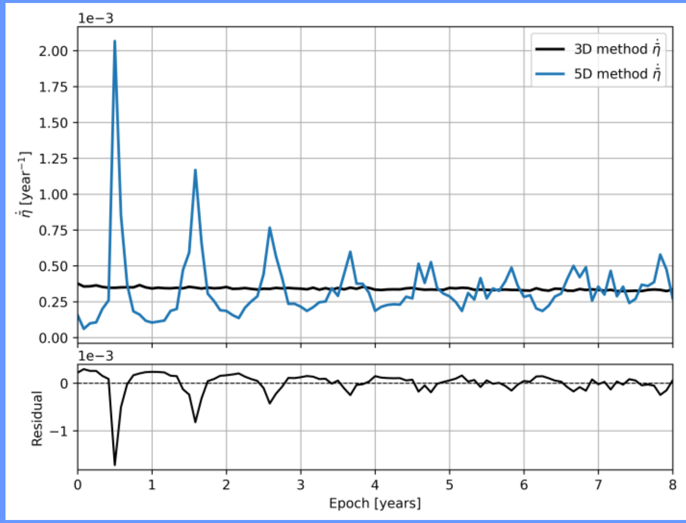
- **More** computationally expensive

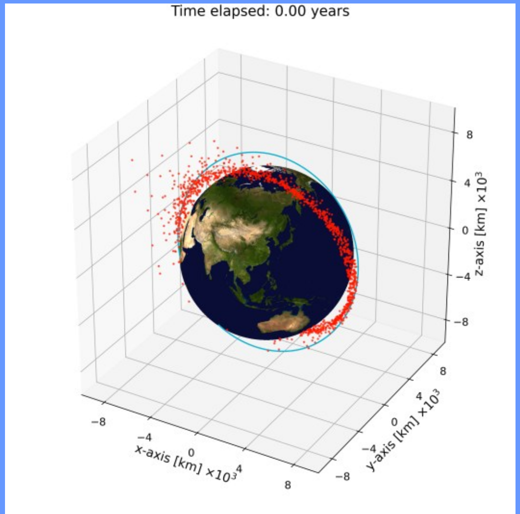
Giudici, Lorenzo, Juan Luis Gonzalo, and Camilla Colombo. "Density-based in-orbit collision risk model valid for any impact geometry." *Acta Astronautica* 219 (2024): 785-803.

Evolution of impact rate

Fragmentation @ 1200 km 100° **Target @ 1200 km 80°**

Fixed target



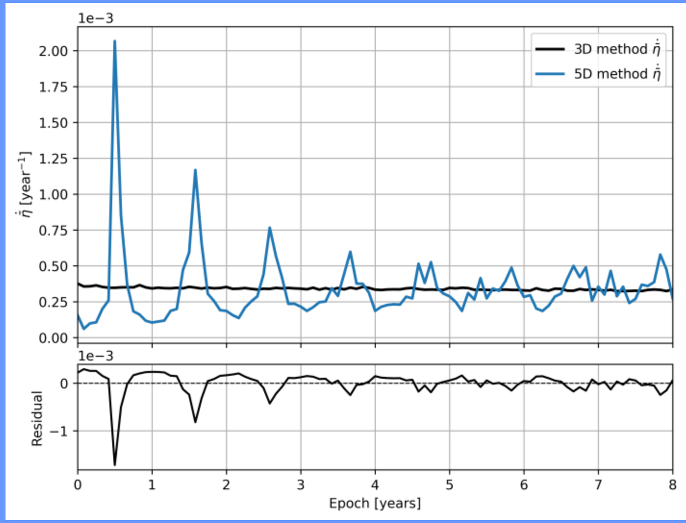


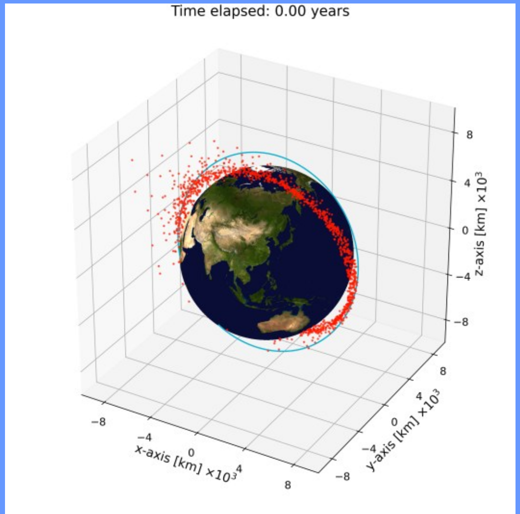
Evolution of impact rate

Fragmentation @ 1200 km 100°

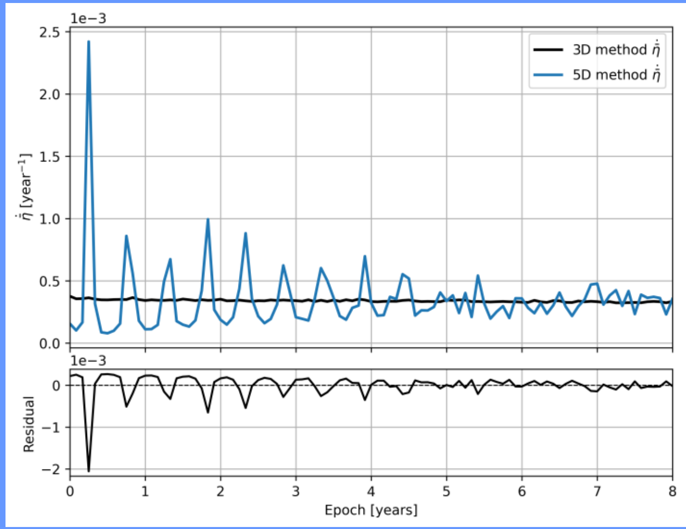
Target @ 1200 km 80°

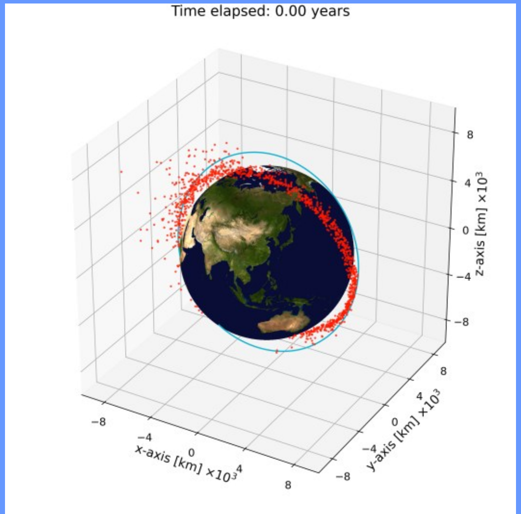
Fixed target





Propagated target





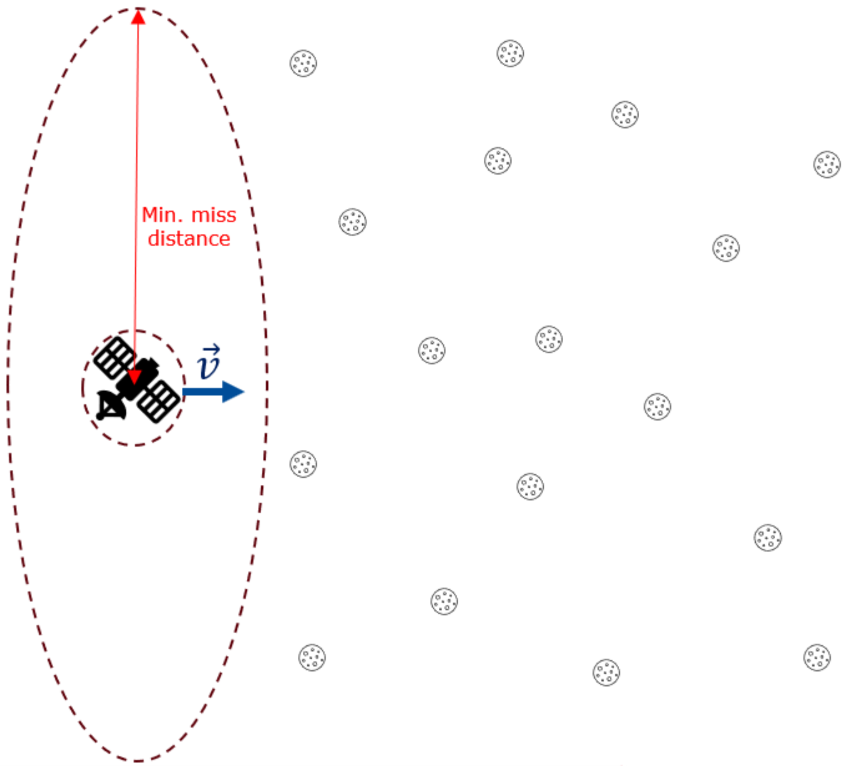
How to estimate conjunctions with debris

- Statistical number of conjunctions between fragments created at a breakup and a target are estimated by:
  - Increasing minimum debris size > **10 cm (trackable)**
  - Extended cross-sectional area to the area of circle **miss distance** ($A_{miss\ distance}$)
  - With these modifications the initial impact rate is replaced by an encounter rate $\dot{\eta}_{enc}$.

$$\dot{\eta}_{enc} = A_{miss\ distance} n(\boldsymbol{r}) v_{rel}$$

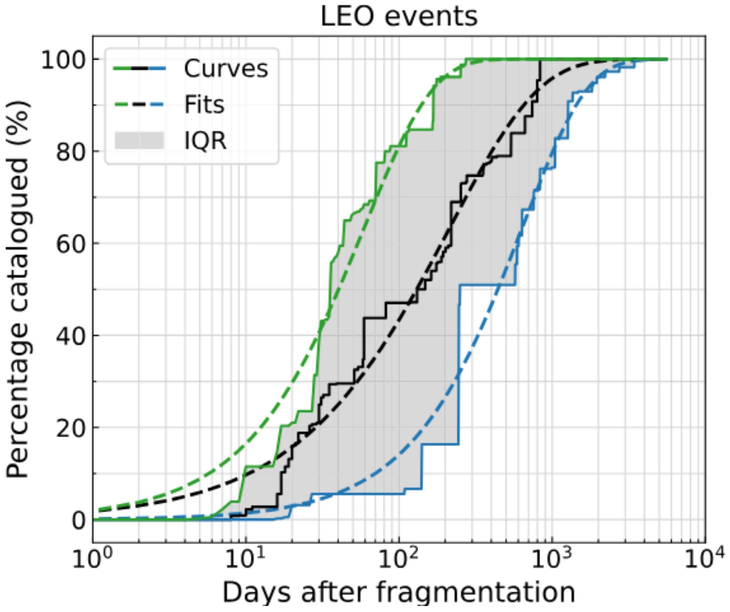
  - From the encounter rate, an estimated cumulative number of conjunctions after a (η_{enc}) can be obtained by integration.

$$\eta_{enc}(\Delta t) = \int_0^{\Delta t} \dot{\eta}_{enc}(\tau) d\tau$$



Validation with real fragmentation data

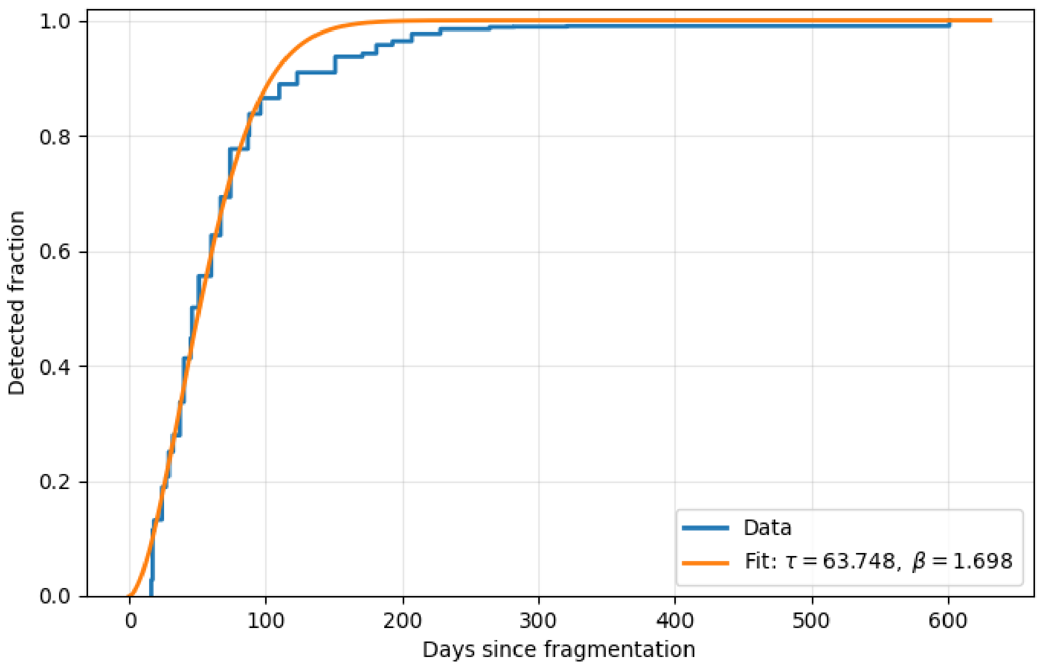
- When comparing with real observations, the cataloguing process is to be accounted for.
- Klinner-Teo et al. have proposed a method to model the delay in the cataloguing processes of debris created at a fragmentation.



		β	t
LEO	Q1	1.02	633
	Q2 (median)	0.746	213
	Q3	0.966	58.9

$$y\ (\%) = 100 \cdot \left(1 - e^{-\left(\frac{x}{t}\right)^{\beta}}\right)$$

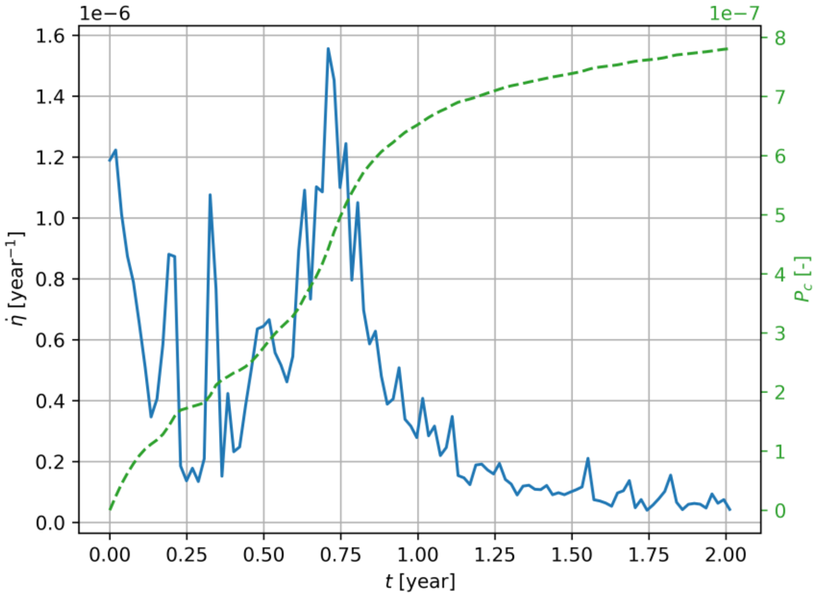
Fit for Cosmos 1408 fragmentation



Klinner-Teo, Teresa, et al. "Dynamic scaling of fragment populations in orbital breakup modelling." Acta Astronautica (2026).

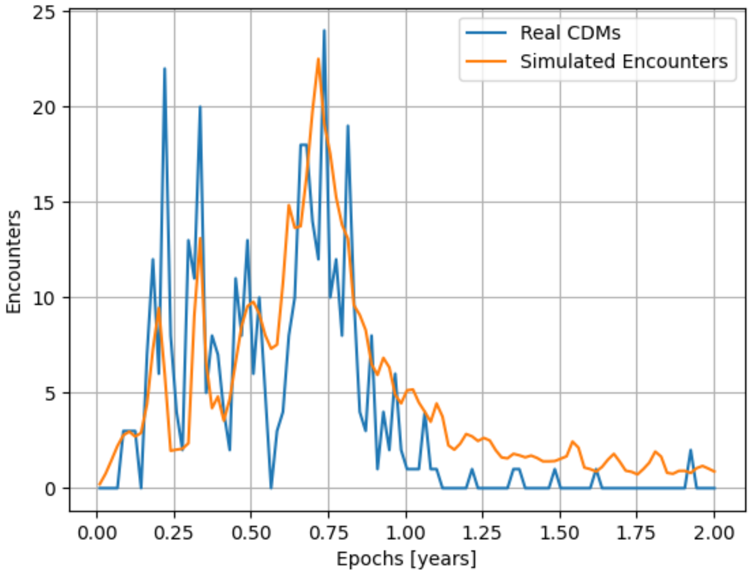
Conjunctions with SWARM B

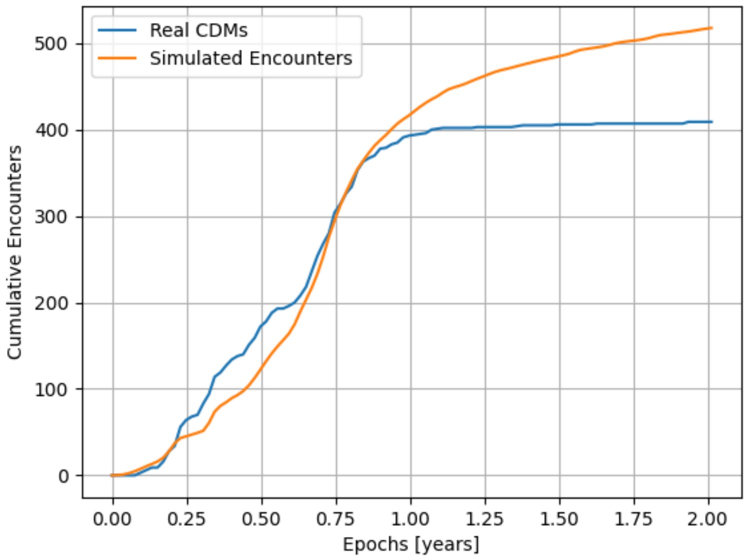
Raw impacts



Filtering CDMs by miss distance

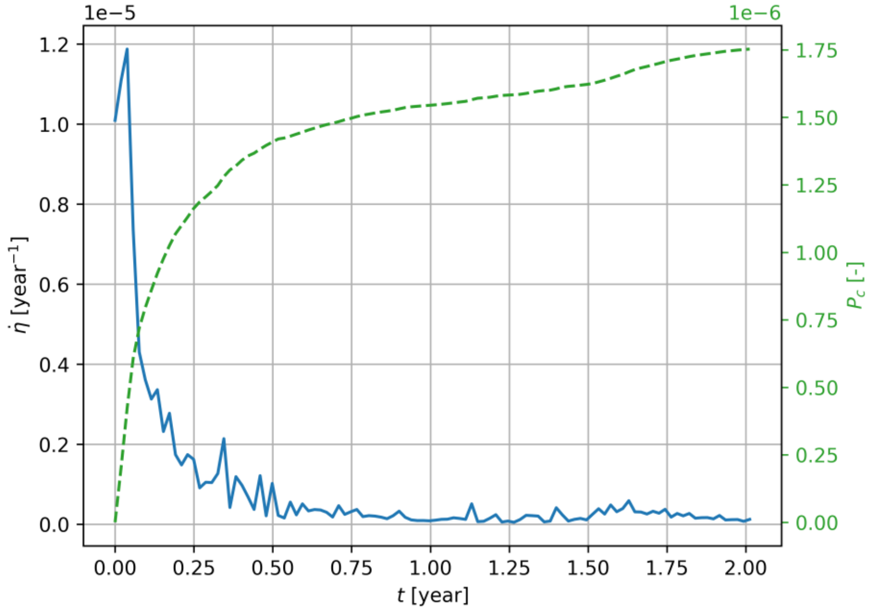
Applying dynamical scaling
and a miss distance of 15 km





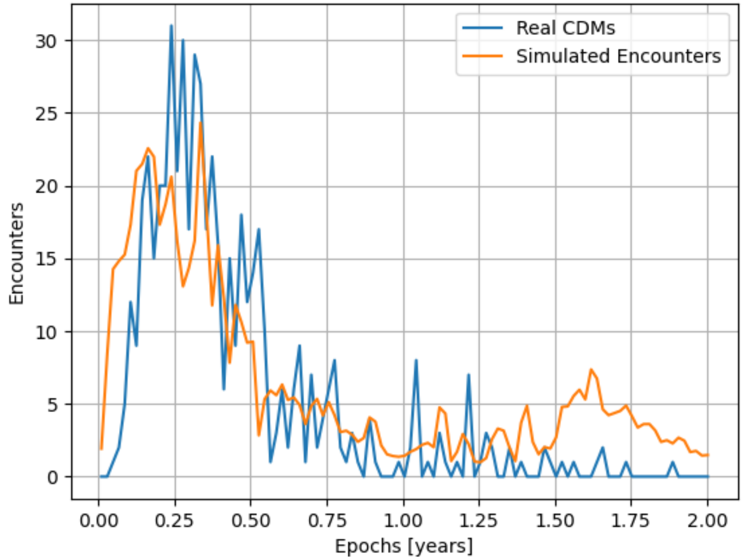
Conjunctions with SWARM C

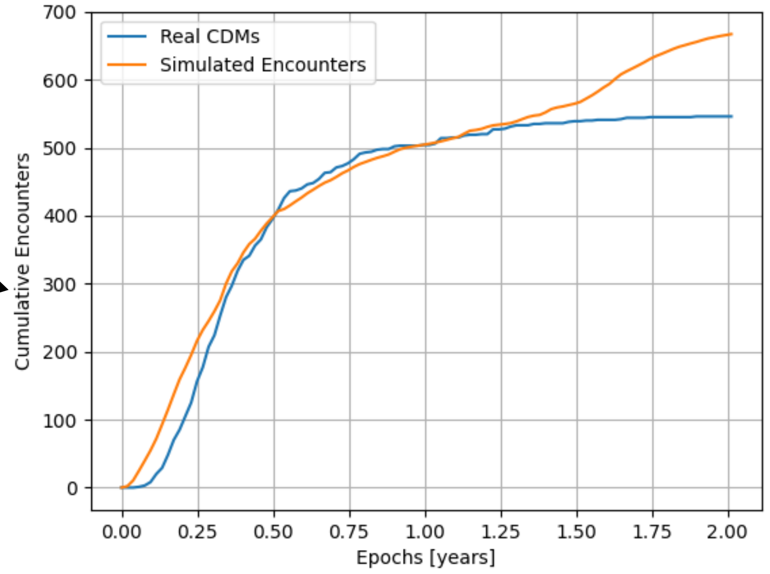
Raw impacts



Filtering CDMs by miss distance

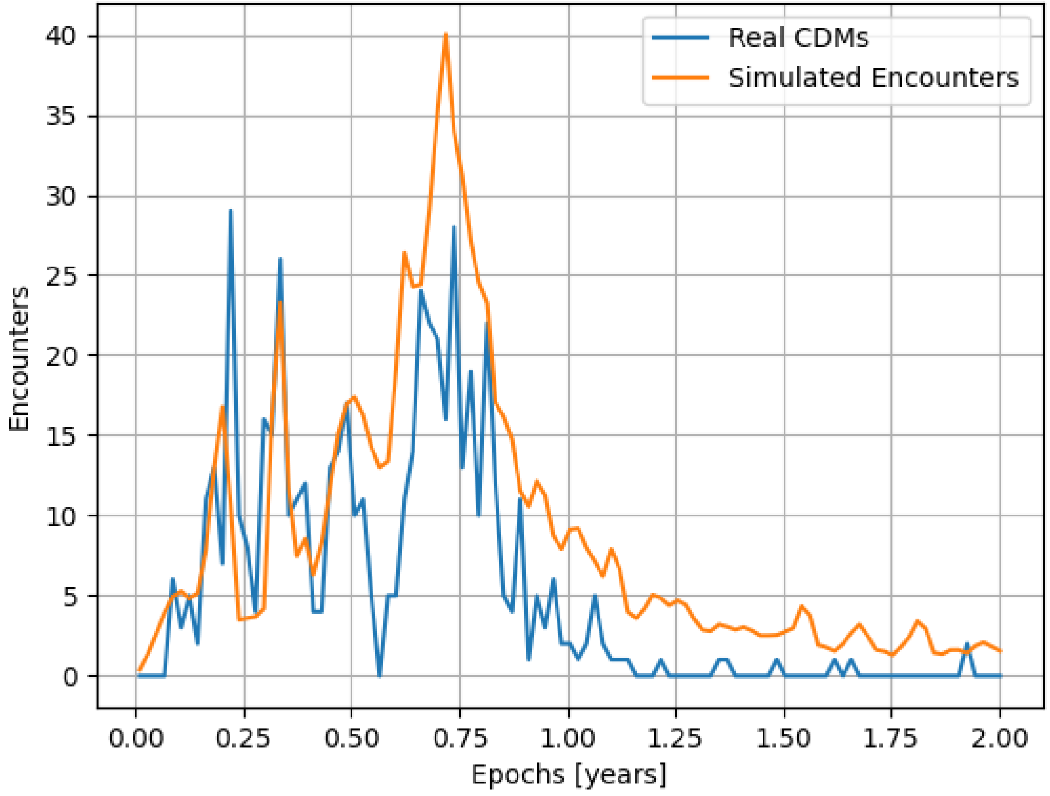
Applying dynamical scaling and a miss distance of 15 km



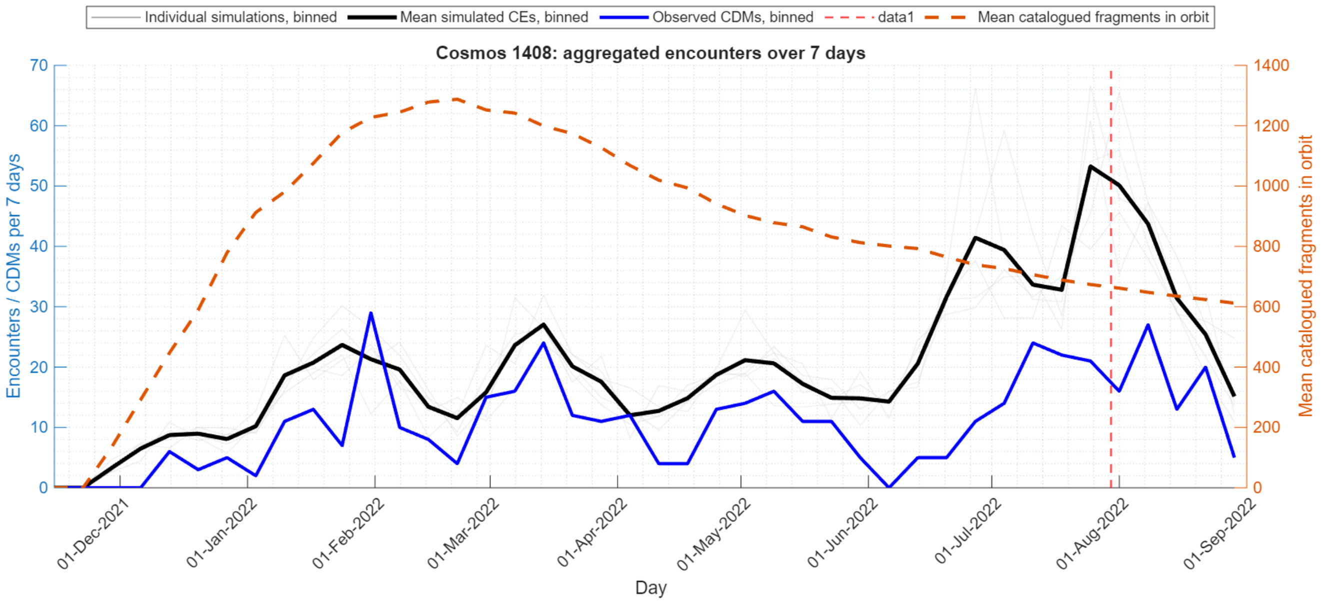


Comparison with a Monte Carlo method

Using a miss distance of 20 km

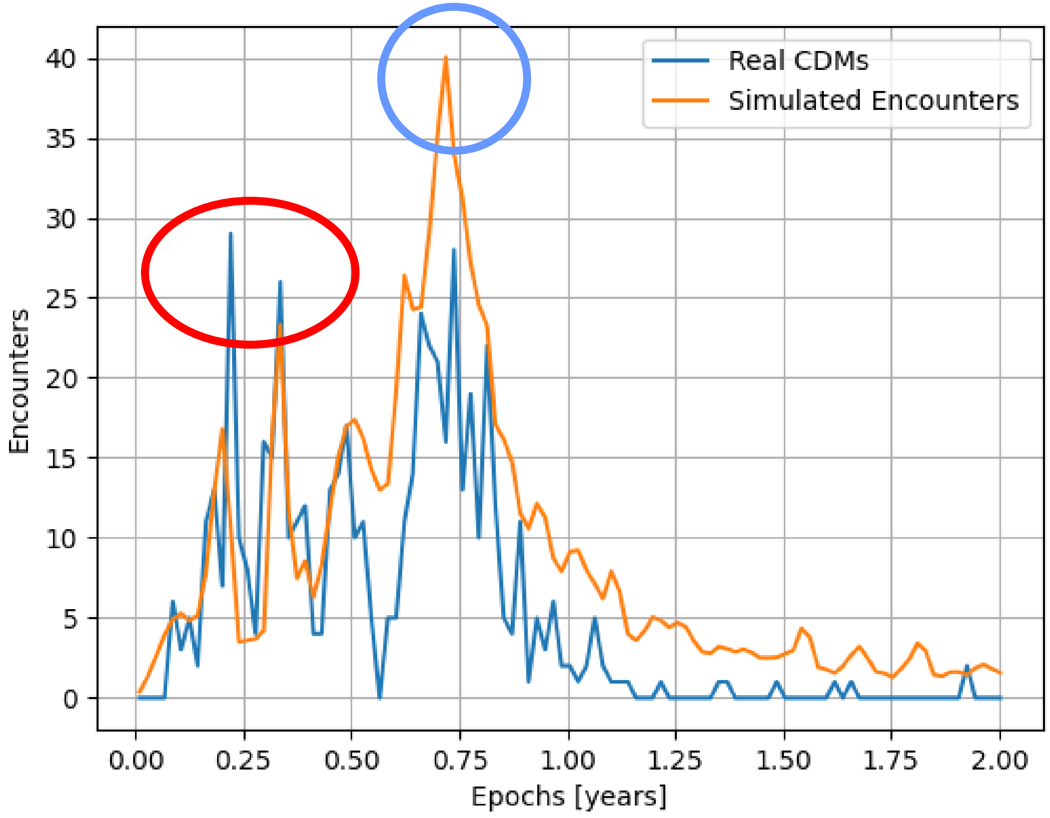


Monte Carlo propagation with GODOT

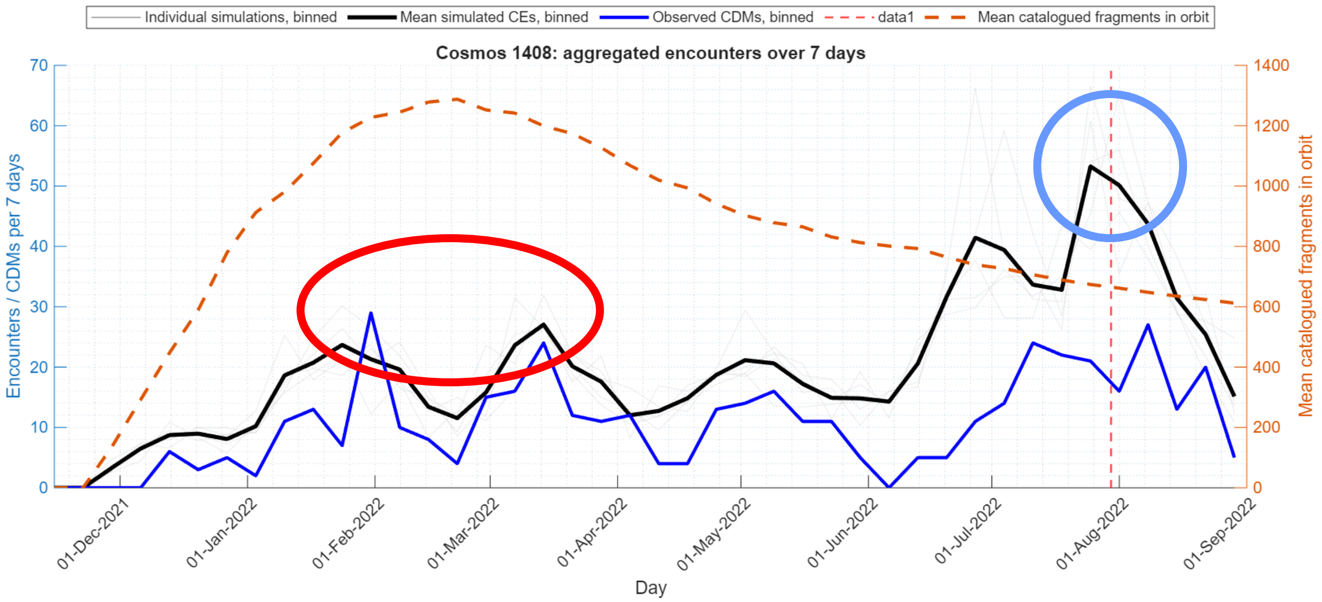


Comparison with a Monte Carlo method

Using a miss distance of 20 km



Monte Carlo propagation with GODOT



Summary

- This work shows the initial development of a method to estimate the **number of conjunctions** that a fragmentation event could create with a given target.
- The method yields comparable results with the **real observed conjunctions** between the fragments of the Cosmos 1408 ASAT test and SWARM satellites.

Future Work

- Trackability modelling should be improved as the current uses a **10 cm cutoff** independent of altitude or size (**In reality smaller fragments can be observed**)
- A realistic **CAM estimation** method is to be implemented linking the current statistical modelling with the operational methods of PoC estimation, including **state covariances** and **object sizes**.
- An adequate link between the estimated encounter/CAM rate and the operational costs to be incurred in terms of labour hours and propellant should be established.

POLITECNICO MILANO 1863 | DEPARTMENT OF AEROSPACE SCIENCE AND TECHNOLOGY

COMPASS

Juan Felipe Cabrera, Daniel Lück, Achraf Mizmizi, Emma Stevenson, Francisco Simarro, Eduardo Arias, Sean Hannon, and Camilla Colombo

Estimation of the Avoidance Manoeuvre Operational Burden Caused by In-Orbit Fragmentation Events

This research has received funding from the European Space Agency (ESA) activities "Space Debris Assessment to Improve Collision Avoidance Metrics for Telecommunication Spacecraft" (TELCOLA) and "ORBITHOOD: Orbital Neighbourhood Awareness"; and from the European Research Council (ERC) under the European Union's Horizon Europe research and innovation program as part of the GREEN SPECIES project (Grant agreement No 101089265).
CDMs were provided by ESA for the TELCOLA and ORBITHOOD projects

Green Species

COMPASS Lab

www.compass.polimi.it
Via La Masa, 34, 20159 Milano

erc
European Research Council
Established by the European Commission

Funded by the European Union