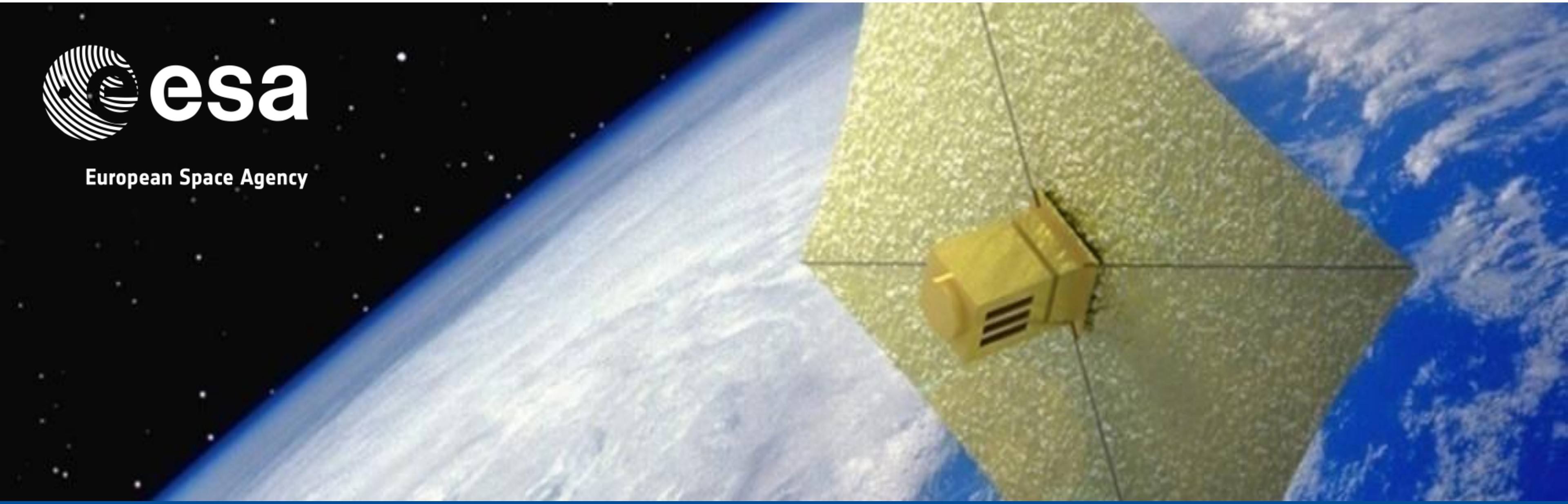


# Environmental aspects of passive de-orbiting devices

Camilla Colombo, Juan Luis Gonzalo, Alessandro Rossi, Alessandro Francesconi, Pierluigi Di Lizia, Mirko Trisolini, Cinzia Giacomuzzo, Shaker Bayajid Khan, Florio Dalla Vedova, Claudio Bombardelli, Ricardo Garcia-Pelayo, Vitali Braun, Benjamin Bastida Virgili, Holger Krag

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# The team

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# Passive devices for end-of-life deorbiting

## Are they worth it?

Passive deorbiting through solar and drag sails and electrodynamic tethers can be a cost-effective end-of-life approach

Performance of deorbiting strategy for passive deorbiting:

- Effective area-to-mass ratio:
  cross area, drag and reflectivity coefficient for sails, plasma collection efficiency for tethers
- Time to deorbit:
  the larger the sail/longer the tether, the faster the re-entry

Augmented collision probability with the whole space debris population caused on and by the sail through its passage in the LEO protected region.

# Net environmental effect of passive de-orbiting

## Main questions of the study

1. Which sail/tether size do we need for deorbiting, is that achievable?
2. How the cumulative collision risk scale?
3. How can we model a collision involving large appendages?
4. What happens to the space debris environment?
5. Can we perform collision avoidance manoeuvres in this case?

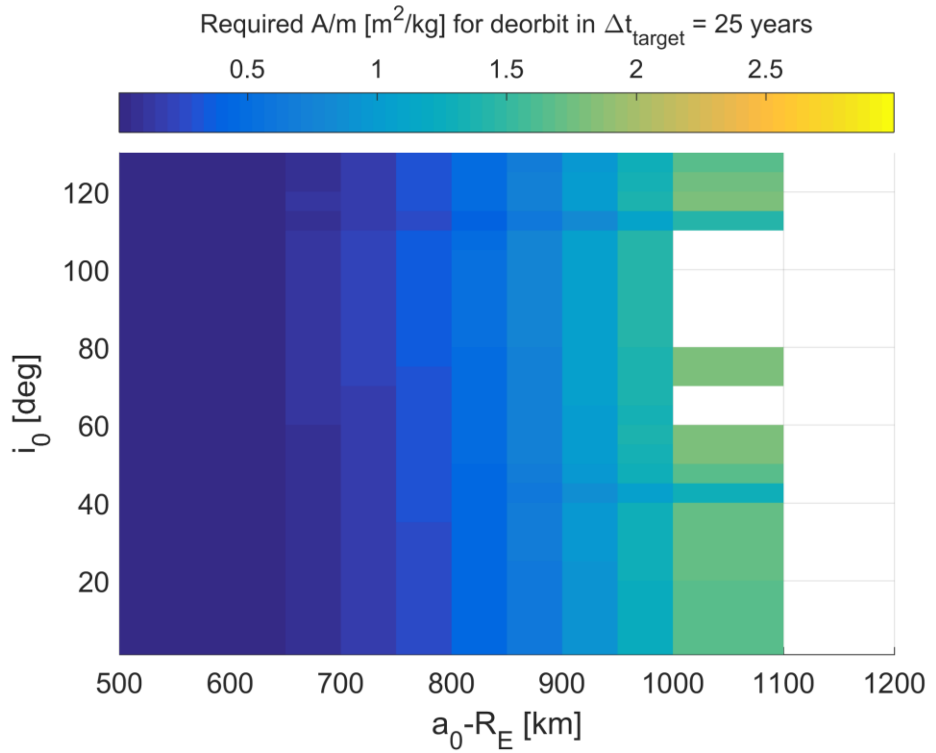
Is it better or worse to use sails/tethers for passive deorbiting?

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

# APPLICABILITY OF DEORBITING DEVICES

# Solar and drag sails for end-of-life deorbiting

## Requirements




### Extensive parametric analysis of sail requirements

- Identify interest orbital regions for each technology
- Tabulate area-to-mass ratio (A/m) requirements.

**Drag sailing:** 900-1000 km for medium satellites, 1200km for small satellites

- Inward spiralling deorbiting
- A/m depends on semi-major axis (exponential)

**Solar sailing:** of interest above 700 km

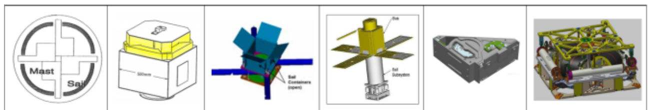
- Outward elliptical deorbiting (eccentricity increase).
- A/m depends on semi-major axis and inclination

# Sail requirements

## What is the limit of current sail technologies?

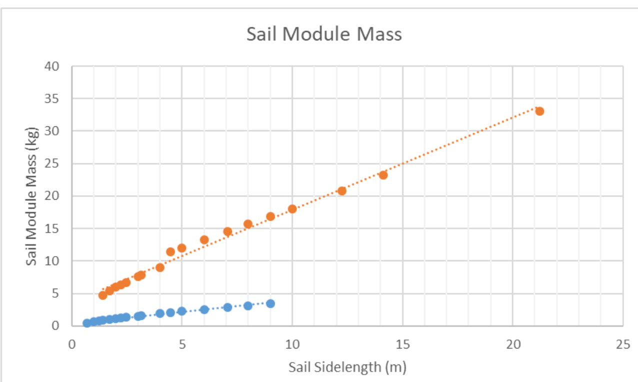
DOM (ESEO)
Icarus-3 (CBNT-1)
CanX-7
Icarus-1 (TDS-1)
NanoSail-D2

ADEO
NEAScout
Daedalus
DLR 20x20 m
VSE

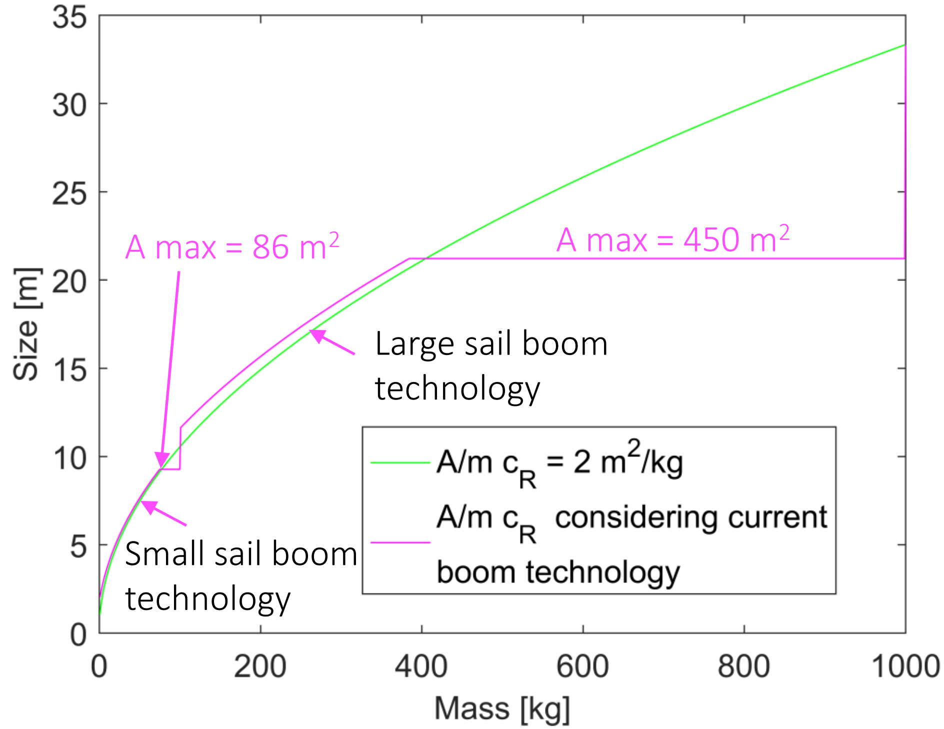



| | | | | | |
|---|---|---|---|---|---|
| ~5000 $m^2$<br>~173 kg<br>~0.1515 $m^3$ | ~113.5 $m^2$<br>~14 kg<br>~0.0900 $m^3$ | ~400 $m^2$<br>~24 kg<br>~0.1553 $m^3$ | ~10 $m^2$<br>< 4 kg<br>~0.0020 $m^3$ | ~4.25 $m^2$<br>~0.95 kg<br>~0.0006 $m^3$ | ~25 $m^2$<br>~19.5 kg<br>~0.0530 $m^3$ |
| **VSE (1994)** | **Daedalus (1997)** | **DLR (1999)** | **NanoSail-D2 (2010)** | **CanX-7 (2014)** | **ADEO (2016)** |

LuxSpace's DRS *DoWn!™*




Reference sail flown modules or designs used to derive mass (and volume) of sail module as functions of deployed area (or side length):




*Sail size technological limits*

# Electrodynamic tether for end-of-life deorbiting

## Required tether length for deorbiting a 200-kg s/c in 1 year

Baseline EDT design (based on technological constraints and study requirements)

- A 50-µm-thick, 3-cm-wide aluminium tape of 0.5 to 5 km length
- Hollow cathode electron emitters at each end
- Applicable for objects of m>20 kg in quasi-circular orbits (e<0.01) at maximum 2000 km altitude
- Estimated total mass of the EDT device <30 kg (depending on length)
- In this study: 3 years deorbiting time "by design"
- Actively controlled (stability+ CAM) during descent

| h / inc | 5° | 15° | 25° | 35° | 45° | 55° | 65° | 75° | 85° | 95° | 105° |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 550 km | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.6 | 0.8 | 1 | 1.4 | 1.4 | 1 |
| 650 km | 0.5 | 0.5 | 0.4 | 0.5 | 0.6 | 0.7 | 0.9 | 1.2 | 1.5 | 1.6 | 1.2 |
| 750 km | 0.5 | 0.6 | 0.5 | 0.6 | 0.7 | 0.8 | 1 | 1.3 | 1.7 | 1.8 | 1.3 |
| 850 km | 0.6 | 0.6 | 0.6 | 0.7 | 0.8 | 0.9 | 1.1 | 1.5 | 2 | 2 | 1.5 |
| 950 km | 0.6 | 0.7 | 0.7 | 0.8 | 0.8 | 1 | 1.2 | 1.6 | 2.2 | 2.3 | 1.6 |
| 1050 km | 0.7 | 0.7 | 0.7 | 0.8 | 0.9 | 1 | 1.3 | 1.7 | 2.3 | 2.4 | 1.7 |
| 1150 km | 0.7 | 0.8 | 0.8 | 0.9 | 1 | 1.1 | 1.4 | 1.8 | 2.5 | 2.5 | 1.8 |
| 1250 km | 0.7 | 0.8 | 0.8 | 0.9 | 1 | 1.1 | 1,5 | 2 | 2.6 | 2.7 | 2 |
| 1350 km | 0.8 | 0.8 | 0.9 | 1 | 1.1 | 1.2 | 1.5 | 2.1 | 2.8 | 2.8 | 2.1 |
| 1450 km | 0.9 | 0.9 | 0.9 | 1 | 1.1 | 1.3 | 1.6 | 2.2 | 2.9 | 3 | 2.2 |
| 1550 km | 0.9 | 0.9 | 1 | 1.1 | 1.2 | 1.4 | 1.7 | 2.3 | 3.1 | 3.1 | 2.3 |
| 1650 km | 1 | 1 | 1 | 1.1 | 1.3 | 1.5 | 1.8 | 2.4 | 3.3 | 3.3 | 2.4 |
| 1750 km | 1 | 1 | 1.1 | 1.2 | 1.3 | 1.5 | 1.9 | 2.5 | 3.4 | 3.4 | 2.5 |
| 1850 km | 1.1 | 1.1 | 1.1 | 1.2 | 1.4 | 1.6 | 2 | 2.6 | 3.5 | 3.5 | 2.6 |

Required tether length for deorbiting a 200-kg s/c in 1 year

2. How the cumulative collision risk scale?

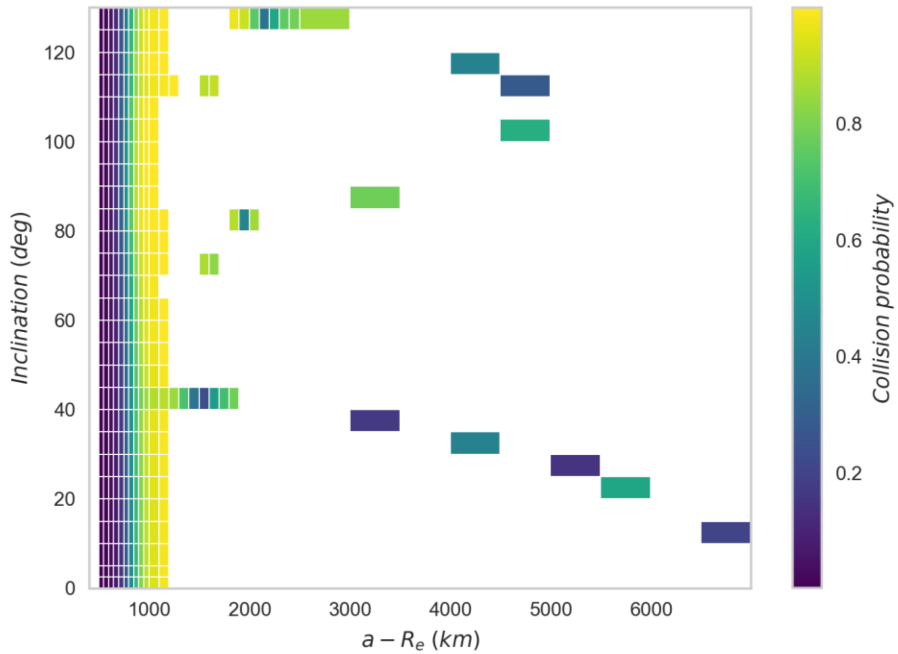
# COLLISION RISK

# Sensitivity analysis of sails collision probability

## Simulations objectives and main conclusions

Study the dependence of the collision probability on a sail as a function of

- Spacecraft mass: quasi-linear increase
- Initial orbit conditions:
  - lower altitudes (drag-dominated), proportional to altitude
  - Higher altitudes (SRP-dominated), lower probabilities
- De-orbiting time:
  - Drag-dominated: linear relation
  - SRP-dominated: the shorter (i.e. bigger sail) the better
- Minimum debris particle diametre: 1 mm, 1 cm, and 10 cm




*Deorbiting with sail in 25 y, s/c: 10 kg, minimum debris particle: 1 mm*

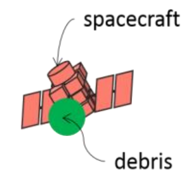
3. How can we model a collision involving large appendices?

# FRAGMENTATION MODEL

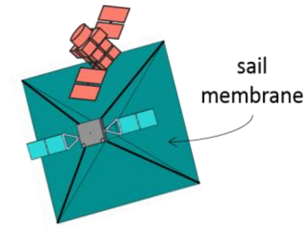
# Collision scenarios for sail and tether systems

## Independent cases

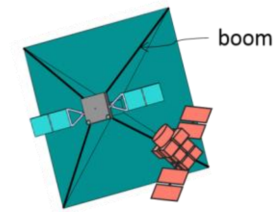
| Target | ID | Impactor | Comment |
|---|---|---|---|
| **Spacecraft** | SC1 | Debris | Possible failure: spacecraft break-up (impact pressure concentrated on the contact point). Collision consequences can be modelled using the NASA SBM. |
| | SC3 | Sail membrane | Possible failure: spacecraft break-up. Collision consequences may be different from SC1 (soft impactor, impact pressure is distributed over a large contact area). |
| | SC4 | Boom | Possible failure: spacecraft break-up. Collision consequences may be different from SC1 and SC3, since the impact pressure is distributed over the contact line. |
| **Sail-membrane** | SM1 | Debris | Possible failure: sail system loss of function. Evaluation of damage extension to sail is requested in function of the impactor properties. |
| **Boom** | B1 | Debris | Possible failure: sail system loss of function due to boom cut-off. |
| **Tether** | T1 | Debris | Possible failure: tether system loss of function |



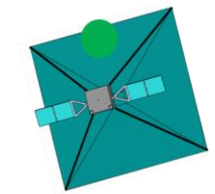
**SC1: debris Vs. spacecraft**

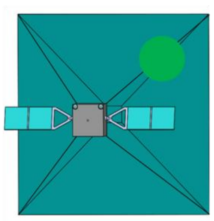


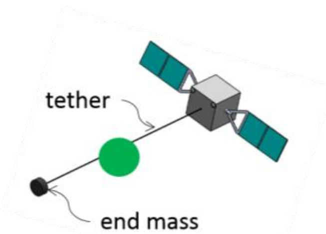
**SC3: membrane Vs. spacecraft**



**SC4: boom Vs. spacecraft**


**SM1: debris Vs. membrane**


**B1: debris Vs. boom**



**T1: debris Vs. tether**

## 6 independent collision scenarios identified:

- Different failure modes depending on specific impactor/target properties
- Failure equations and collisional cross sectional areas required for these scenarios

# Approach to break-up

## Introduction and basic assumptions

- The NASA SBM is the starting point for fragments distributions
  - It is the only model founded on a credible empirical dataset
  - It is widely employed by the international debris community
- However, the NASA SBM does not consider:
  - Impacts involving soft objects (such as sails and tethers)
  - Glancing impacts, partial overlap of colliding objects

**ASSUMPTIONS**

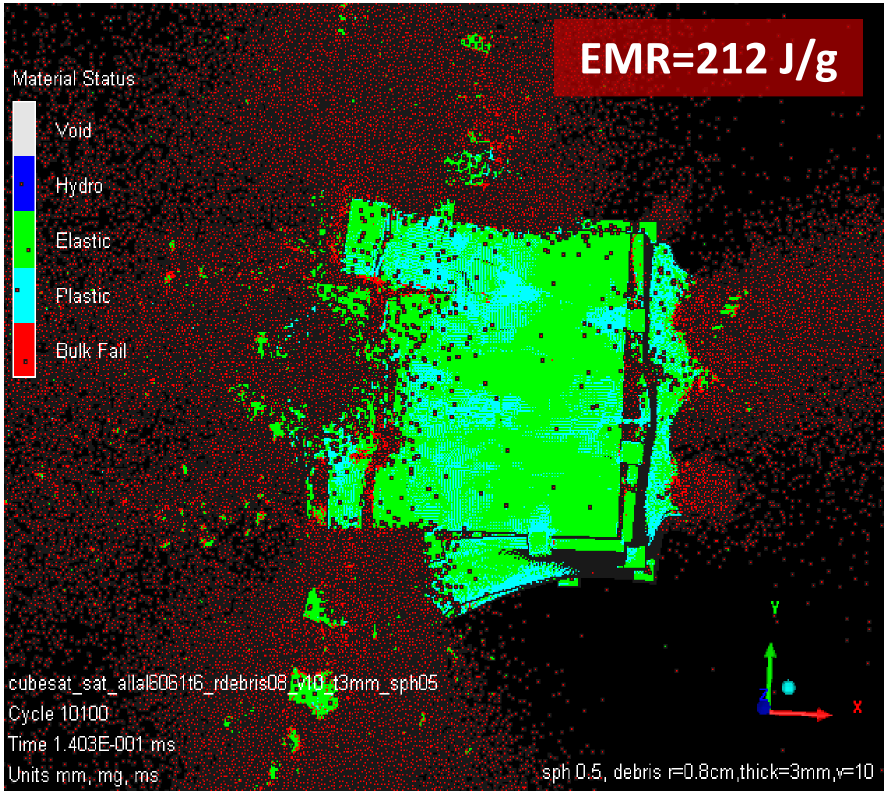
A. If any of the elements of a sail/tether system hits a spacecraft body, the NASA SBM is applied with **impactor mass is limited to that of its overlap with the target**

B. If any of the elements of a sail/tether system is hit by another object, a "geometric" approach is used: tethers, booms and sail membranes are cut in two pieces with **negligible production of additional fragments of significant characteristic length**.

# Hydrocodes simulations

## Validations of proposed break up modelling

| | Projectile | Target |
|---|---|---|
| **Description** | Spherical debris hitting the centre of one cube face | 1U-CubeSat with components (boxes) inside |
| **Size** | D=8 mm<br>D=9.4 mm<br>D=16 mm | 10x10x10 $cm^3$ |
| **Total mass** | 1.548 -1.553 kg | |
| **Material** | Al-6061-T6 | Al-6061-T6 |
| **EOS** | Shock | Shock |
| **Strength model** | Johnson-Cook | Johnson-Cook |
| **Failure model** | Johnson-Cook | Johnson-Cook |
| **SPH size/no.** | 0.5mm / >2E3<br>0.5mm / >3E3<br>0.5mm / >17E3 | 0.5 mm />1.6E8 |
| **Impact speed** | 10 km/s | |
| **EMR** | 26 J/g<br>43 J/g<br>212 J/g | |




- Assumptions validated
- Soft impactors unlikely to cause catastrophic fragmentations

4. What happens to the space debris environment?

# SPACE DEBRIS LONG-TERM SIMULATIONS

# Reference scenarios

| Case | Launch | Compliance to PMD 25 year | Collision avoidance manoeuvre probability of success | Simulation time span [years] | Large constellation |
|---|---|---|---|---|---|
| REF-01 | Business as usual (IADC) | 60% | 90% | 100 | no |
| REF-02 | Business as usual (IADC) | 90% | 90% | 100 | no |
| REF-03 | Business as usual (IADC) + launch traffic 2010-2016 | 90% | 90% | 100 | no |
| REF-04 | Business as usual (IADC) + launch traffic 2010-2016 | 60% | 90% | 200 | yes |
| REF-05 | Business as usual (IADC) + launch traffic 2010-2016 | 90% | 90% | 200 | yes |

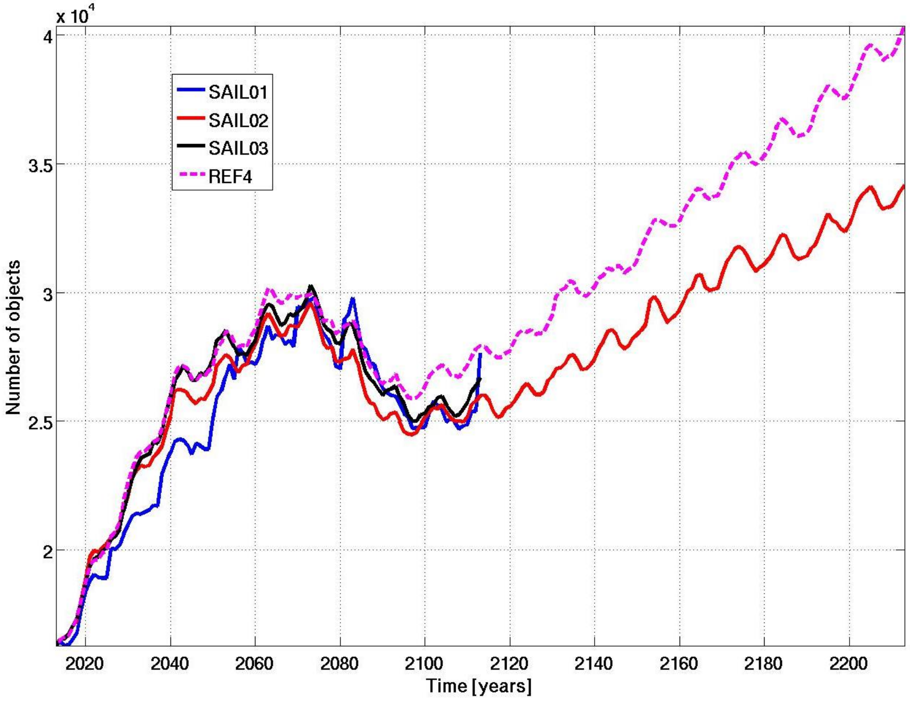
# Sail scenarios

| Case | Set-up | S/c using the sail | Percentage of s/c using the sail | Sail deorbiting time [years] | Large constellation | Sail/Balloon percentage | Simulation time [years] |
|---|---|---|---|---|---|---|---|
| SAIL-01 | REF-04 | < 1000 kg | 50% below 800 km<br>100% above 800 km | 25 | No sail | 90% sail<br>10% balloon | 100 |
| SAIL-02 | REF-04 | < 1000 kg | 100% below 800 km<br>100% above 800 km | 25 | No sail | 90% sail<br>10% balloon | 200 |
| SAIL-03 | REF-04 | < 1000 kg | 100% below 800 km<br>100% above 800 km | 10 | No sail | 90% sail<br>10% balloon | 100 |
| SAIL-04 | REF-05 | < 1000 kg | 100% below 800 km<br>100% above 800 km | 10 | No sail | 90% sail<br>10% balloon | 200 |

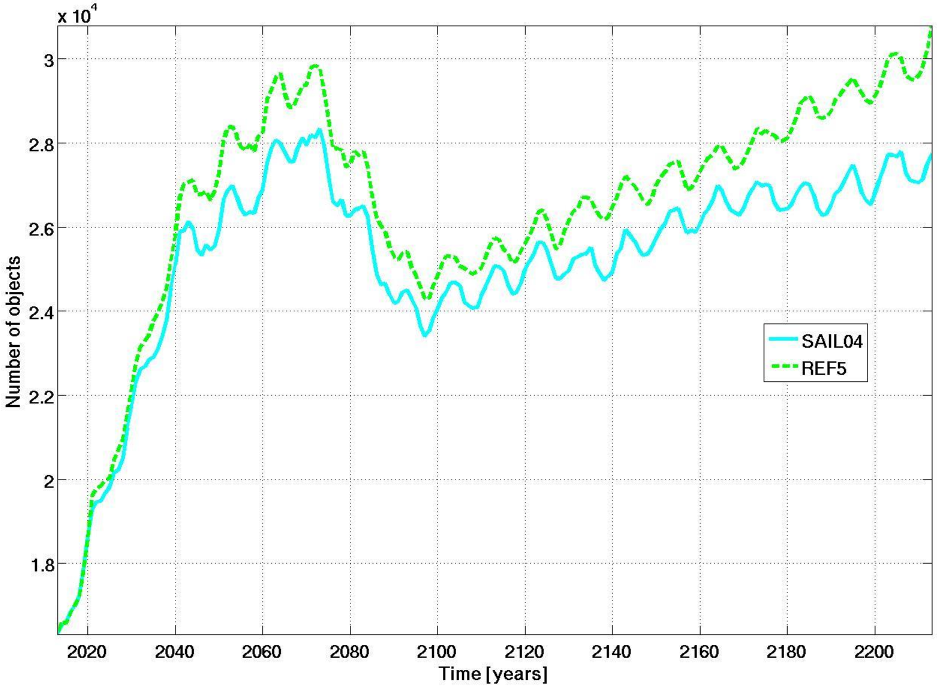
# Some selected results

## Number of objects > 10 cm in the SAIL scenarios

*SAIL01-SAIL03 vs REF4*



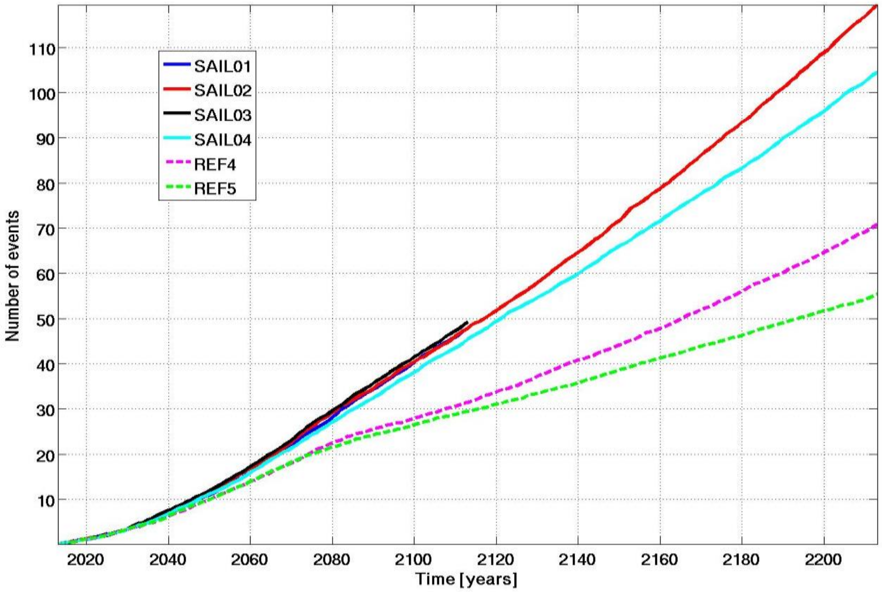

*SAIL04 vs REF5*




10-15% decrease in final population for sail cases.

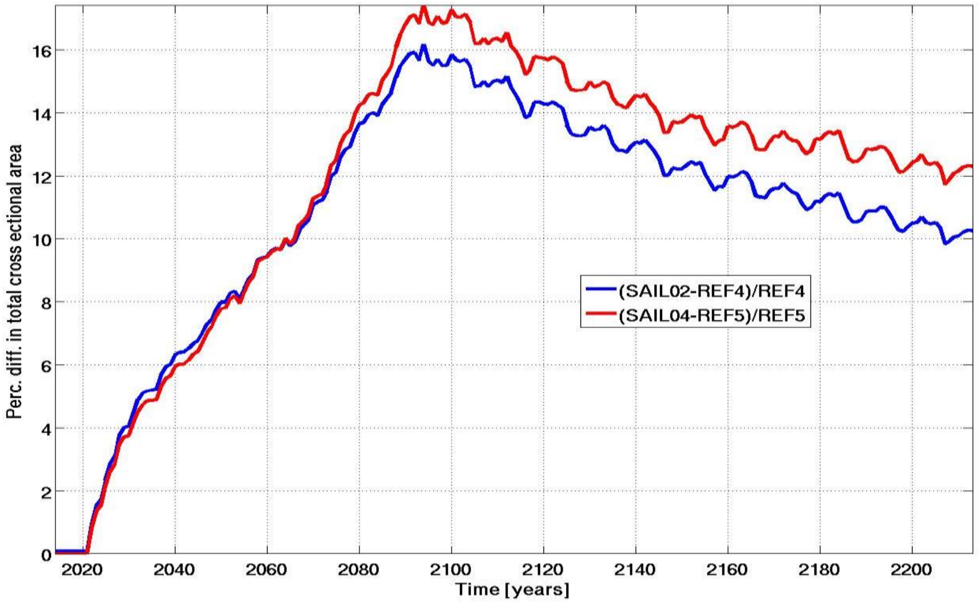
# Results for sail scenarios

*Number of catastrophic fragmentations*

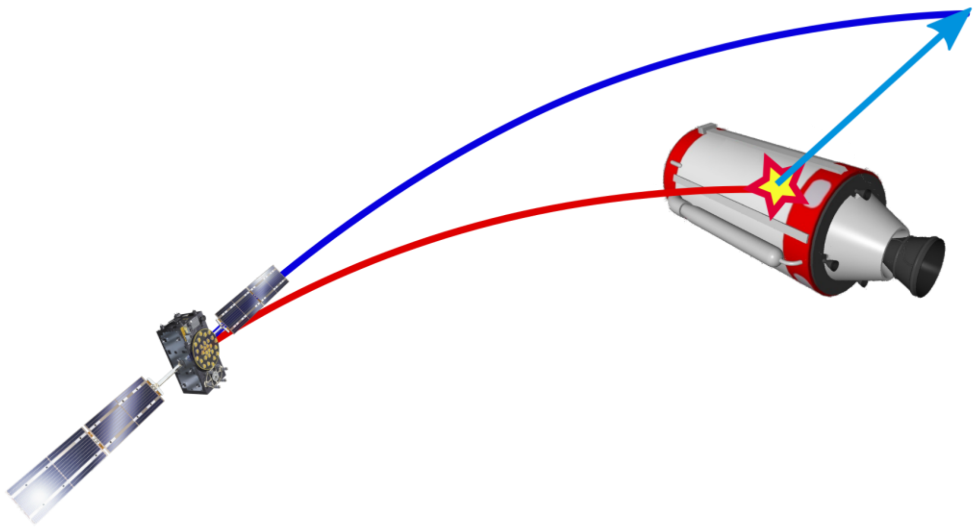



80% increase in the catastrophic collisions, 250% increase in the non-catastrophic collisions (SAIL02-REF04, SAIL04-REF05)

*Total cross sectional area in orbit: percentage differences between SAIL and REF cases*




An increase of a factor 10 in the total area leads to an increase of a factor of 2 in the number of total collisions.



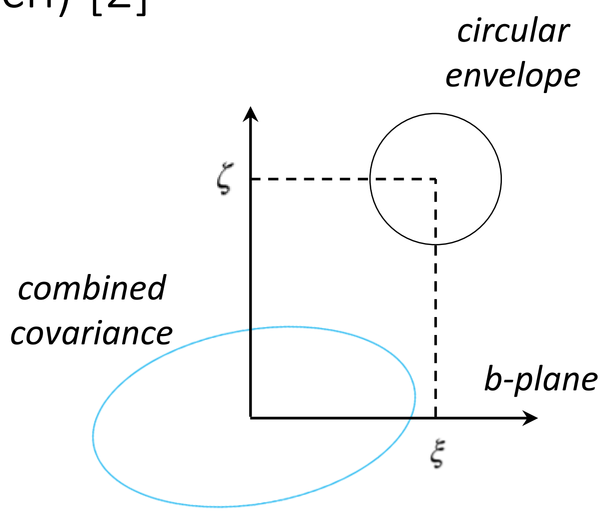
5 – Can we perform collision avoidance manoeuvres in this case?

# COLLISION AVOIDANCE MANOEUVRES

# Collision Avoidance Manouvres

## Collision avoidance manoeuvre design

- Modelling of Collision Avoidance Manoeuvre (CAM) in the b-plane
- Uncertainties are included by propagation of covariance matrix
- Two options for CAM design (all analytical)
  - Maximum deviation in the b-plane [1]
  - Minimum collision probability (Chan's approach) [2]
- Debris orbits are constructed with conjunction information from ESA's MASTER-2009
- Impact of the increased area and uncertainty in CA operations





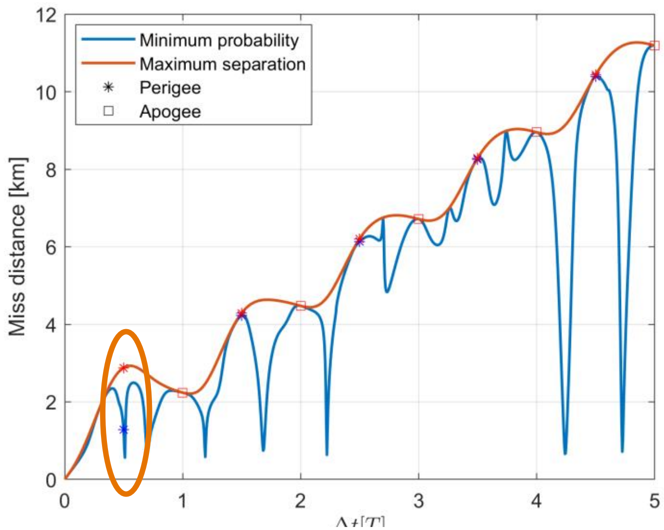
[1] M. Vasile, and C. Colombo, "Optimal impact strategies for asteroid deflection, *JGCD*, 31(4):858-872,2008

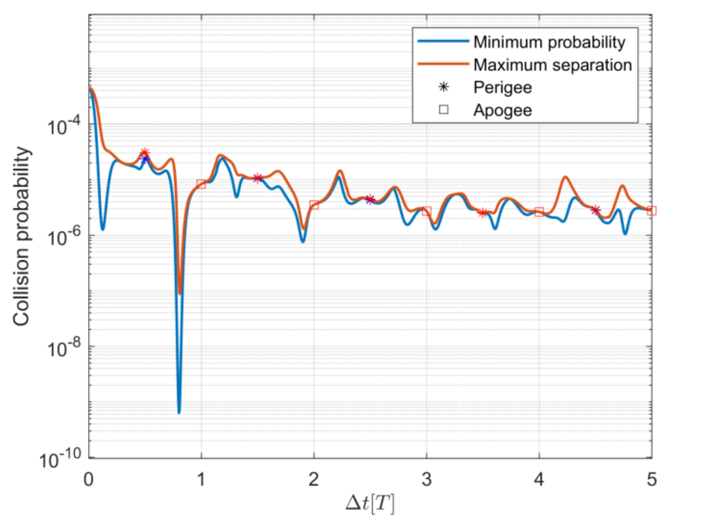
[2] C. Bombardelli, and J. Hernando-Ayuso, "Optimal impulsive collision avoidance in low earth orbit", JGCD, 38(2):217-225, 2015

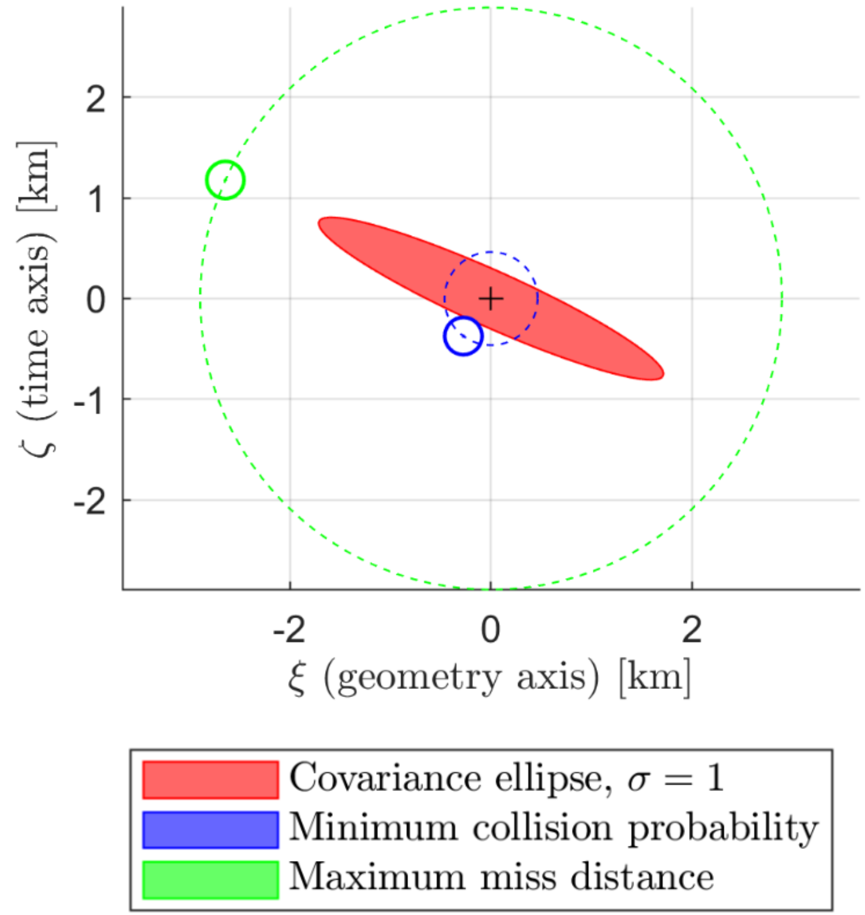
# CAMs by spacecraft

## Maximum miss distance versus minimum collision probability

$\Delta v = 0.7$ m/s
$r_A = 10\ m$



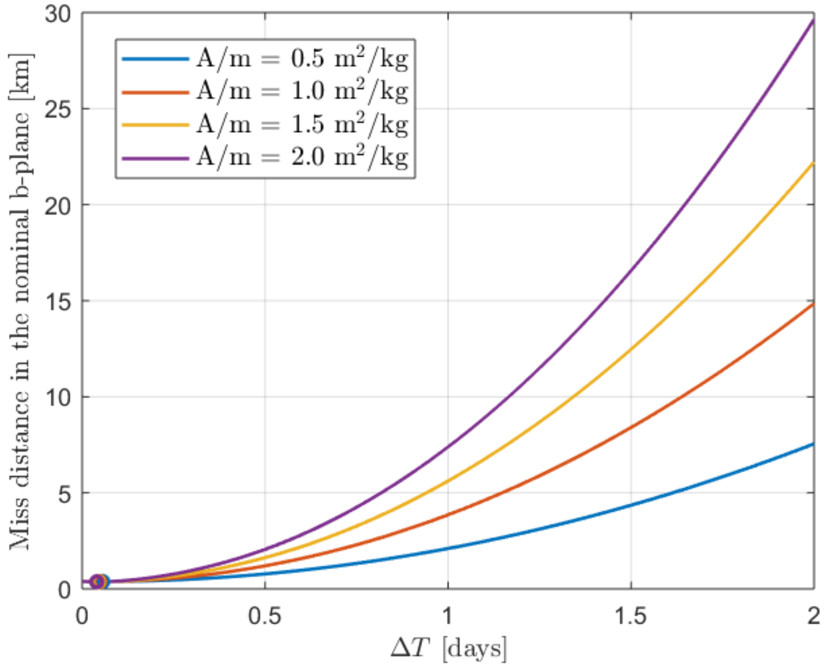



# CAM by sail of tether

## Evaluation of CA capabilities by the deorbiting device

- Drag sail:
  - An on/off (perpendicular/parallel to main force) control law is effective with sufficient lead time.
  - Required time depends on A/m




- Tether:
  - Provides control corresponding to a tangential force
  - Works well except for nearly polar orbits

# CONCLUSION

# Conclusions

## Have the study questions been answered?

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

- Requirements derived and verified with current technological capabilities. Possible deorbiting in LEO (sail or tether) and some MEO (sail).

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

- Drag-dominated region: remains the same (area vs deorbit time)
- SRP-dominated region: decreases with sail size

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

- New models proposed (partial collision, soft impactor, etc)
- Validated with hydrocode simulations

# Conclusions

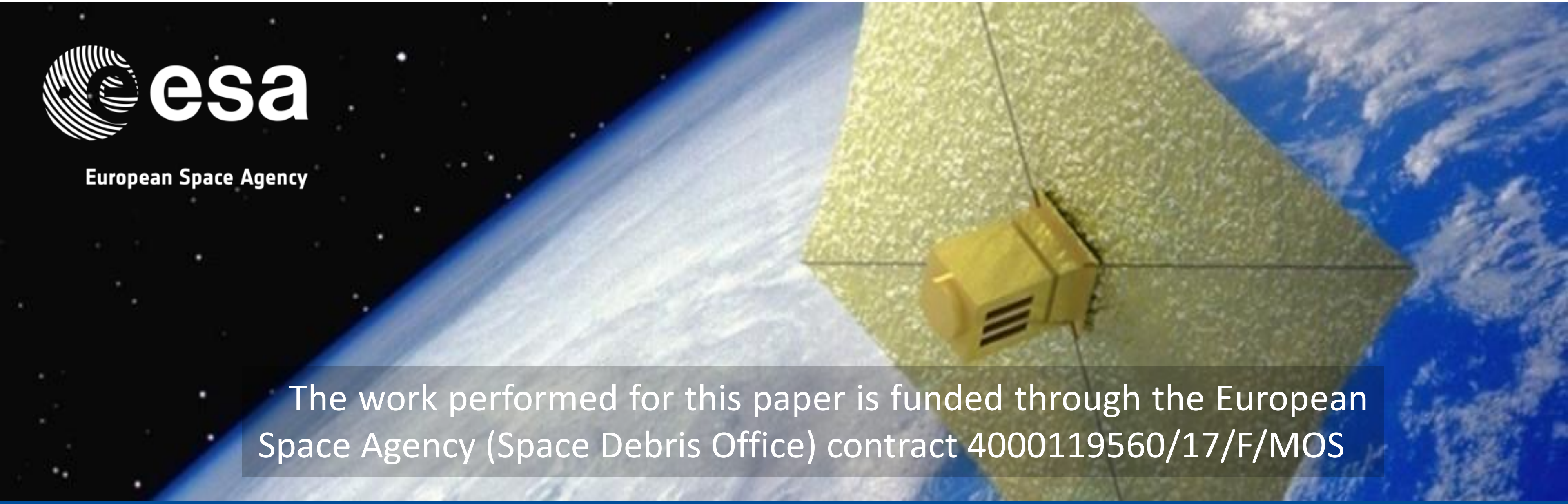
## Have the study questions been answered?

### 4. What happens to the space debris environment?

- **No negative net effect in terms of number of objects produced.**
- **Significant increase in the collisional activity**
- Sails: 10-15 % decrease in LEO objects after 200 years
- Tethers: 15-20% decrease in LEO objects after 200 years

### 5. Can we perform collision avoidance manoeuvres in this case?

- Analytical models for max. distance and min. probability CAMs
- Feasible even with extended area+uncertainty
- CAMs by sails and tethers feasible (more lead time may be needed)

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