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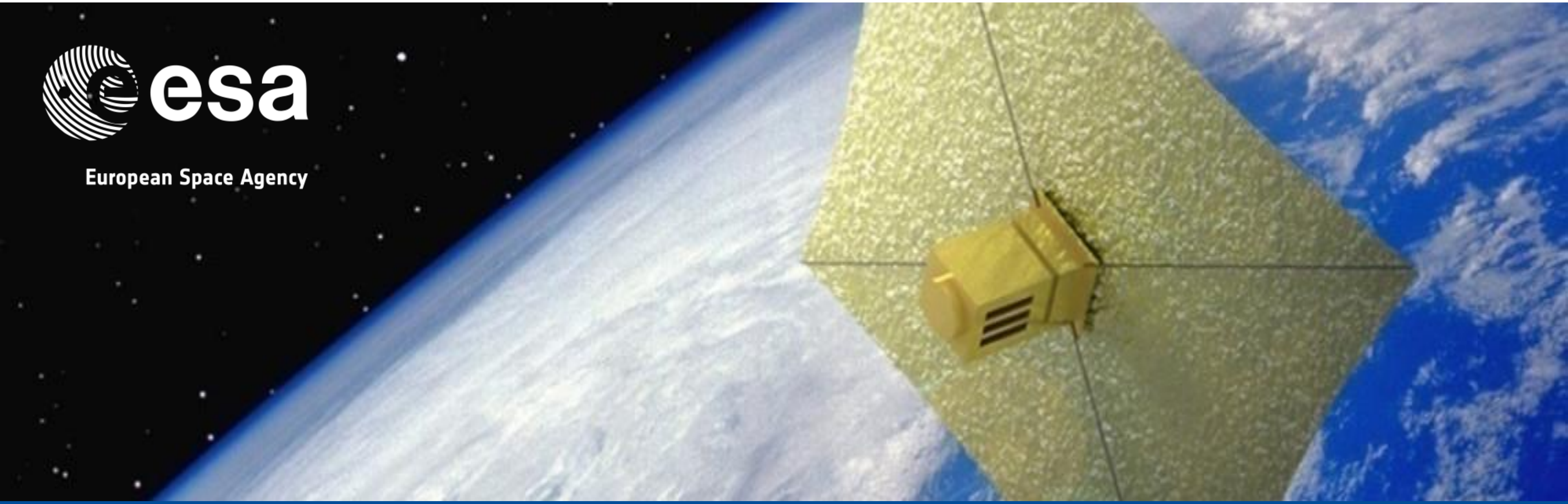

Effects of passive de-orbiting with sails on the space debris environment

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

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Solar and drag sails for end-of-life deorbit

Interaction with space debris population

Performance of sailing strategy for passive deorbiting:

- **Effective area-to-mass ratio**
- **Time to deorbit**:
  the larger the sail 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.

Introduction

ESA study questions

1. Which sail 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 for passive deorbiting?

In the study results for tether and sails, here only sail cases are presented.

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

APPLICABILITY OF DEORBITING DEVICES

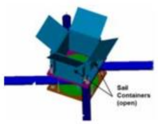
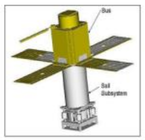
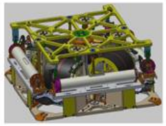
Sail requirements

What is the limit of current sail technologies?

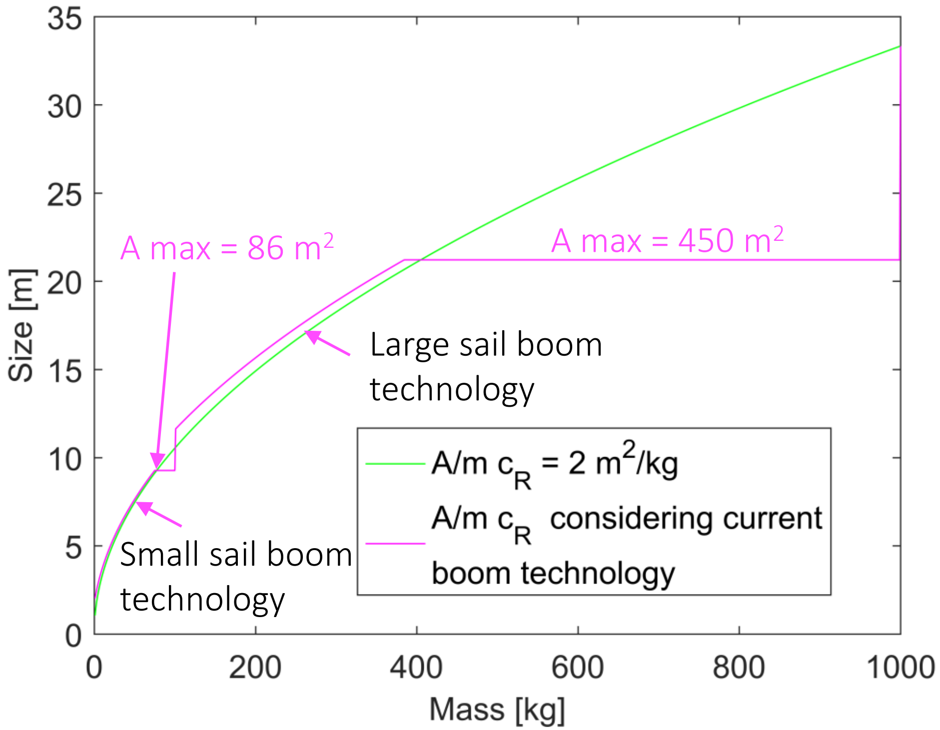
DOM (ESEO)
Icarus-3 (CBNT-1)
CanX-7
Icarus-1 (TDS-1)
NanoSail-D2

ADEO
NEAScout
Daedalus
DLR 20x20 m
VSE

LuxSpace's DRS
DoWn!™

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

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

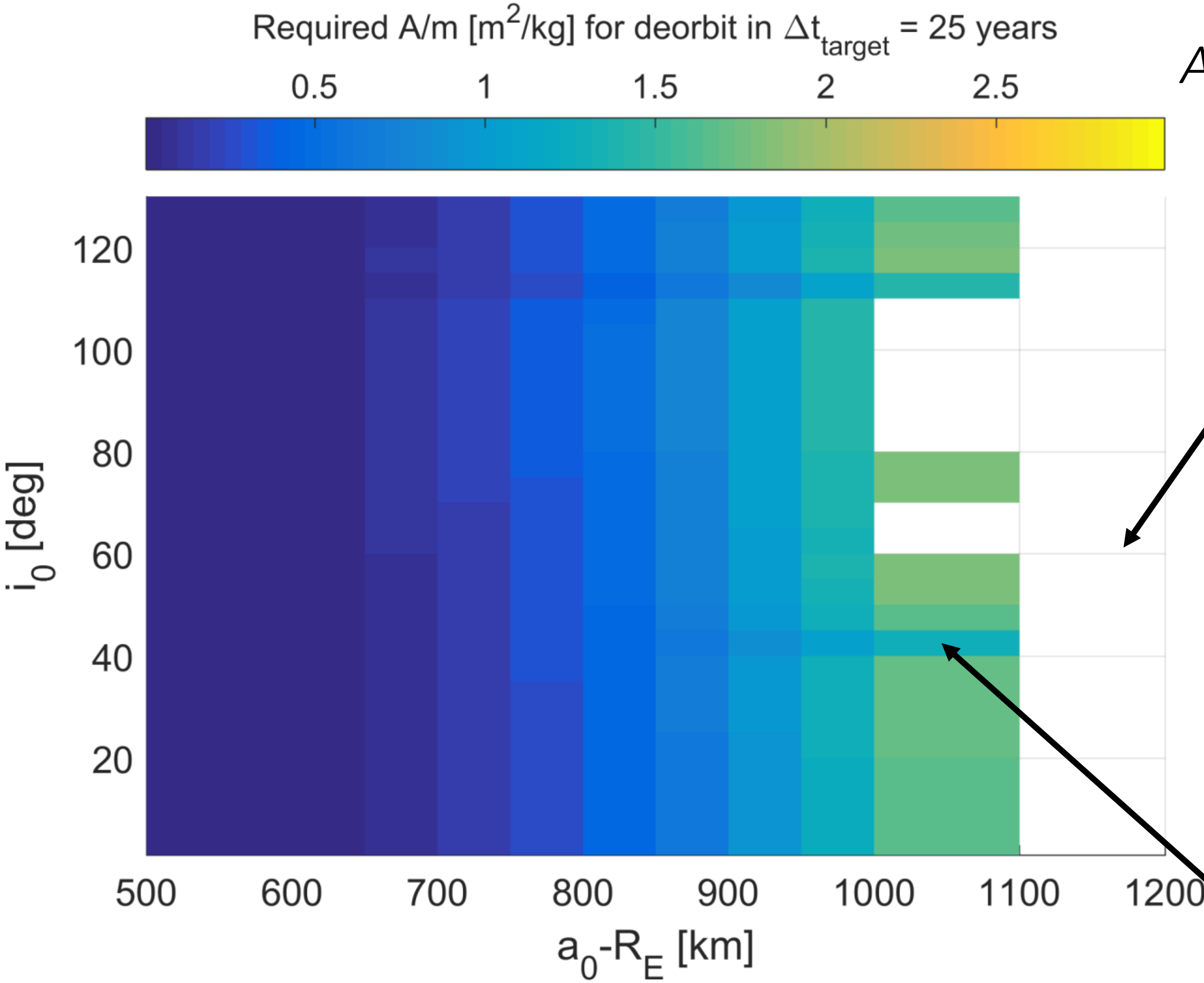


Sail size technological limits

Sail requirements

Which sail size is needed to deorbit in chosen deorbiting time?

$A/m\ c_R$ or $A/m\ c_D$

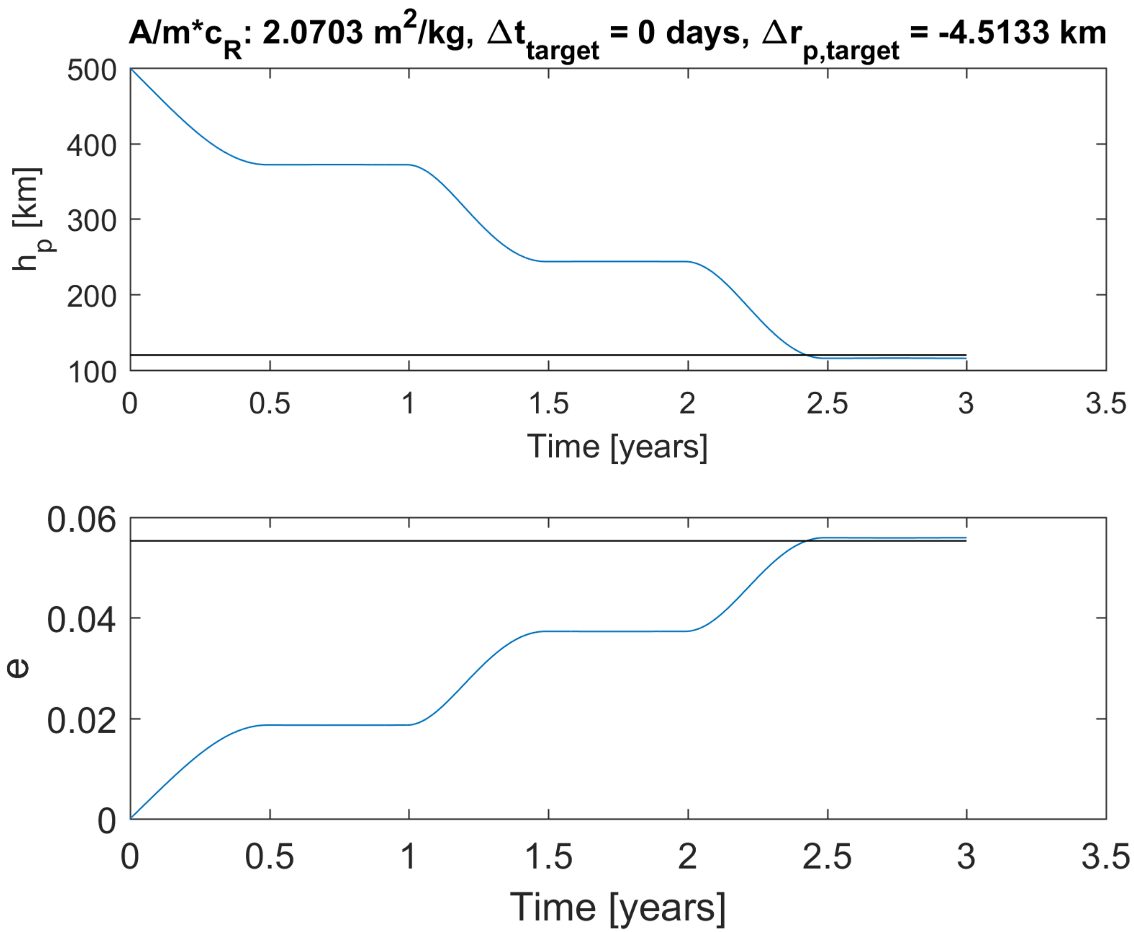


For orbit with higher inclination and semi-major axis more complex solar sailing strategies can be used to allow passive deorbit (e.g., modulating sail)

SRP enhanced deorbiting

Sail requirements

Modulating solar sailing



Available technologies

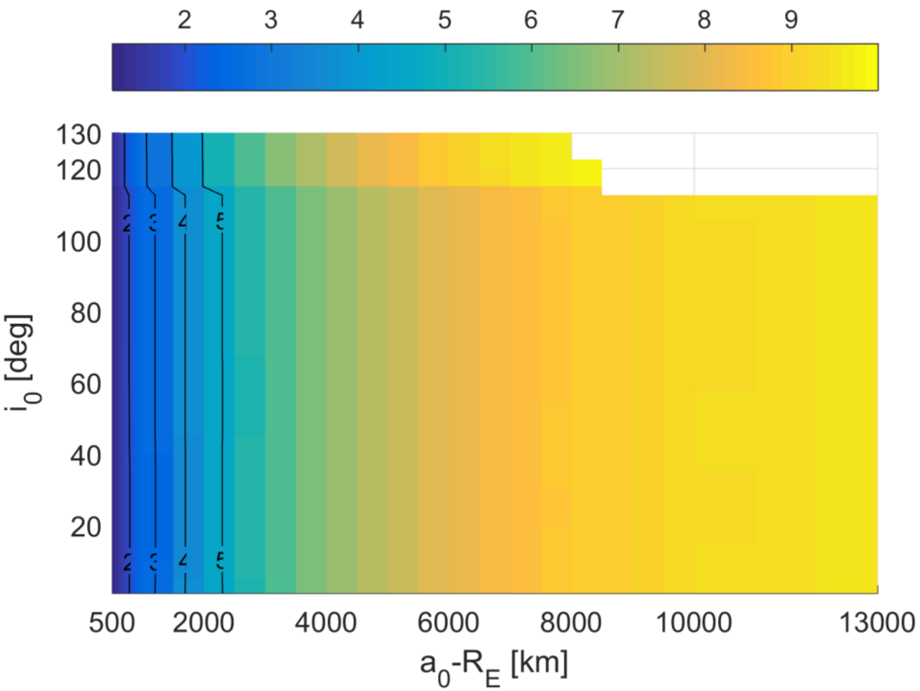
- Heligyro (1967 McNeal, JPL, MIT)
- Quasi-rombic pyramid shape sail (Ceriotti et al.)
- IDEA OSG 1 (Astroscale)

Sail requirements

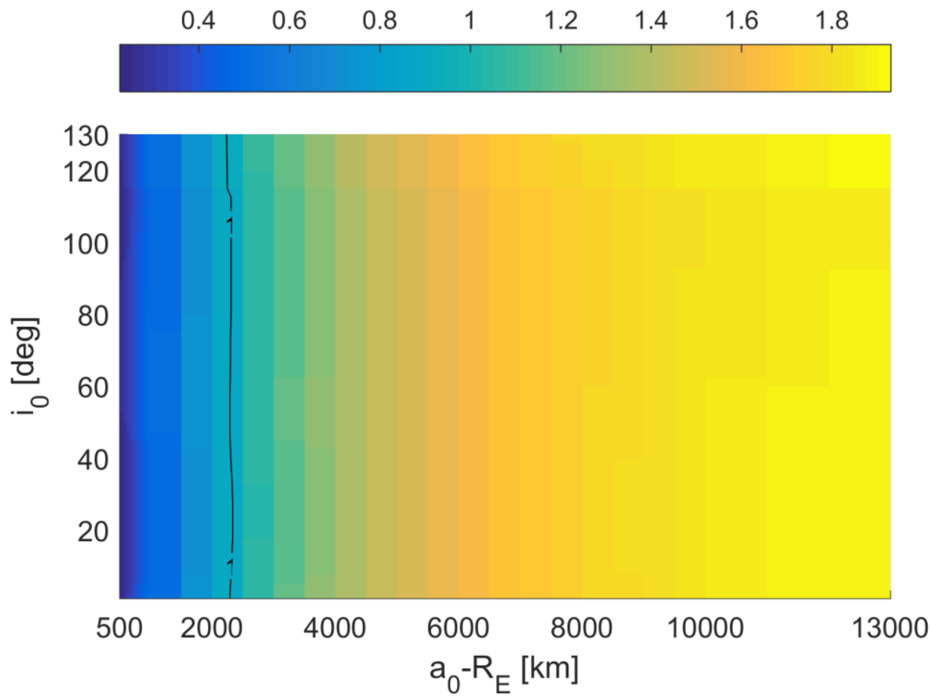
Modulating solar sailing

Requirements in terms of effective area-to-mass ($c_R A/m$) for different deorbiting times with modulating solar radiation pressure strategy. The colour bar represents the required effective area-to-mass.

Maximum deorbiting time set to 5 years



Maximum deorbiting time set to 25 years



2. How the cumulative collision risk scale?

COLLISION RISK

Sensitivity analysis of sails collision probability

Simulations objectives and characteristics

Objective

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

- Spacecraft mass: 1 kg, 10 kg, 100 kg, and 1000 kg
- Decay time: 5, 10, 15, and 25 years
- Initial orbit conditions
- Minimum debris particle diametre: 1 mm, 1 cm, and 10 cm

Method

- The orbits are used to assess the residence time in the different orbital regions, which have different debris densities
- Collision probability (p_c) evaluated using the standard gas theory and fluxes using ESA MASTER-2009

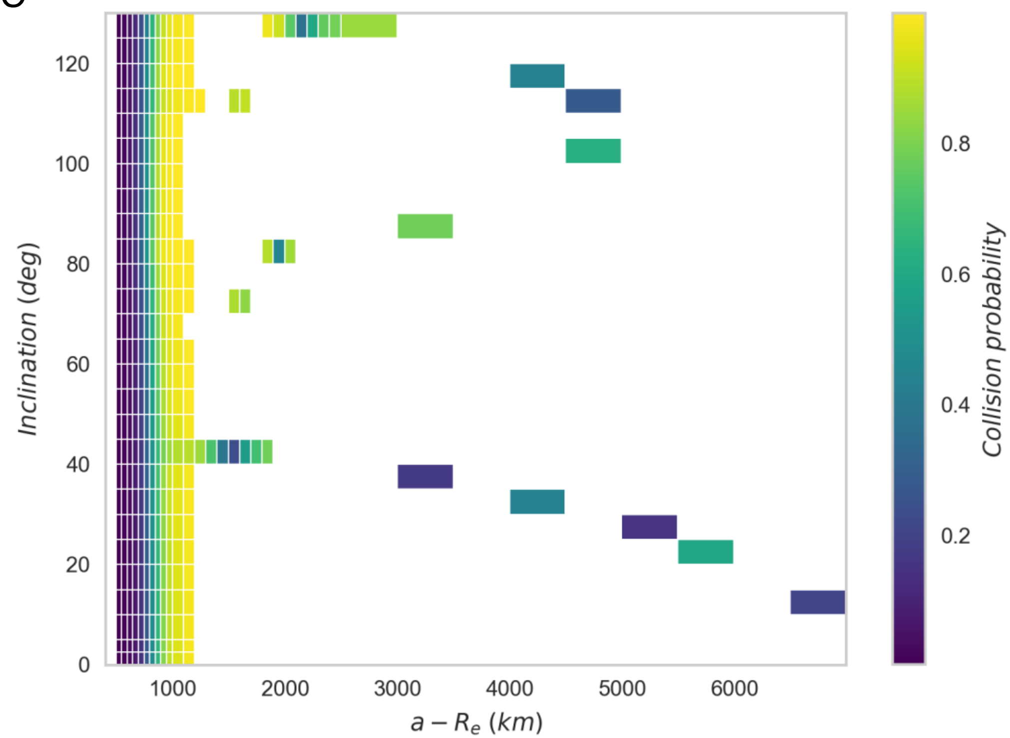
$$p_c = 1 - \exp\left(-\varphi \cdot A \cdot \Delta T\right)$$

Sensitivity to spacecraft mass and initial orbit

- Collision probability with spacecraft mass: quasi-linear increase as sail cross area increases with mass

- Collision probability with initial orbit:
  - At lower altitudes (up to 1000 km) is noticable a regular behaviour, with a greater collision probability for spacecraft starting at higher altitudes and thus passing through the most populated debris regions.
  - At higher altitudes the deorbiting is SRP driven (elliptical path) therefore collission probability is lower

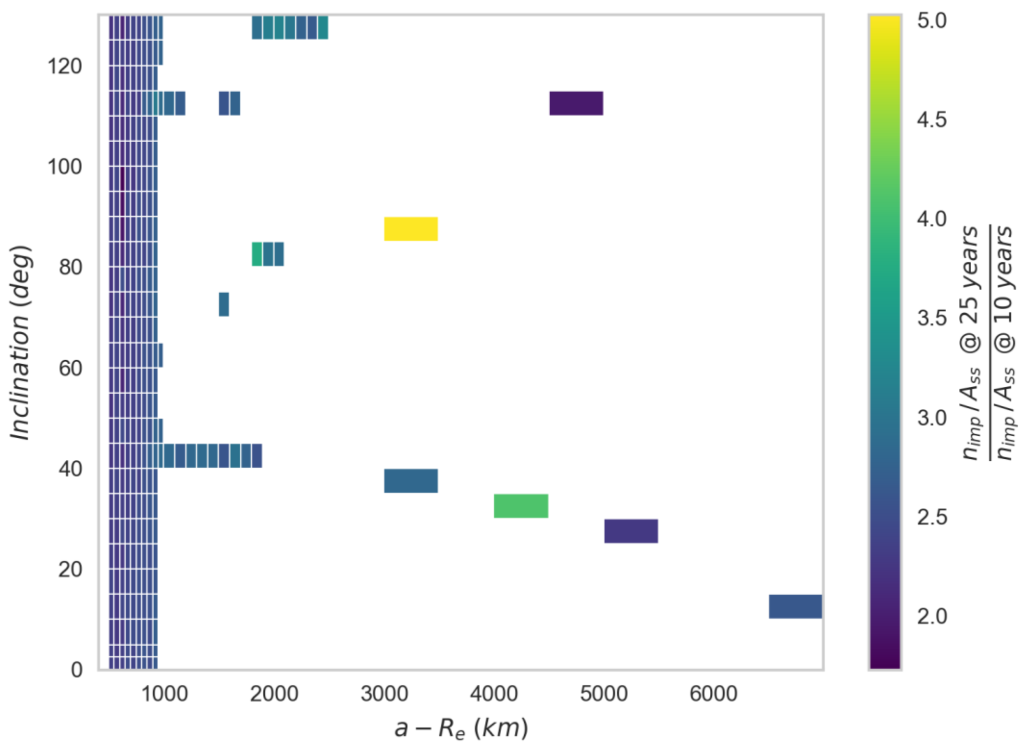
Deorbiting with sail in 25 y, s/c: 10 kg, minimum debris particle: 1 mm



Sensitivity to deorbiting time

- Collision probability with deorbiting time:
  - For drag driven deorbit the ratio is around 1 (linear relashionship)
  - For SRP deorbiting the ratio is higher than 1: shorter deorbiting with bigger sail are better than longer deorbiting with smaller sail!

Ratio between the number of impacts for a 25 years decay orbit and a 10 years decay orbit, minimum debris particle: 1 mm



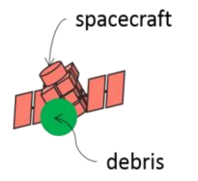
3. How can we model a collision involving large appendices?

FRAGMENTATION MODEL

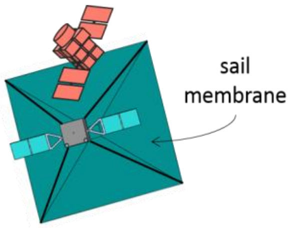
Collision scenarios for sail and tether systems

Independent cases

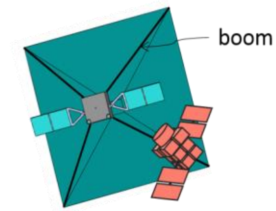
Target	ID	Impactor	Comment
Spacecraft	SC1	Debris	Possible failure: spacecraft break-up (impact pressure concentrated on the contact point). Collision consequences can be modelled using the NASA SBM.
	SC3	Sail membrane	Possible failure: spacecraft break-up. Collision consequences may be different from 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



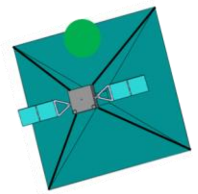
SC1: debris Vs. spacecraft

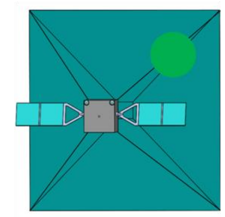


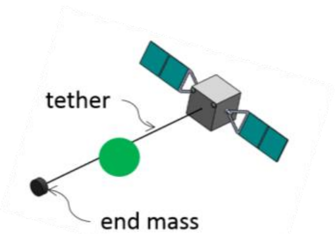
SC3: membrane Vs. spacecraft



SC4: boom Vs. spacecraft


SM1: debris Vs. membrane


B1: debris Vs. boom



T1: debris Vs. tether

In summary, 6 independent collision scenarios:

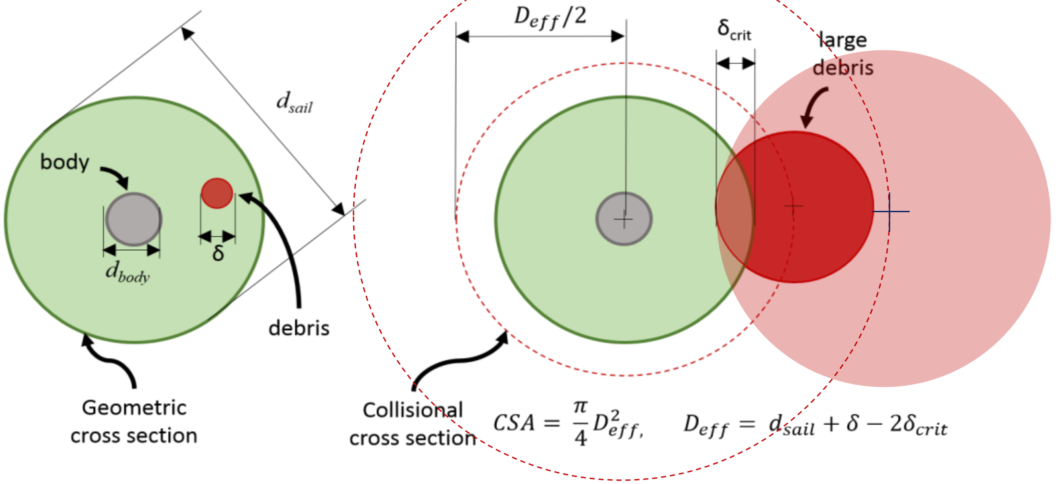
- Different failure modes depending on specific impactor/target properties
- Failure equations and collisional cross sectional areas required for these scenarios

Risk assessment methodology

Failure probability

For each of the elements of a sail or tether system, the number of critical impacts per unit time is:

$$\dot{n}_{el} = \int_{d_{crit,el}}^{\delta_\infty} \frac{\partial F}{\partial \delta} CSA_{el} d\delta$$



- Cumulative debris flux: *F*
- **Critical debris size $d_{crit,el}$** is the equivalent diameter (or characteristic length) of the smallest object which makes the element fail
- **Collisional cross sectional area CSA_{el}** is the geometric cross section of the element, properly augmented to account for the impactor size
- Debris diameter: δ

Approach to break-up

Introduction and basic assumptions

- The NASA SBM is the starting point for fragments distributions
- 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;

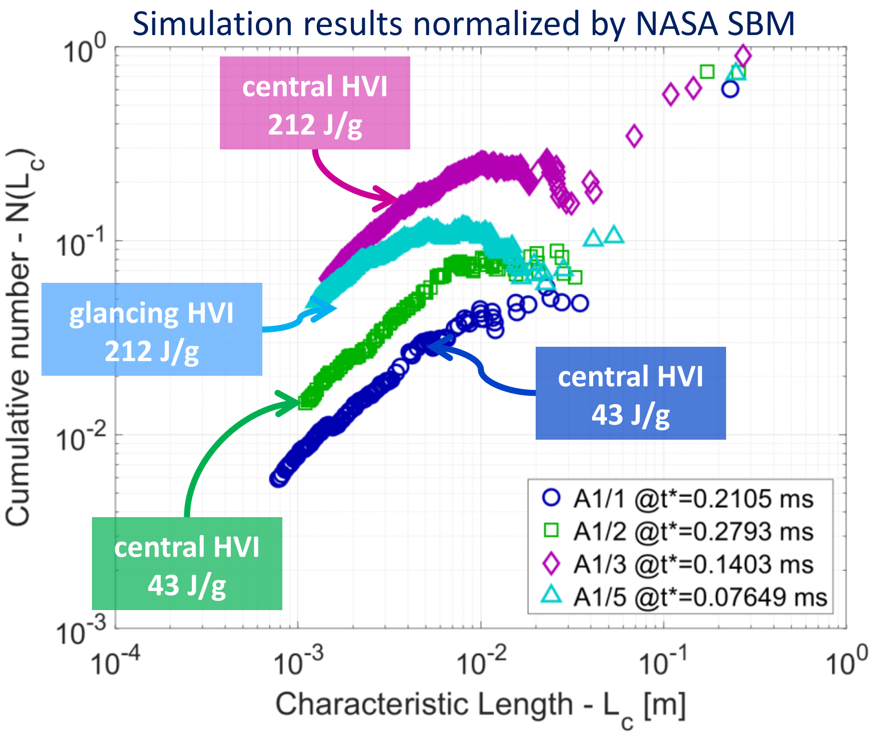
B. If any of the elements of a sail/tether system is hit by another object, a “geometric” approach is used: tethers, booms and sail membranes are cut in two pieces with negligible production of additional fragments of significant characteristic length.

- Hydrocodes simulations have been used to evaluate the assumptions on which the proposed break-up modelling approach is based

Hydrocodes simulations

Simulations on 1U-CubeSat targets: summary

- Simulations catch well the **NASA SBM trend**, with **predicted good accuracy**
- Central collisions and glancing impacts cause similar consequences in terms of fragments distributions
- It is unlikely that **soft** impactors cause catastrophic fragmentation, since they could be destroyed before S/C break-up
- **New fragments** are produced where impactor and target overlap, but these fragments are **very tiny** (characteristic length in the order of boom/sail membrane thickness)



4. What happens to the space debris environment?

SPACE DEBRIS LONG-TERM SIMULATIONS

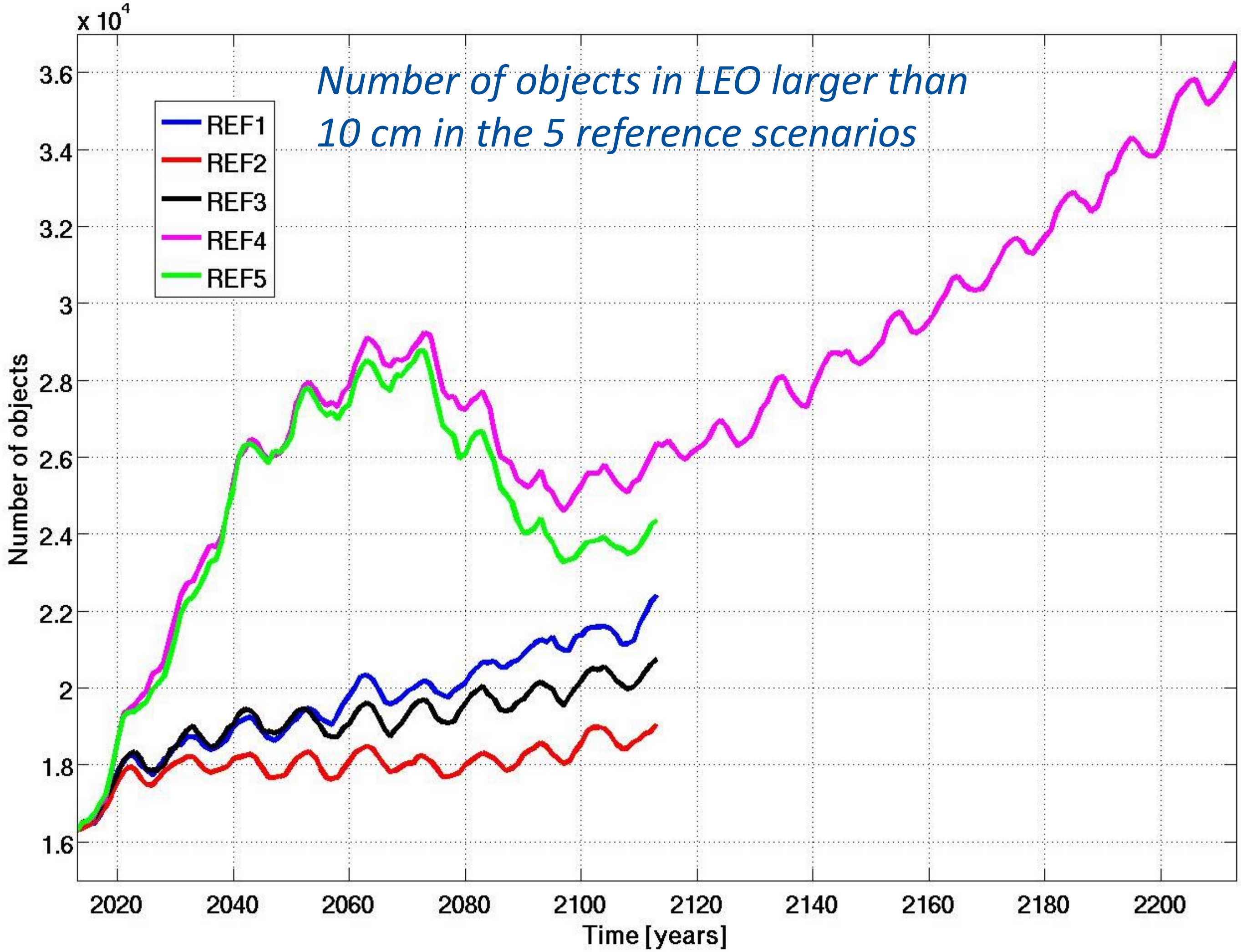
Debris reference scenarios

Reference test cases

Case	Launch	Compliance to PDM 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

Debris reference scenarios

Number of LEO objects in the reference cases



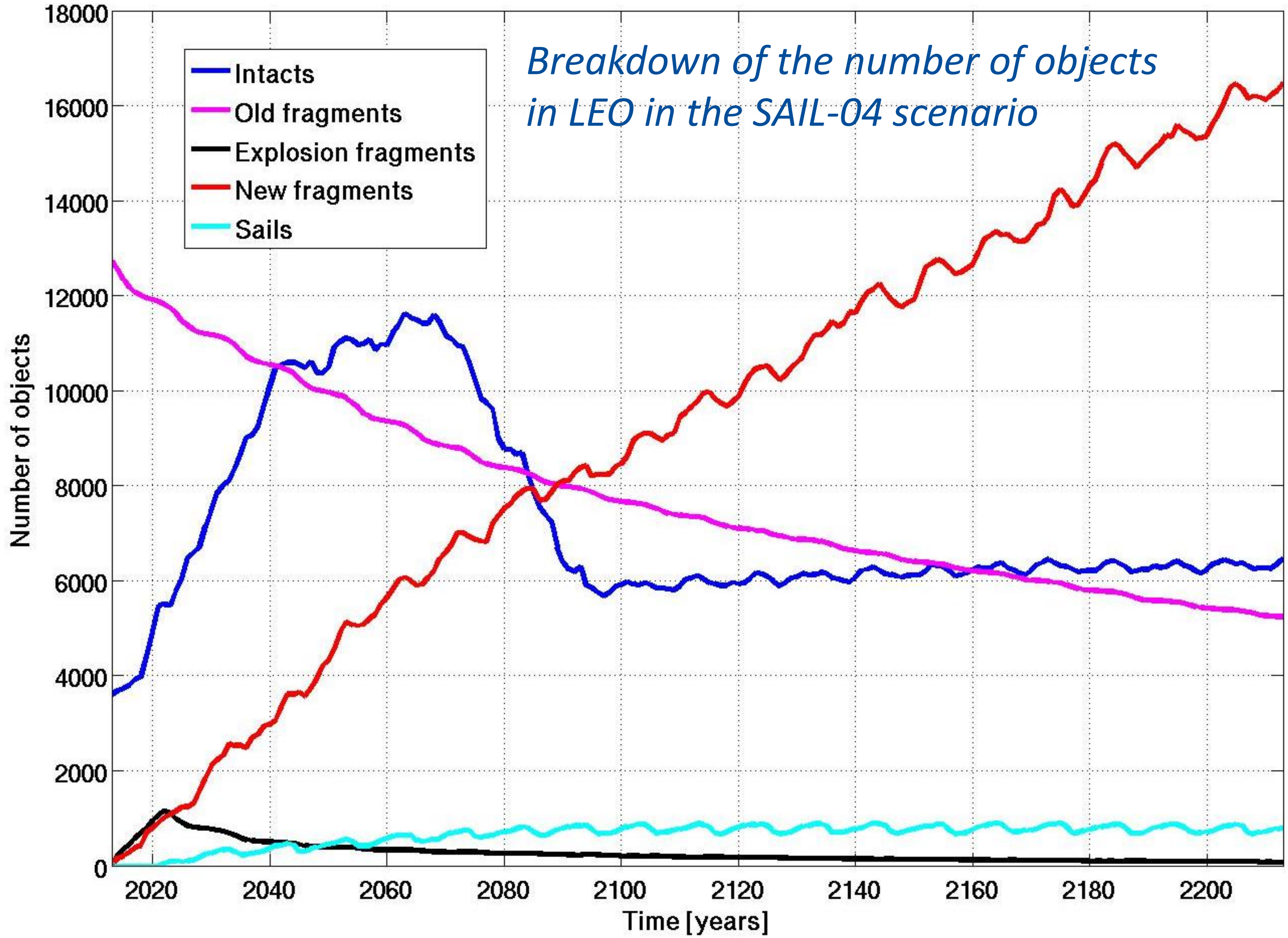
Debris scenario with sails

Sail test cases

Case	Set-up	S/c using the sail	Percentage of s/c using the sail	Sail dimension for deorbit	Large constellation	Sail/balloon percentage	Simulation time [years]
SAIL-01	REF-04	< 1000 kg	50% below 800 km 100% above 800 km	25 years	Do not use the sail	90% sail 10% balloon	100
SAIL-02	REF-04	< 1000 kg	100% below 800 km 100% above 800 km	25 years	Do not use the sail	90% sail 10% balloon	200
SAIL-03	REF-04	< 1000 kg	100% below 800 km 100% above 800 km	10 years	Do not use the sail	90% sail 10% balloon	100
SAIL-04	REF-05	< 1000 kg	100% below 800 km 100% above 800 km	10 years	Do not use the sail	90% sail 10% balloon	200

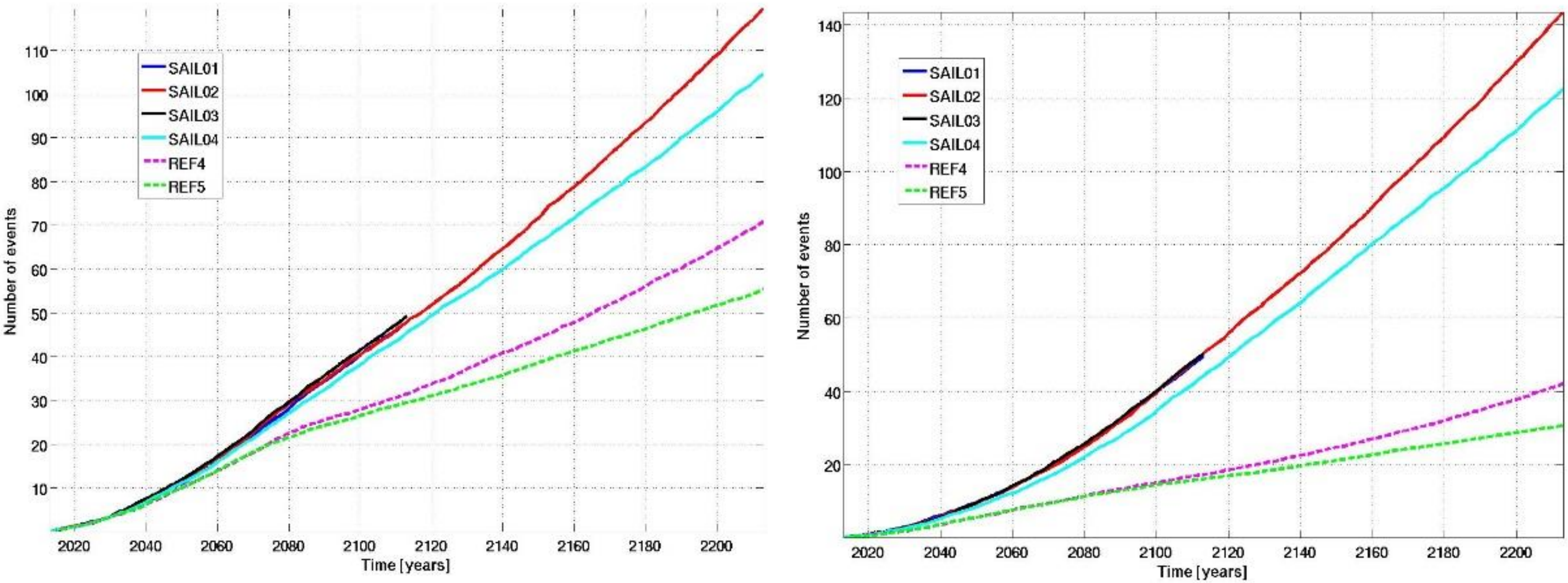
Debris scenario with sails

Number of objects in case SAIL03



Debris scenario with sails

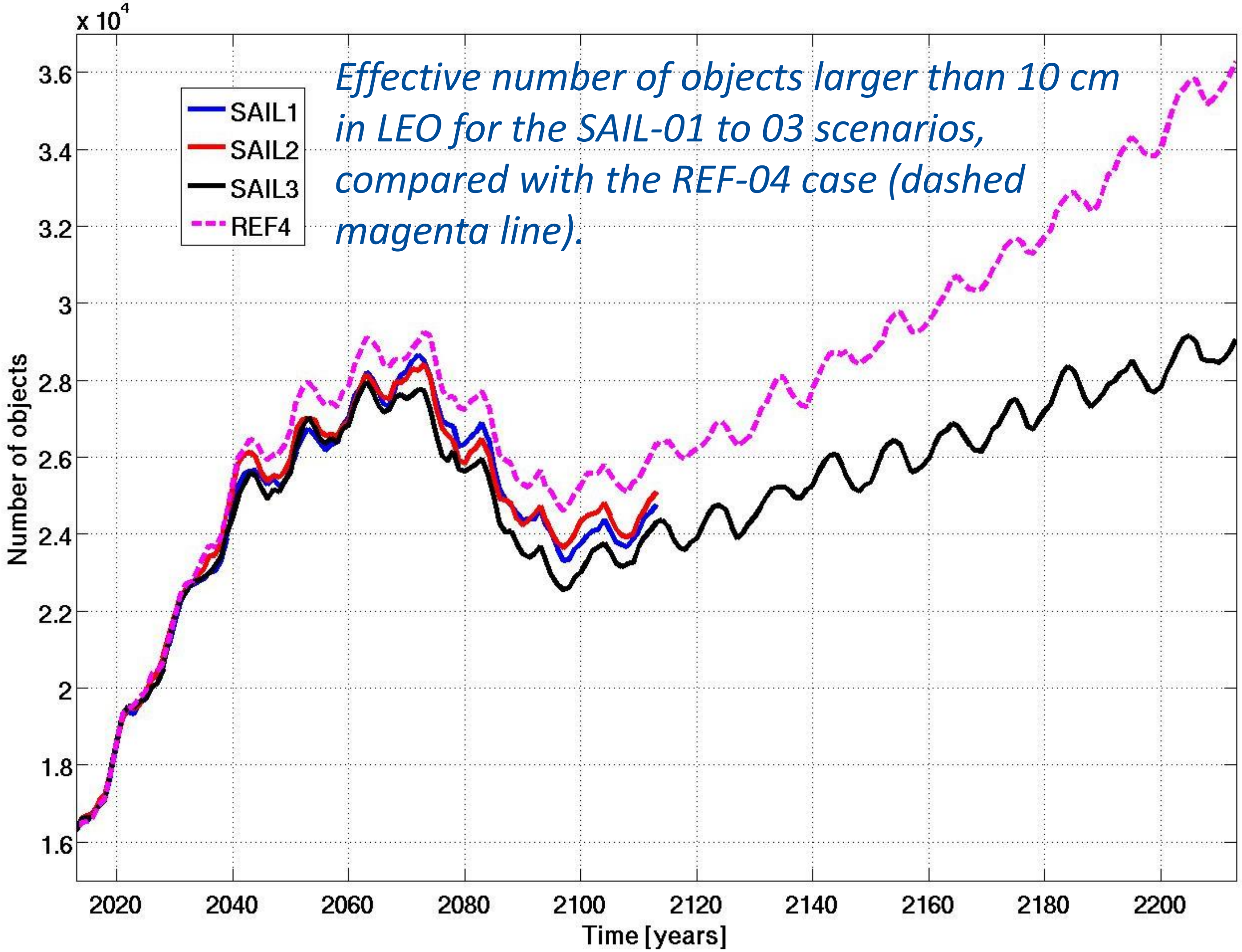
Cumulative number of (a) catastrophic and (b) non-catastrophic collisions



Cumulative number of (a) catastrophic and (b) non-catastrophic collisions in the four sail cases, compared to the REF-04 and REF-05 scenarios

Debris scenario with sails

Number of objects in sail cases



Effective number of objects larger than 10 cm in LEO for the SAIL-01 to 03 scenarios, compared with the REF-04 case (dashed magenta line).

Collision statistics (percentages)

	SAIL1 (100 y)			SAIL2 (100 y)			SAIL3 (200 y)			SAIL4 (120 y)		
Average	89 collisions			90 collisions			230 collisions			108 collisions		
	%	Catast. Coll.	Involve sails	%	Catast. Coll.	Involve sails	%	Catast. Coll.	Involve sails	%	Catast. Coll.	Involve sails
Body vs body	8	80	10	8	82	11	5	80	13	11	76	11
Body vs appendix	53	35	93	54	33	94	62	33	96	80	42	94
Appendix vs appendix	1	82	74	2	83	77	1	87	84	2	78	77
Body vs boom	3	92	100	3	92	100	3	92	100	4	82	100
No appendix	34	61	0	34	60	0	28	57	0	3	58	0

Conclusion

Any benefit in using solar/drag sail deorbiting?

- Reducing collision risk now (small cross area) vs long-term sustainability (large sail).
  - For drag sails reducing area decreases slope of cumulative collision probability but not the whole collision probability (proportionality)
  - For solar sails the larger the sail, the lower is the total collision probability as the deorbiting is elliptical.
  - The time of deorbit and cross area do not enter in a simple proportional way in computation of the total collision probability
- Revised fragmentation model has been developed
- Long term simulation currently shows that the use of sails might have a beneficial effect onto the mitigation practices considering the whole space debris environment

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