Assessment of passive and active solar sailing strategies for end-of-life re-entry

C. Colombo[1], T. De Bras De Fer[1], C. Bewick[2], C. McInnes[3]

[1] University of Southampton
[2] OHB
[3] University of Glasgow

Clean Space Workshop

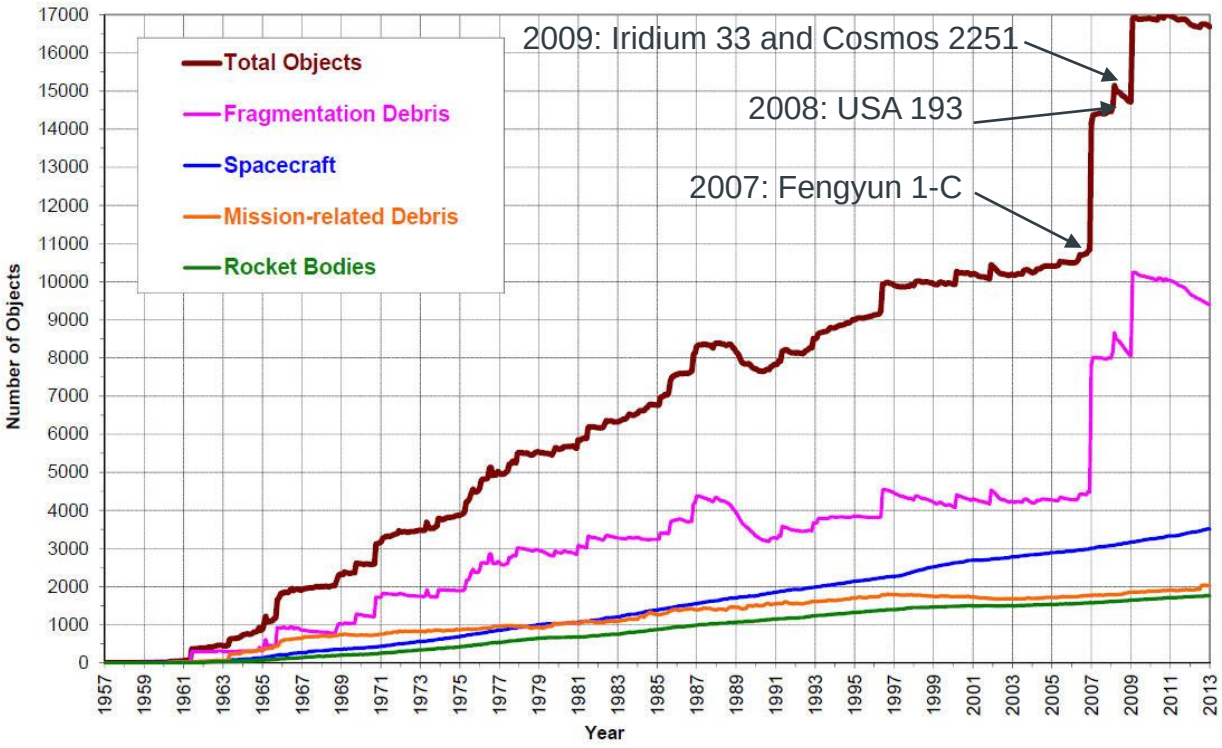
23-27 May ESA/ESTEC

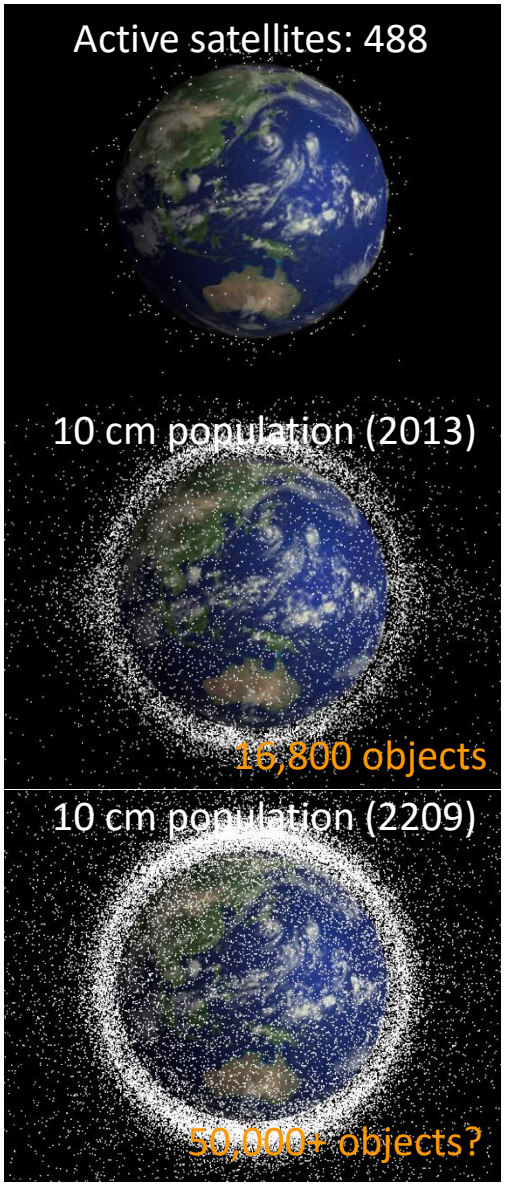
INTRODUCTION

Introduction

Sustainability of the space environment

- Current guidelines for Low and Geostationary orbits
- Ongoing discussion on Medium Earth Orbits guidelines
- Re-entry analysis is also performed for Highly Elliptical Orbits and Libration Point Orbits



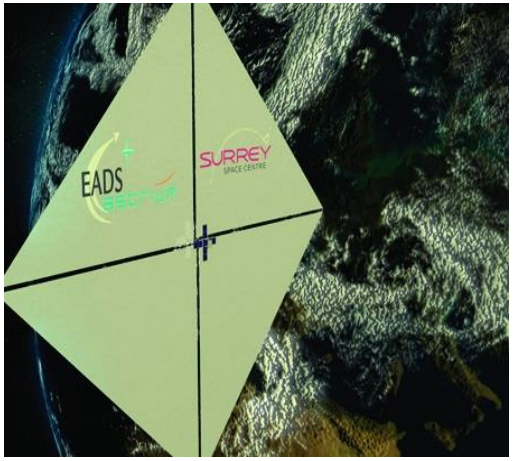


Area-to-mass-ratio augmented deorbiting

Passive end-of-life disposal

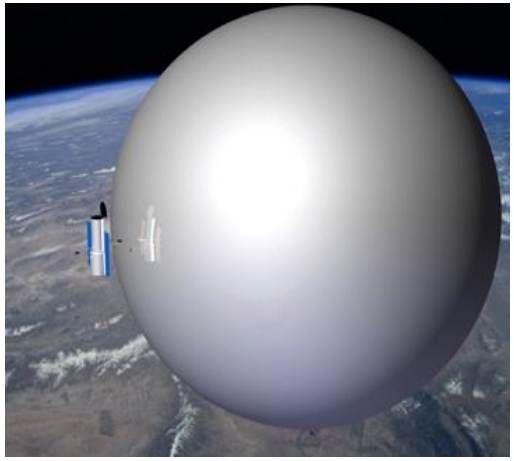
- Area-to-mass-ratio is increased by inflating or deploying large light-weight structure
- Effect of surface perturbation enhanced

Drag augmentation



Example: Drag Sail
by Surrey Space Centre

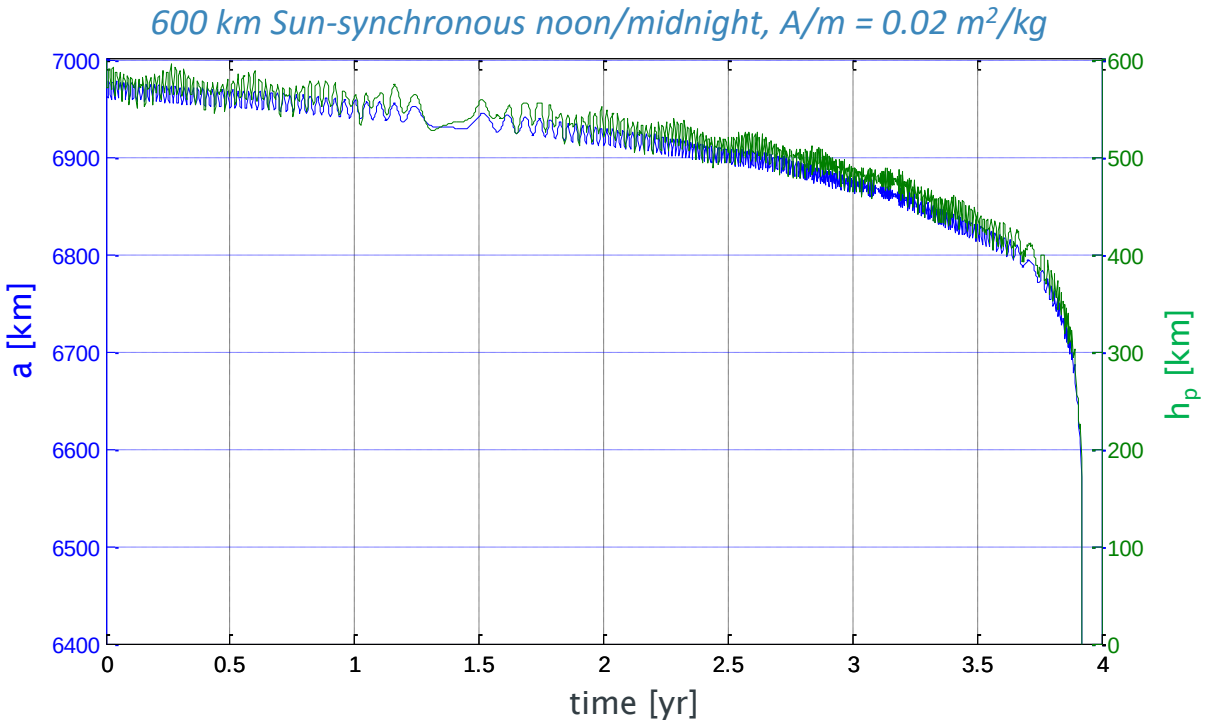
Solar radiation pressure augmentation



Example: Gossamer Orbit Lowering Device by Global Aerospace Corp

Drag augmentation deorbiting

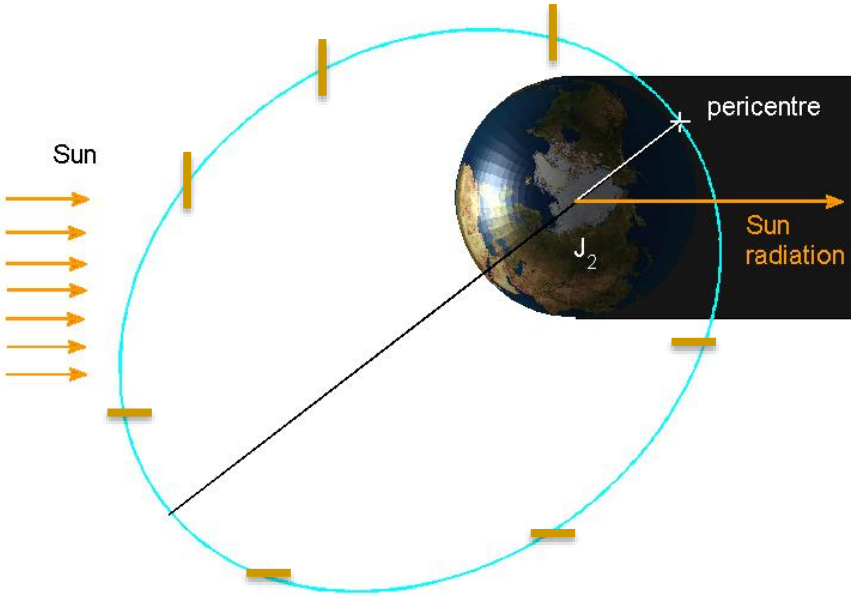
- Altitude below 800 km
- Aerodynamic drag decreases the semi-major axis causing the spacecraft to spiral down over time.
- Function of atmospheric density: loses effectiveness with altitude



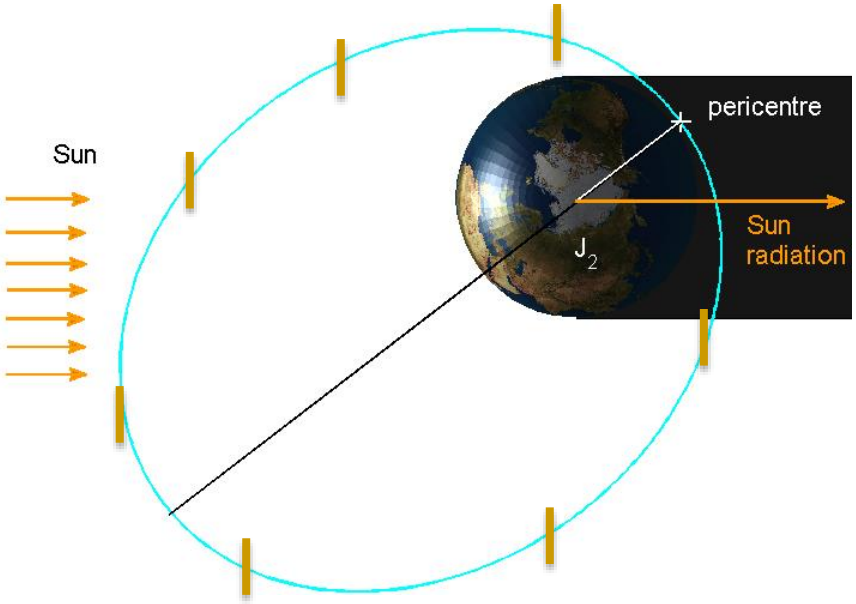
Solar radiation pressure deorbiting

- Altitude above 1000 km
- Governed by complex dynamics under Earth's oblateness and solar radiation pressure: effectiveness mainly dependent on semi-major axis and inclination
- Sail attitude control

Active navigation
i.e. controlled during the orbit



Passive navigation
i.e. always in the Sun direction

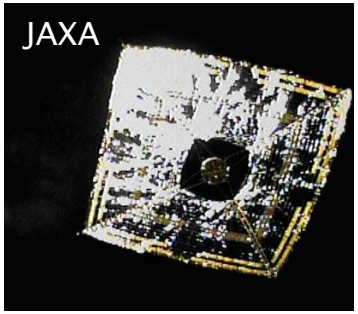


Solar radiation pressure deorbiting

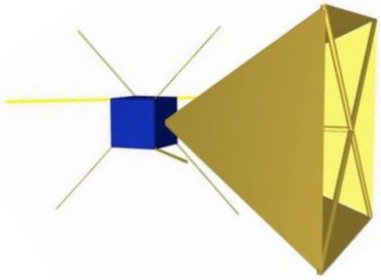
- Altitude above 1000 km
- Governed by complex dynamics under Earth's oblateness and solar radiation pressure: effectiveness mainly dependent on semi-major axis and inclination
- Sail attitude control

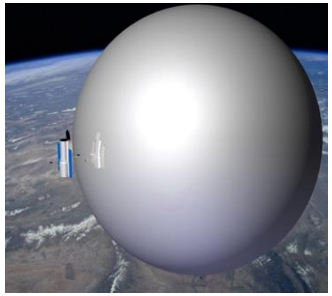
Active navigation
i.e. controlled during the orbit

Passive navigation
i.e. always in the Sun direction



e.g. flat sail or geometry variable pyramid shape

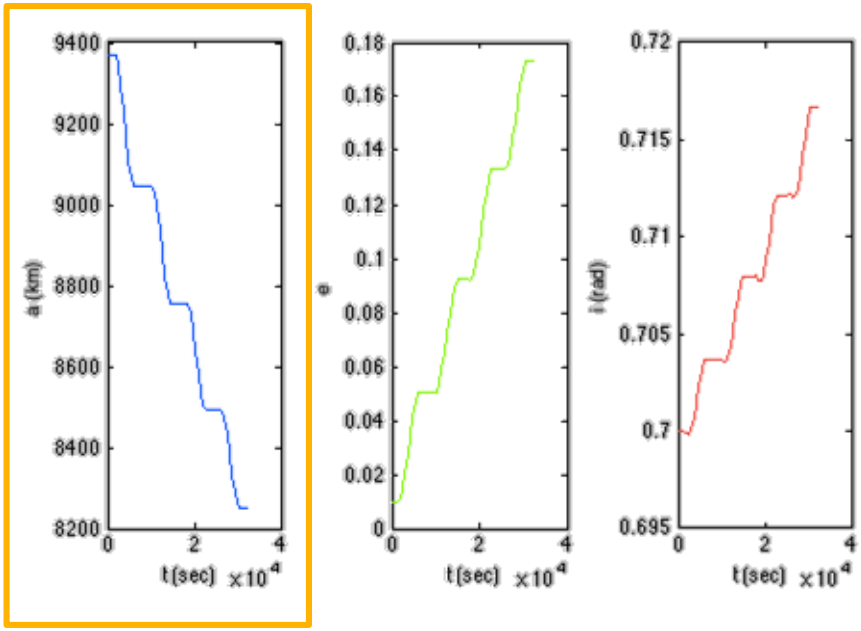




e.g. pyramidal shape or deployable balloon

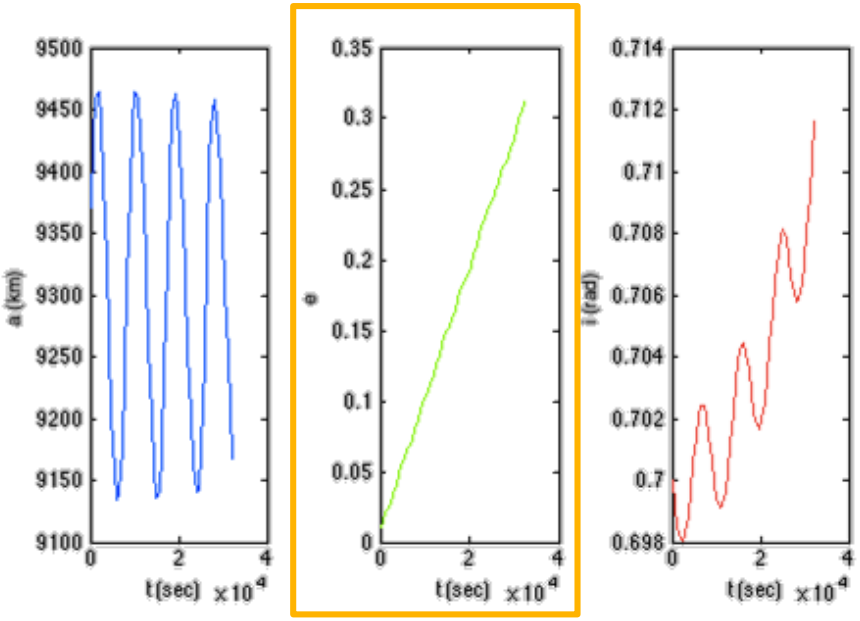
Solar radiation pressure deorbiting

Active navigation
i.e. controlled during the orbit



Similar effect to drag sail, i.e. energy of the orbit is decreased

Passive navigation
i.e. always in the Sun direction

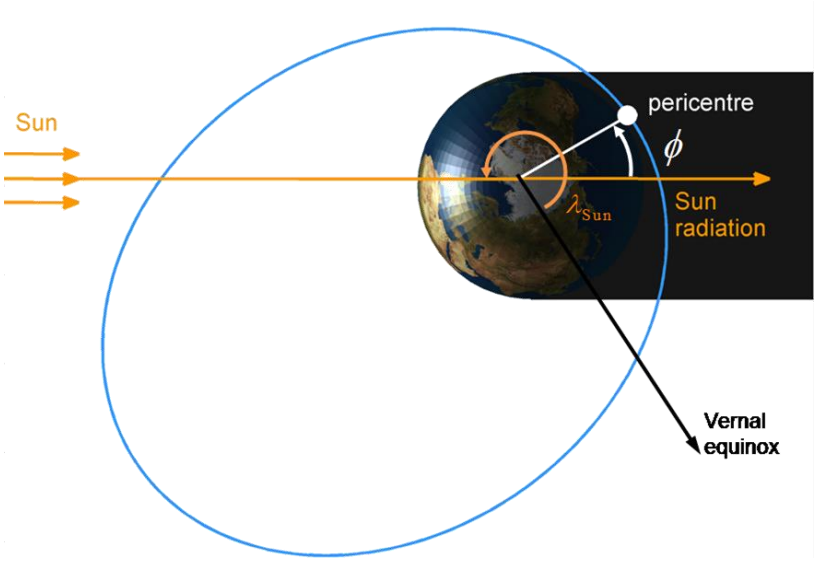


Long term effect on semi-major axis is zero, i.e. energy of the orbit is constant

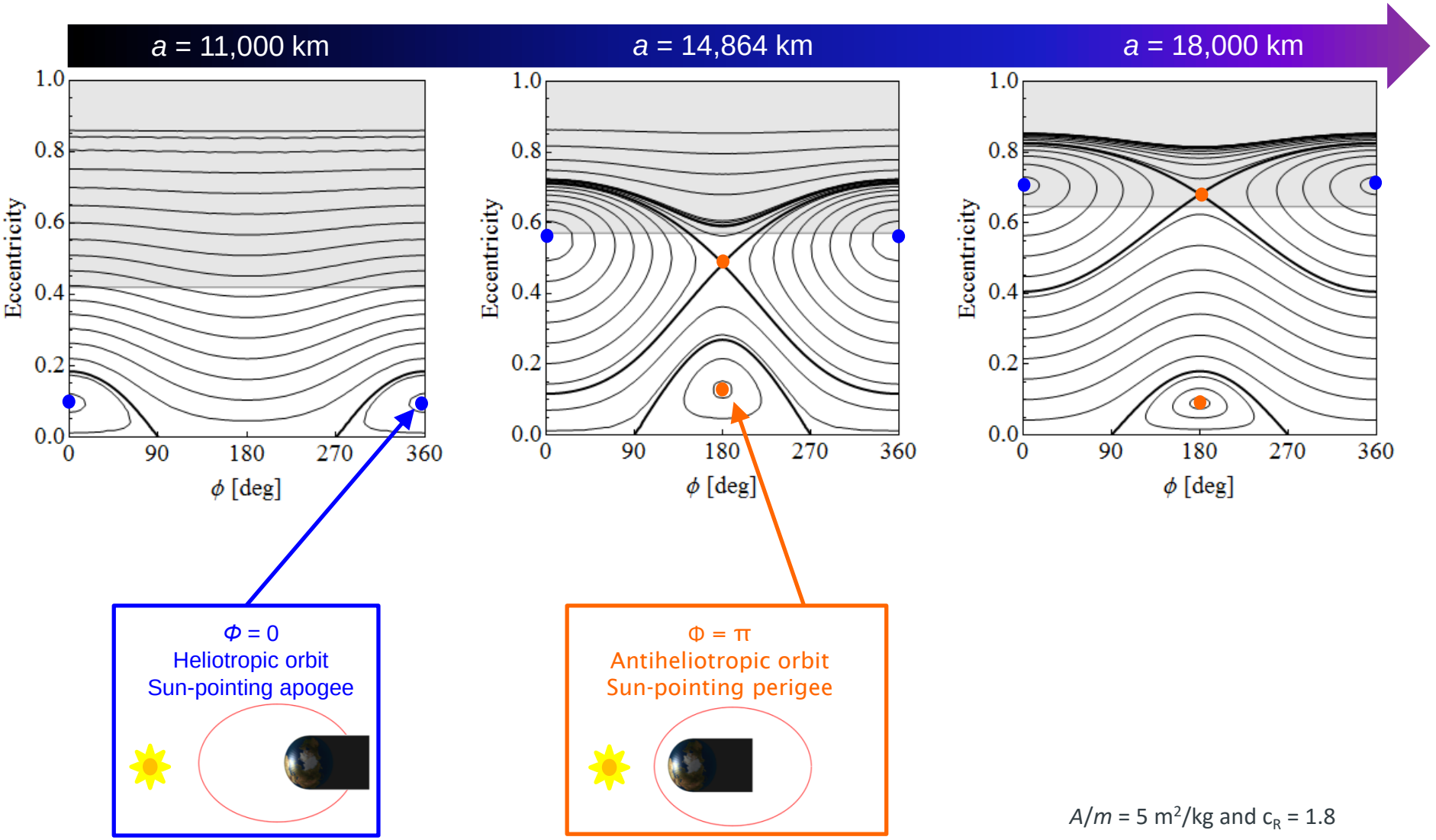
PASSIVE SRP-AUGMENTED DEORBITING

Solar radiation pressure deorbiting: passive

- Main perturbing effects: Earth's oblateness and solar radiation pressure
- Long term effect on eccentricity (e) and sun-perigee angle (ϕ)
- Effect depends on orbit inclination and semi-major axis
- Effect can be engineered by defining deployable area $\sigma = c_R A/m$

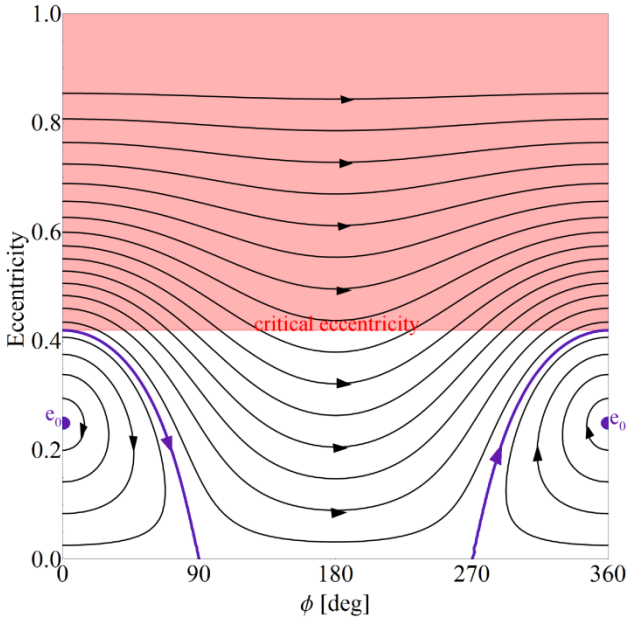


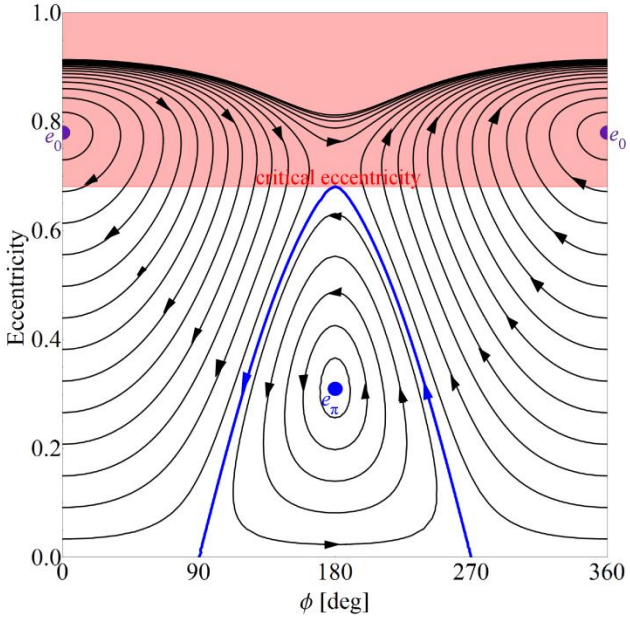
Solar radiation pressure deorbiting: passive

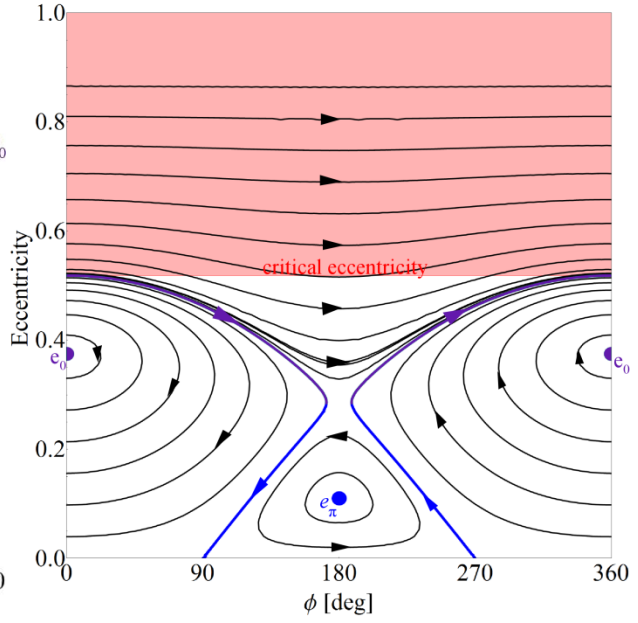


A/m = 5 m^2/kg and c_R = 1.8

Solar radiation pressure deorbiting: passive





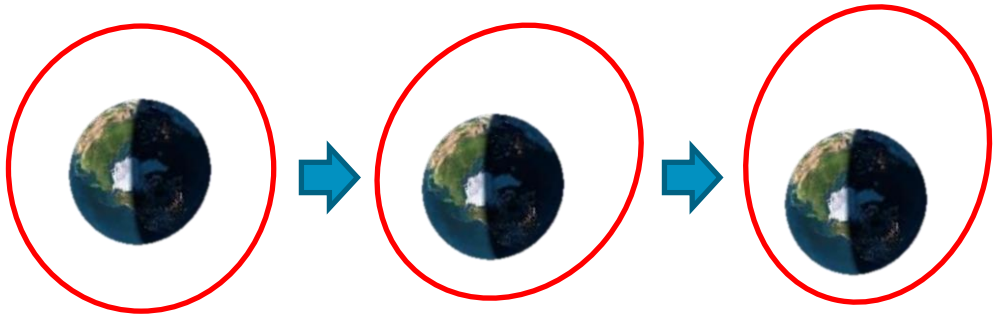


- Lücking, Colombo, McInnes, "A Passive Satellite Deorbiting Strategy for MEO using Solar Radiation Pressure and the J_2 Effect", *Acta Astronautica*, 2012.

Solar radiation pressure deorbiting: passive

Deploy area-increasing device to augment effect of solar radiation pressure

Phase 1: Passive eccentricity increase due to SRP from initial circular orbit (until reach critical eccentricity in drag region)

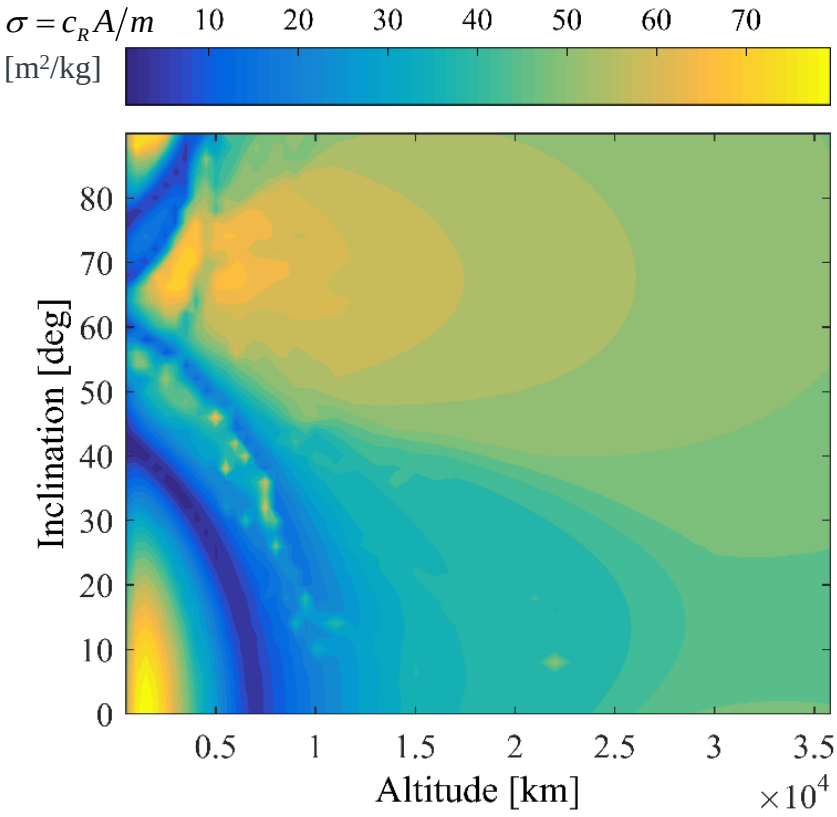


Phase 2: Deorbit augmented through drag

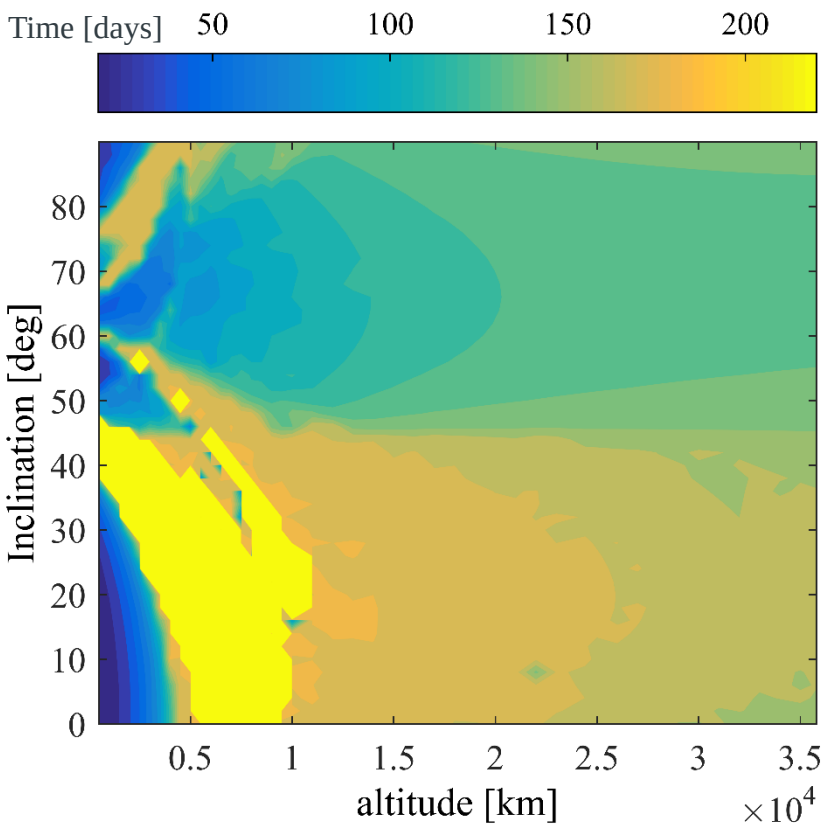
- Lücking, Colombo, McInnes, "A Passive Satellite Deorbiting Strategy for MEO using Solar Radiation Pressure and the J_2 Effect", *Acta Astronautica*, 2012.

Solar radiation pressure deorbiting

Sail requirements to de-orbit from circular orbit



Time to de-orbit from circular orbit



High sensitivity with respect to initial orientation ($\Omega_0 = 0$)

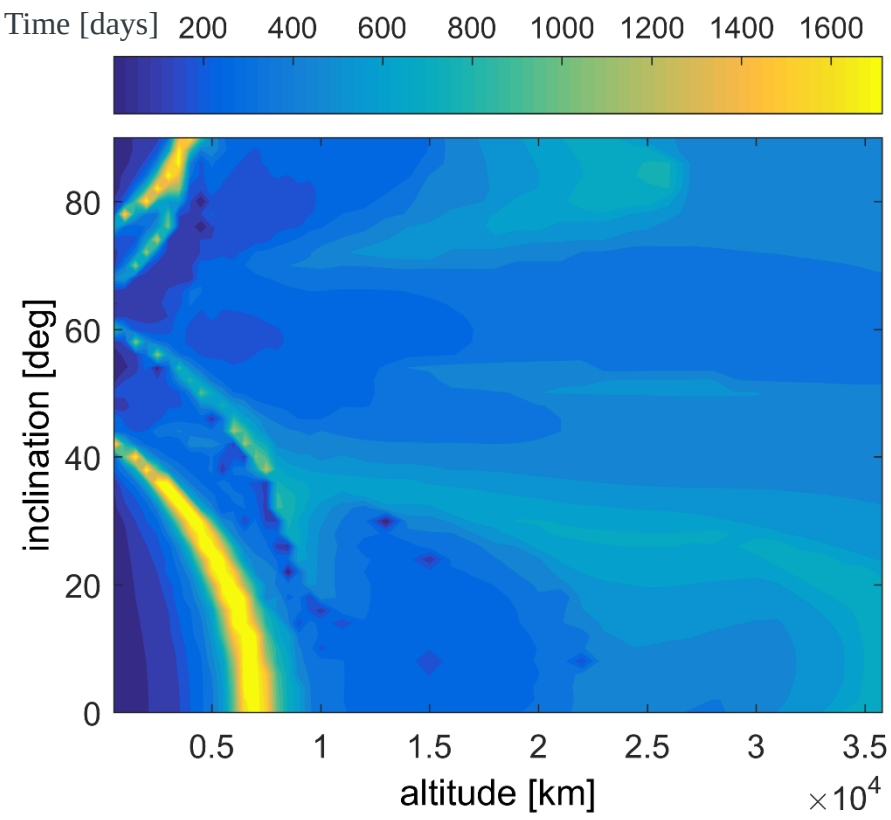
- Lücking, Colombo, McInnes, "A Passive Satellite Deorbiting Strategy for MEO using Solar Radiation Pressure and the J_2 Effect", *Acta Astronautica*, 2012.

ACTIVE SRP-AUGMENTED DEORBITING

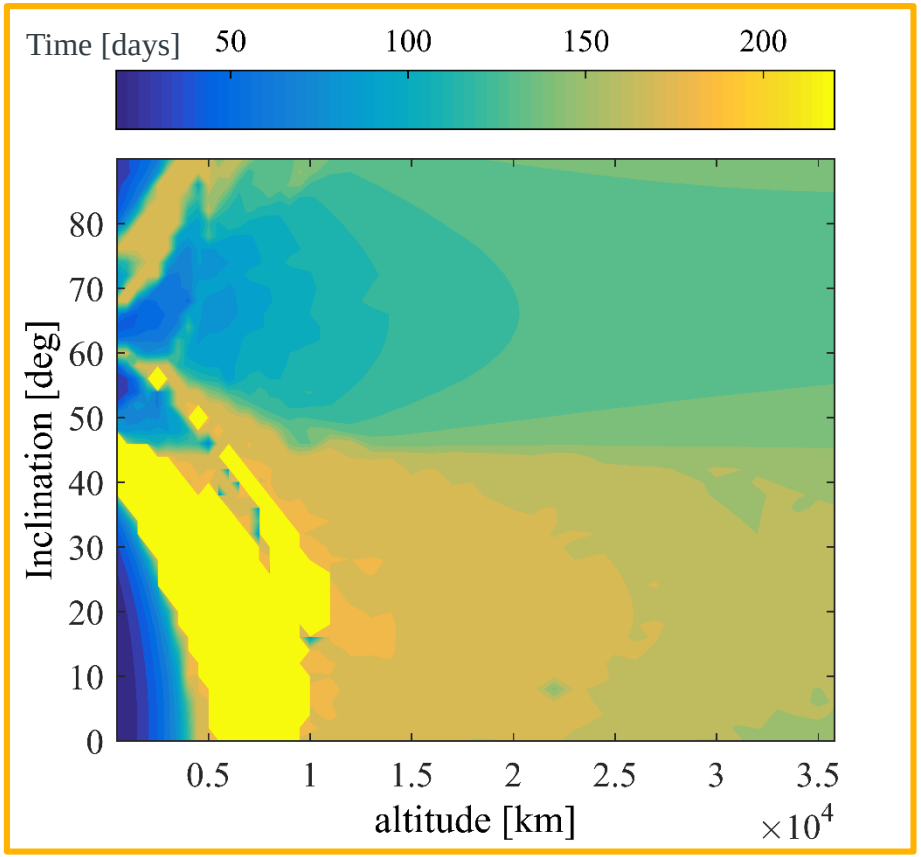
Solar radiation pressure deorbiting

Active navigation

Time to de-orbit from circular orbit



Time to de-orbit from circular orbit

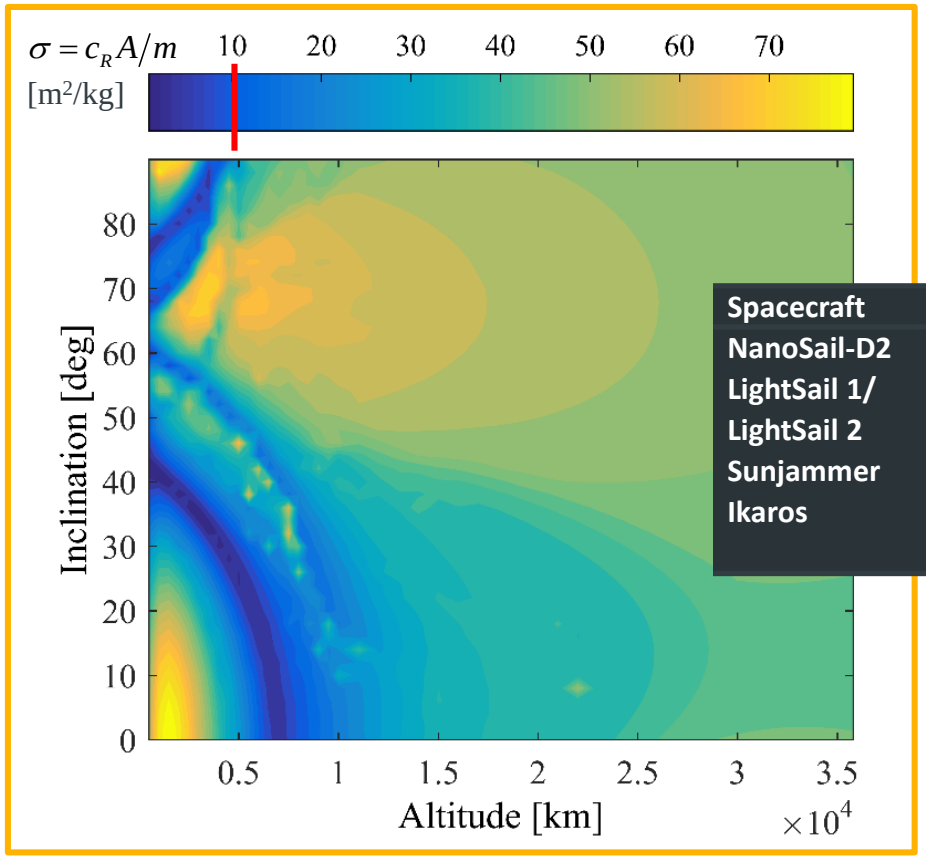


- De Bras De Fer, Colombo, “Assessment of passive and active solar sailing strategies for end of life re-entry”, University of Southampton, 2015

MODULATED SRP-AUGMENTED DEORBITING

Solar radiation pressure deorbiting

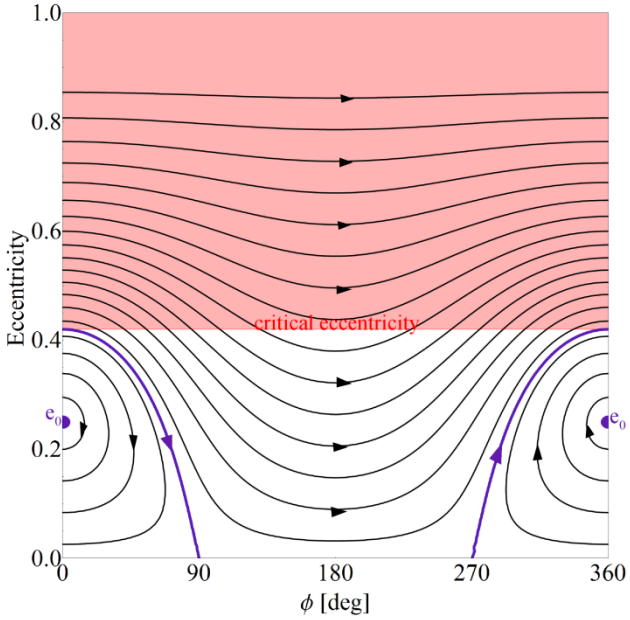
Sail requirements to de-orbit from circular orbit



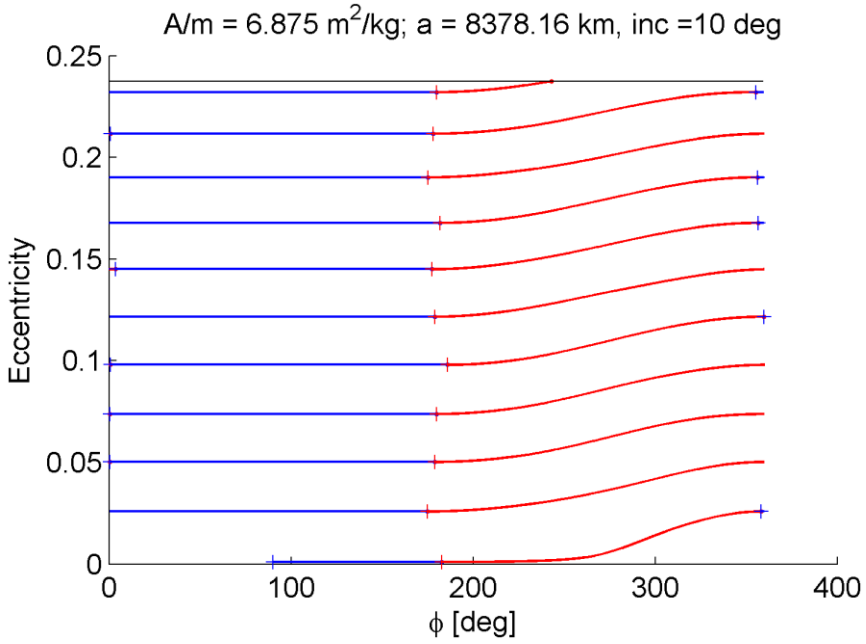
Spacecraft	Sail size [m]	Mass [kg]	TRL	Year
NanoSail-D2	3	4	9	2011
LightSail 1/ LightSail 2	5.66	4.6	9	2015/2016
Sunjammer	38		8	2013 (L_1)
Ikaros	15	310	9	2010 (interplanetary)

Solar radiation pressure deorbiting

Passive navigation
(single sail deployment)

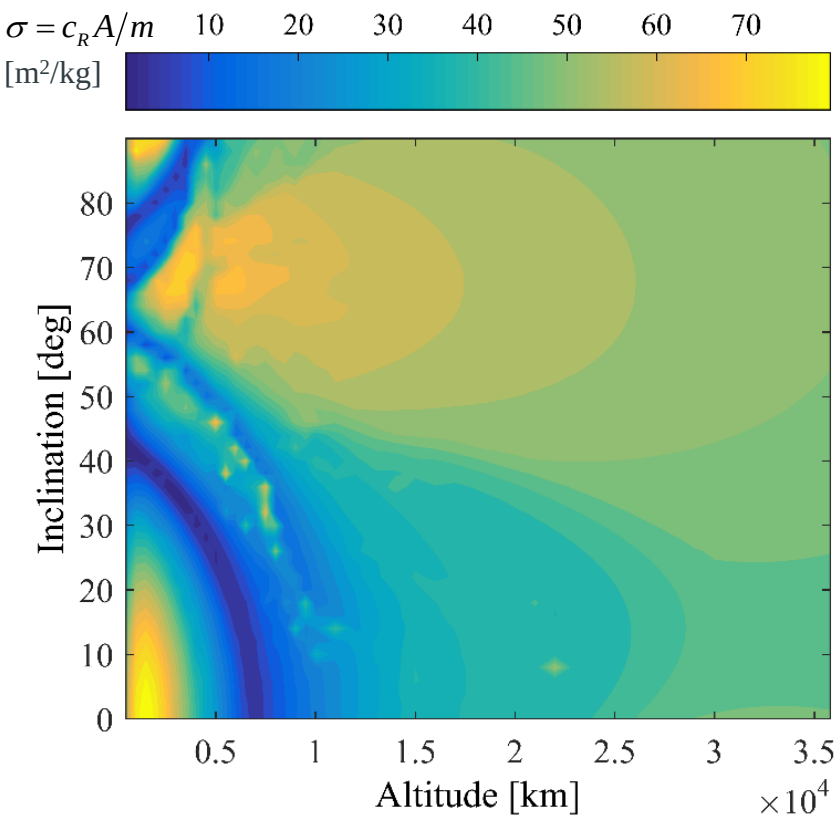


Modulating navigation
(multiple sail deployment)



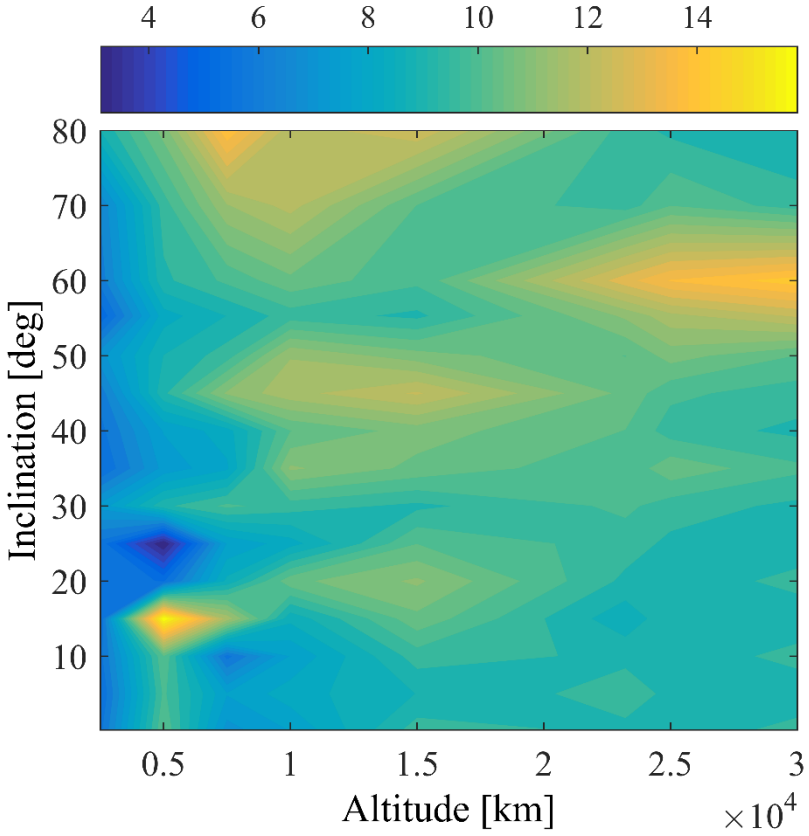
Solar radiation pressure deorbiting

Sail requirements to de-orbit from circular orbit



Passive navigation
(single sail deployment)

Sail requirements to de-orbit from circular orbit



Modulating navigation
(multiple sail deployment)

SRP-modulation strategy

On-off strategy (sail or multiple deployment)

- A lower area-to-mass is required to reach the critical eccentricity (more than one cycle in the phase space are allowed)
- The number of cycles is strictly fixed by the maximum time allowed for deorbiting
- It determines also the number of time the area-to-mass increasing device needs to be activated/deactivated
- Technological solution:
  - by changing the attitude of a solar sail with respect to the Sun on an average of 6 months (attitude Sun-pointing during the on-arcs, whereas the normal to the sail must be kept perpendicular to the Sun-spacecraft line during the off-arc).
  - by designing a reflective surface with a pyramidal shape, whose area can be controlled.

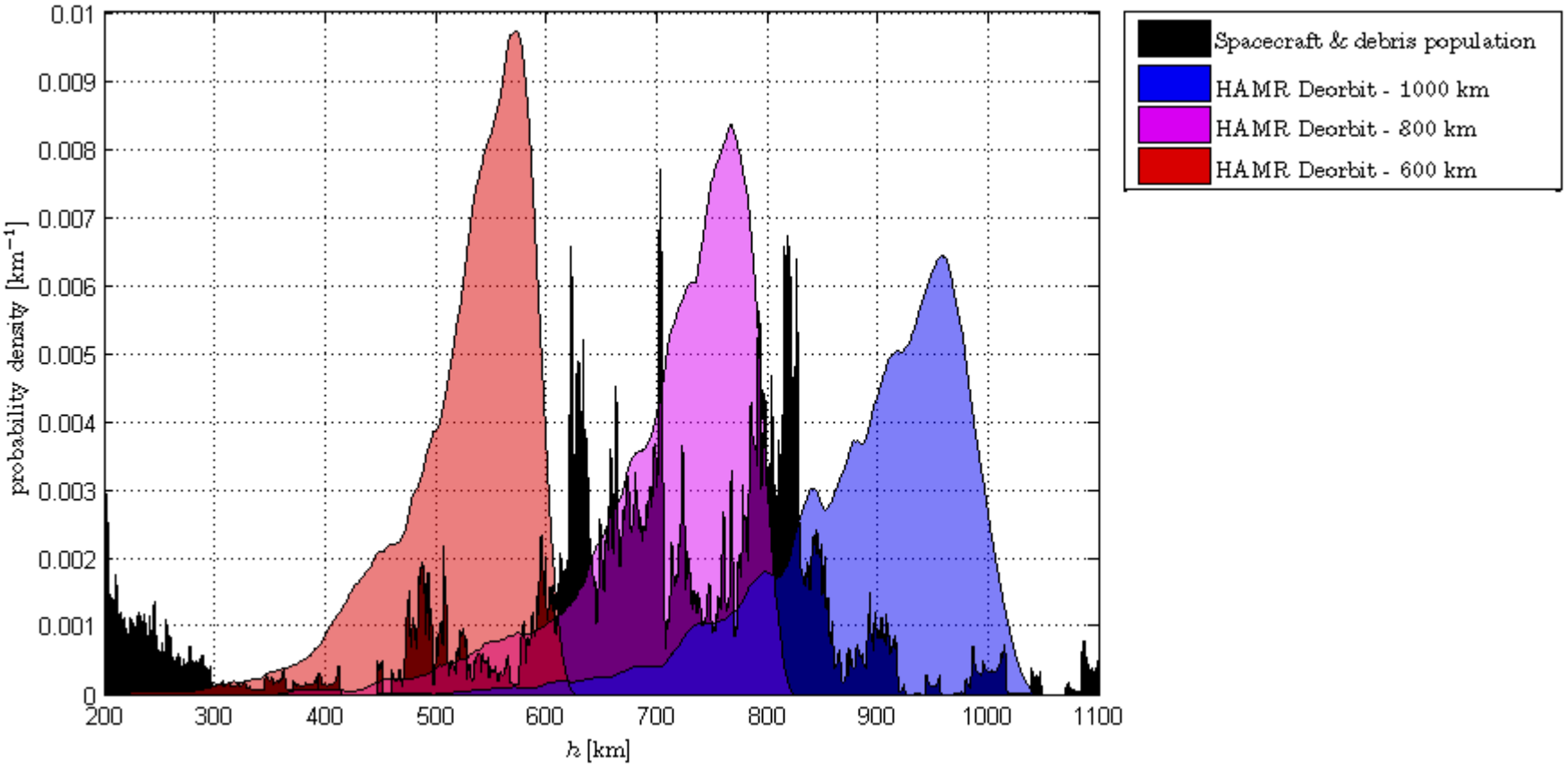
COLLISION RISK

What about the augmented collision risk?

Orbit cases				
Altitude	Inclination	LTAN	Area-to-mass-ratio [m^2/kg]	Dominating force
600 km	SSO	12:00 h	0.02	Drag
800 km	SSO	6:00 h	0.5	Drag
1000 km	SSO	0:00 h	2	Drag/SRP
2000 km	38°	N/A	2	SRP
4000 km	90°	N/A	6	SRP
7000 km	0°	N/A	5	SRP

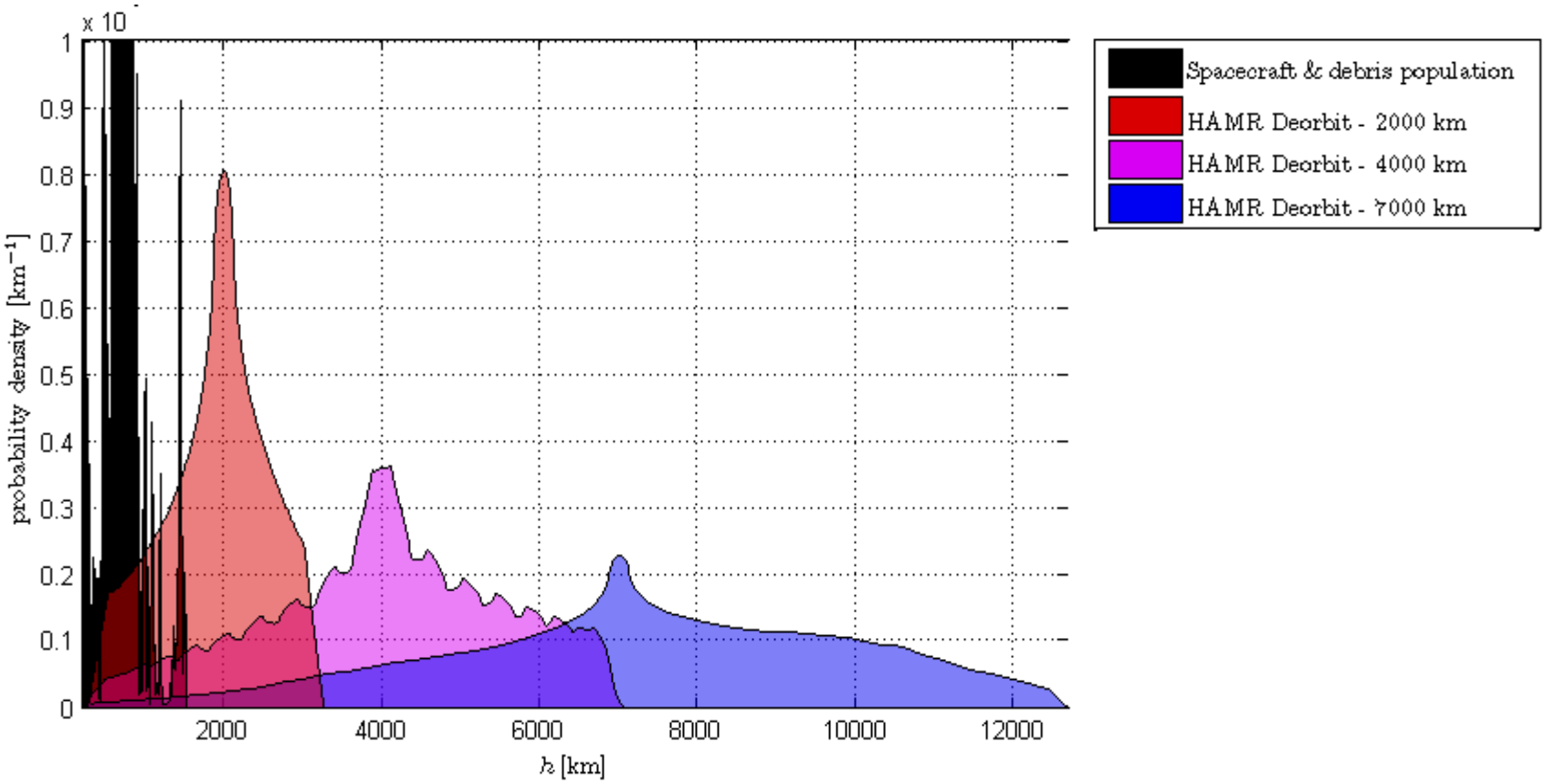
- Ref. Lücking, Colombo, McInnes, Lewis, Small Sat Conf. 2013

Drag-augmented deorbiting



- Ref. Lücking, Colombo, McInnes, Lewis, Small Sat Conf. 2013

Solar radiation pressure-augmented deorbiting



- Ref. Lücking, Colombo, McInnes, Lewis, Small Sat Conf. 2013

Conclusions

- Solar sail deorbiting is a viable option for satellite up to 100 kg
- Passive sailing requires only control to stabilise, not to manoeuvre
- Modulating sailing opens up sail deorbiting to higher orbital regions
- Deorbiting time can be designed based on collision probability max level

Future work

- Orbit attitude full simulation, verify passive stabilisation
- Trade off-augmented collision probability (on the sail and by the sail) vs decreased deorbiting time
- System design variable sail geometry

Assessment of passive and active solar sailing strategies for end-of-life re-entry

Camilla Colombo
c.colombo@soton.ac.uk

Clean Space Workshop

23-27 May ESA/ESTEC