# Environmental aspects of passive de-orbiting devices

## Executive Summary

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## Executive Summary

The technical objective of this study [1] is to understand the net effect of using deorbiting technologies like sails or tethers over the future debris population around the Earth. In principle, indeed, these attractive technologies will support the compliancy to post-mitigation disposal guidelines, for small missions. However, the increased cross section also increases the collision risk. What will happen in case of collisions with deorbiting satellites using these techniques? When will a catastrophic collision take place and how can it be modelled? How will the debris population around the Earth evolve in the future when more and more satellites will use these technologies to deorbit? Is it possible to performe collision avoidance manoeuvre when a sail or a tether are employed? The current study will answer to all these questions.
The research activities carried out by the team, summarised in the Final Report [2] and detailed in TN1 [3],[4], TN2 [5], TN3 [6], and TN4 [7], have successfully addressed the 5 key questions of the study. The main takeaways for each question can be condensed as follows:

### 1. *Which sail/tether size do we need for deorbiting, is that achievable?*

Requirements for deorbiting with sail and tethers were derived for different deorbiting times, and verified with current technological capabilities

- Deorbiting with sail is possible up to high Low Earth Orbit (LEO) and some medium Earth orbits, for particular inclinations, leveraging the effect of drag and solar radiation pressure (SRP), with an area-to-mass ratio up to $2\ \mathrm{m}^2/\mathrm{kg}$, compatible with current technology development in boom manufacturing for sails.
- Deorbiting with tether is possible in LEO up to 1800 km, observing a decrease in efficiency with orbit inclination. Tether lengths up to 3 km have been considered.
- A large number of satellites with a mass less than 1000 kg has been identified that could benefit from passive deorbiting devices.

### 2. *How does the cumulative collision risk scale?*

A sensitivity analysis of the collision risk to the sails deorbiting characteristics was performed: the spacecraft mass, the sail cross-section area, the deorbiting time and the minimum debris particle size considered. This analysis only considers the cumulative collision risk and not yet the consequences on the debris environment.

- For the same deorbiting time there is a quasi-linear increase of the cumulative collision probability with spacecraft mass, as the sail cross-section area increases with mass
- Dependence of the collision probability with initial orbit:
  - Regular behaviour can be observed up to 700 km: a greater cumulative collision probability for spacecraft in higher orbits
  - When deorbiting is driven by solar radiation pressure, so taking place following elliptical orbits, the cumulative collision probability is lower
- Influence on the minimum debris size considered:
  - As the limit diameter increases, the overall collision probability decreases
  - For the smallest diameter of 1 mm a saturation of the cumulative collision probability is visible to the maximum level of 1 for all the high-altitude orbits, independently from the inclination.

- For a fixed area there is an expected increase of the collision probability as the prescribed decay time increases, because of the increased exposure of the satellite and the sail to the space debris environment. However, when the required area is computed to deorbit in a deorbiting time, looking at the sensitivity analysis of the number of impacts to the deorbiting time:
  - For drag driven deorbit the ratio between the number of impacts with different deorbiting times (i.e., different sail areas) is around 1: there is a linear relationship between sail size and number of impacts over the deorbiting time.
  - For SRP deorbiting the ratio is higher than 1: the linear relationship is not valid anymore as the deorbiting is happening on an elliptical path
  - A faster deorbiting with larger solar sail gives a lower cumulative collision probability than a longer deorbiting with smaller solar sail (or not solar sail at all), when the deorbit is driven by solar radiation pressure.
  - The ratio between the number of impacts does not depend directly on the mass of the satellite. In fact, in this case the most influential parameter in evaluating such ratio is the area-to-mass ratio of the sail and the spacecraft, which determines the orbit evolution of the decay trajectory.

## 3. *How can we model a collision involving large appendages?*

To address shortcomings in current models (which do not consider impacts with soft, large objects such as sails and tethers), a generalised procedure was developed to analyse consequences of collisions involving sails and tether systems, from local damage to catastrophic break-up. For each element of sail and tether systems, this includes the following new analytical formulas:

- Failure equations including partial impactor/target overlap
- Collisional cross-sectional areas, i.e. geometric cross sections increased to account for the impactor size. This effect may be significant when impactors are large.
- Fragments distributions based on the NASA Standard Break-up Model (SBM) in the case the spacecraft is the target, and on a different *geometric* approach in the case soft parts of the sail/tether systems are the targets.

Hydrocode simulations were run to verify the assumptions on fragments distributions and validate the new models:

- It is unlikely that soft impactors could cause catastrophic fragmentation, since they could be destroyed before s/c break-up, and the NASA SBM is conservative in these cases
- Large collisions between soft parts of sail/tether systems behave according to the assumed *geometric approach* and do not produce new fragments of significant characteristic length

## 4. *What are the consequences of the massive use of sails and tethers onto the space debris environment?*

Extensive numerical simulations run in this study show that the massive use of sails leads to a decrease in the number of objects in LEO of about 10-15% at the end of a 200-year time span. It must be noted that the post mission disposal rate considered in the simulations is quite optimistic (100% or 50%), but any small spacecraft can carry a solar sail or tether as it does not need a propulsion system.

- There is not a negative effect on the debris environment due to the use of the sails, in terms of number of objects produced.

- When sails are used on a massive scale, there is a significant increase in the collisional activity (80% and 250% for the catastrophic and non-catastrophic collisions, respectively), due to the increased collisional cross section in orbit (in excess of 1000%).
  - A collision against a sail does not cause a large cloud if it happens against the membrane of the sail system or the booms
  - Only relatively small spacecraft targets are destroyed (mass less than 1000 kg) and they are not producing very large clouds of fragments, thus not creating long term signatures in the environment
- An increased Collision Avoidance Manoeuvre (CAM) activity is needed to exploit the advantages in the deorbiting using sails. However, the increased CAM requirements might limit the advantages represented by their use.

## 5. *What are the consequences of the massive use of electrodynamics tethers onto the space debris environment?*

The massive use of tethers leads to a decrease in the number of objects in LEO of about 15-20% at the end of a 200-year time span. However, it must be noted that part of the observed improvement is related to the tether scenario definition.

- There is not a negative effect on the debris environment due to the use of the tethers, in terms of number of objects produced.
- A significant increase in the collisional activity is observed, due to the increased collisional cross section in orbit related to the approximately 1500% increase in the total "length" in space.
  - Non-catastrophic collisions increase about 40%. Catastrophic collision rate is almost unaffected, and collision activities increase in the 400 – 600 km band.
  - Further investigation in view of possible interactions with critical lower orbits, such as the International Space Station one.
- Most collisions involving tethers do not generate large fragment clouds.
- An increased CAM activity is needed to exploit the advantages in the deorbiting using tethers. However, the increased CAM requirements might limit the advantages represented by their use.

## 6. *Can we perform collision avoidance manoeuvres when sails or tether are employed?*

As part of this study, an analytical method for the design of maximum deviation (in b-plane) and minimum collision probability impulsive CAMs has been proposed and analysed.
Nimerical simulations were performed for spacecraft performing CAMs to avoid debris or sails. These results show that:

- As the lead time before the possible collision increases, both the covariance ellipse and the maximum miss distance CAM in the b-plane tend to align with $\zeta$ (time shift axis). This limits the effectivity of the CAM and justifies the differences between the maximum miss distance and minimum collsion probability strategies.
- The required $\Delta \boldsymbol{v}$ for both CAMs is mostly tangential for lead times larger than 0.5 the orbital period.
- Drag and SRP do not introduce significant changes in the covariance matrix of the sail for short lead times (checked numerically with Monte Carlo methods)

When is the sail the one to perform CAMs, effective CAMs for a deorbiting sail can be designed through a simple on/off control law, where the sail is put parallel or perpendicular to the incoming flow (of SRP or drag). This would require sail manoeuvrability, at least until it deorbits below the most pospulated region of 800 km.

Electrodynamics tethers offer manoeuvrability bandwidth even for last-minute (i.e. less than 1 orbit) manoeuvres except for near polar inclinations, where the manoeuvre should be initiated a few orbits in advance

The results of this study lead us to the answer of the overall question: *Is it better or worse to use sails/tethers for passive deorbiting?* Considering the project outcomes, the answer is *possibly yes*, but there are yet some scientific and technical issues to tackle before the widespread adoption of passive deorbiting devices. The key milestones in the way forward identified by the team are:

Regarding the use of passive deorbiting devices

- Compare sails, low-thrust propulsion and impulsive propulsion, regarding: their effects onto the environment, the strategy cost, operational and propulsion cost
- Evaluate how the sail attitude control can improve the sail performances

Regarding long-term simulations: perform more targeted simulations

- Perform sensitivity analysis only on the passive device effects
- Reduce the simulation “combination” (i.e. separate different effects)
- Remove noise factors (e.g., do not consider for some simulation the effect of large constellations that becomes relevant on the environment and makes difficult the understanding on what the effect of sails and tethers is. Moreover, deorbiting with sails or tethers and conventional deorbiting of spacecraft should have same space debris mitigation compliances)
- Consider only small spacecraft constellations
- Consider only sail/tether population

Introduce a more robust definition of a disposal index leveraging new long-term simulations and advances in the modelling

Extend the CAM design during deorbiting

- Study and develop low-thrust CAMs
- Extend the developed analytical approach for computing CAMs to include SRP and drag (in the current study it is done with Monte Carlo)
- Study CAM design by enhancing SRP (in the current study it is done only in the drag dominated regimes)

The study logic is shown in Fig. 1

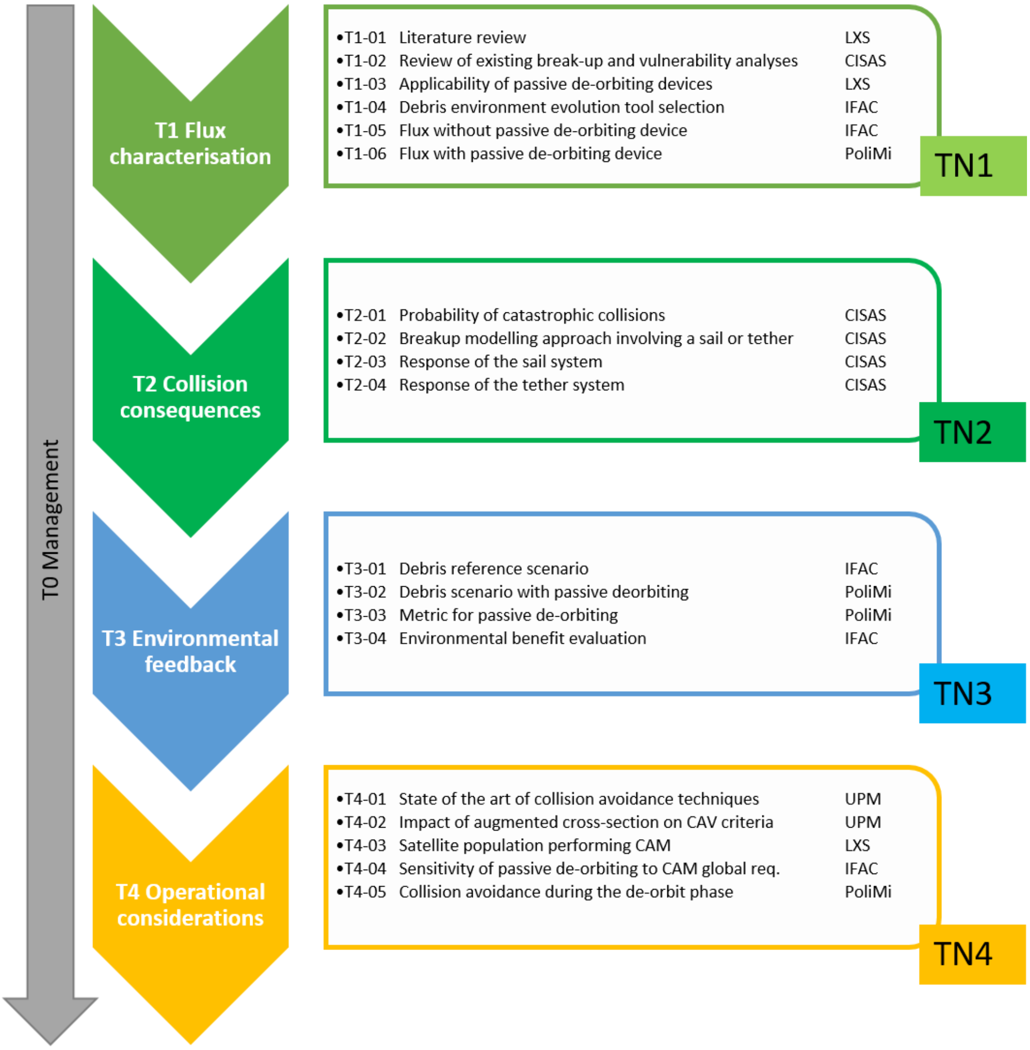


**Fig. 1. Work logic of the study.**

# References


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