DEPLOYABLE SURFACE-BASED DEBRIS MONITORING (DSBDM)

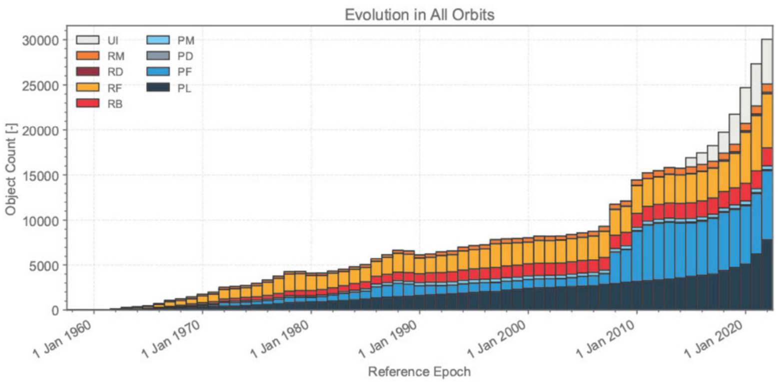
SPACE DEBRIS RISK ASSESSMENT AND MITIGATION ANALYSIS WORKSHOP

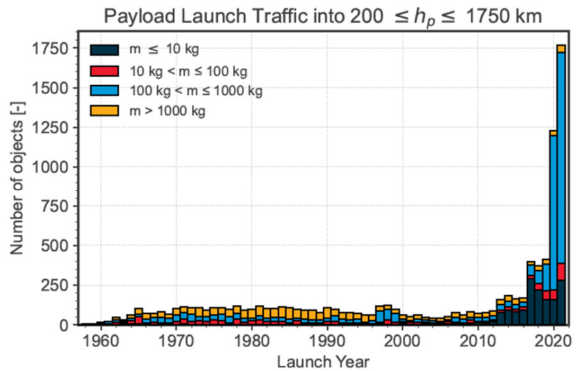
XENIA LOPEZ CORRALES, 24.06.22

AGENDA

INTRODUCTION

SPACE DEBRIS ENVIRONMENT

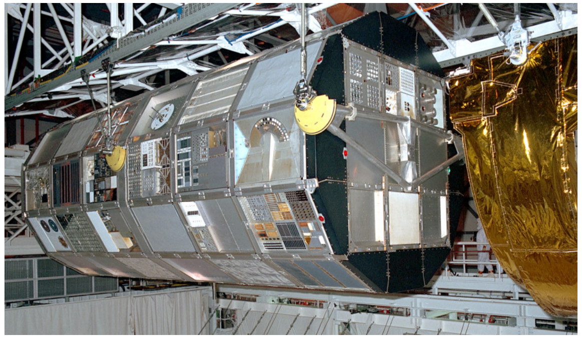




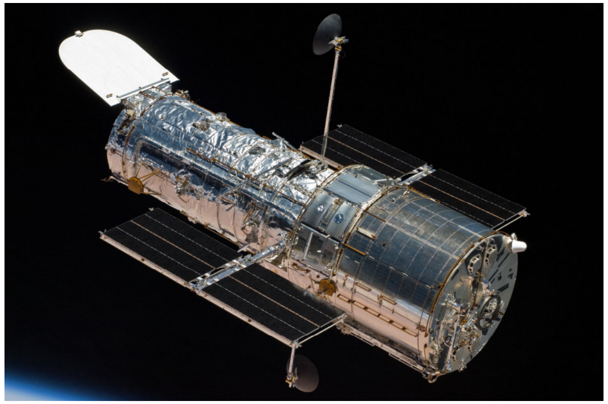
- Space Debris Models

INTRODUCTION
RETURNED SURFACES

- LDEF (Long Duration Exposure Facility)



- Hubble Space Telescope (HTC) Solar Panels



- EURECA (European Retrievable Carrier)

INTRODUCTION

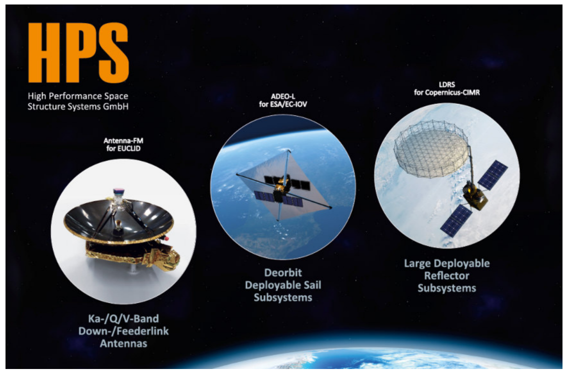
CONSORTIUM

- **OHB**
  - Marc Scheper
  - Charlotte Bewick
  - Alvaro Sanz Casado
  - Stephan Jahnke
  - Volker Scheurich

- **Politecnico di Milano**
  - Camilla Colombo
  - Andrea Muciaccia
  - Juan Luis Gonzalo
  - Mirko Trisolini
  - Martina Rusconi

- **Etamax**
  - Esfandiar Farahvashi
  - Jorge Antunes Panagopoulos
  - Kalle Bunte

- **HPS**
  - Daniel Stelzl
  - Xenia López Corrales



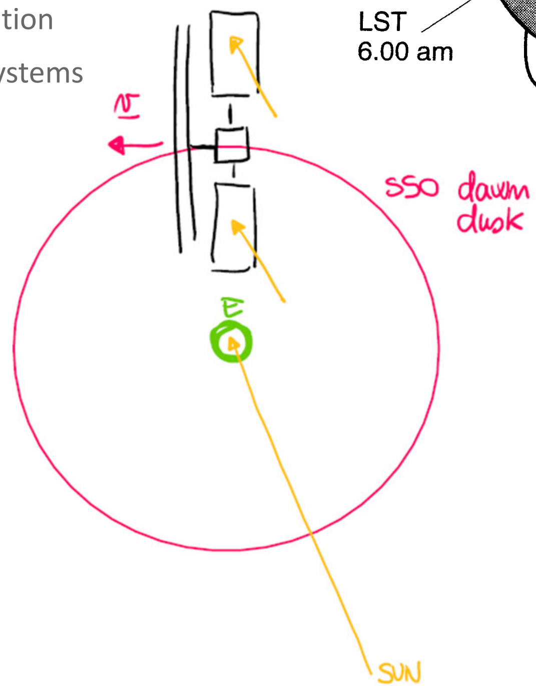
ORBIT TRADE OFF

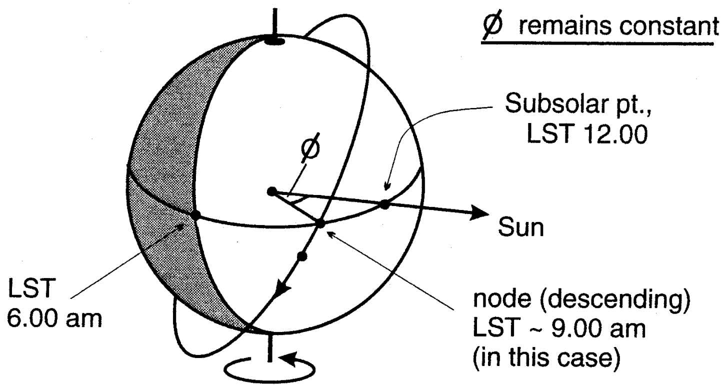
ORBIT SELECTION

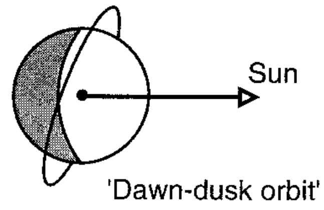
Parameter	Criterion	Selection
Semi-major axis	• Maximise debris flux • Consider drag station keeping if needed • Deorbiting with sail	[850 – 950] km
Inclination	• Sun-syncronicity for thermal, power design and stable illumination conditions	Function of *a:* [97-99] deg
Eccentricity	1. Circular: same Earth-distance range for telecom 2. Elliptical: more regions in one orbit but different orbit evolution	For now *e*=0 TBC
Right Ascension of the Ascending Node (RAAN)	• Spacecraft configuration, payload configuration and illumination conditions	LST AN: 6 am or 6 pm

ORBIT SELECTION

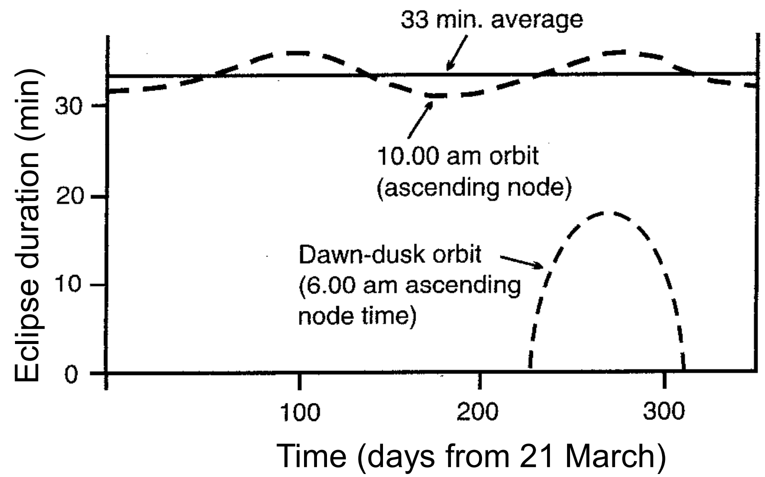
- Selected configuration and orbit: SSO dawn-dusk
- Orbit RAAN: Dawn-dusk orbit:
  - LST AN: 6 am or 6 pm
- Orbit node time influences eclipse duration
  - Impact on power and thermal subsystems







Eclipse history for 800 km altitude Sun-Synchronous Orbit



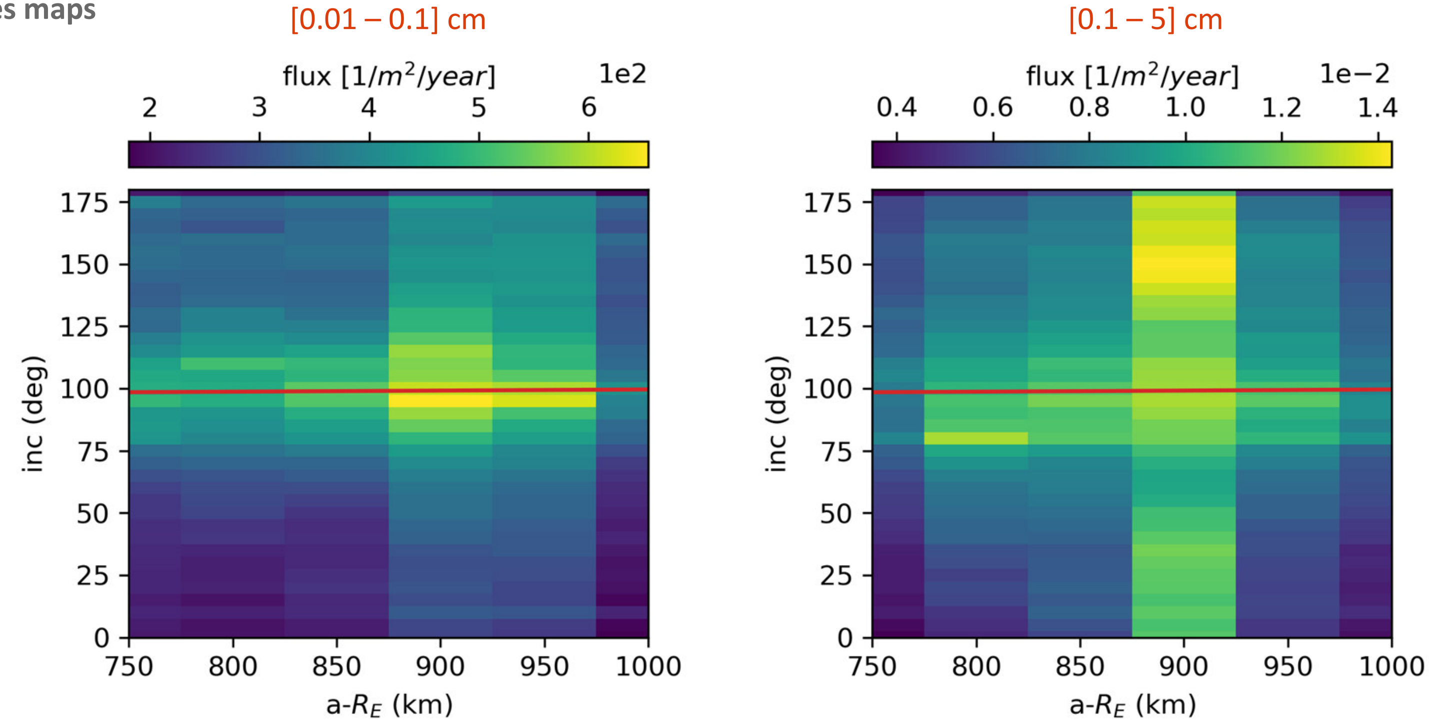
1. Camilla Colombo, «Introduzione all'Analisi di Missioni Spaziali. Mission case study of a remote sensing mission: Impact of mission analysis on spacecraft system design. Politecnico di Milano, Course slides AY 2021-2022

ORBIT AND ALTITUDE SELECTION

SPACE DEBRIS FLUX

- **Use of ESA MASTER to create debris fluxes maps**
  - Debris size: 0.01 – 5 cm
  - Grid definition:
    - Altitude range: 750 – 1000 km
    - Altitude step: 50 km
    - Inclination range: 0 – 180 deg
    - Altitude step: 5 deg
  - Year of analysis: 2026

Sun synchronous orbit



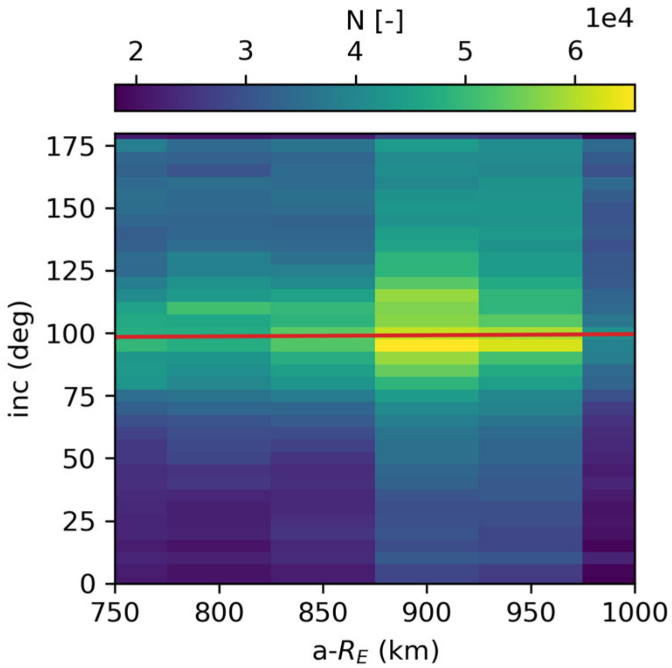
ORBIT AND ALTITUDE SELECTION

NUMBER OF IMPACTS

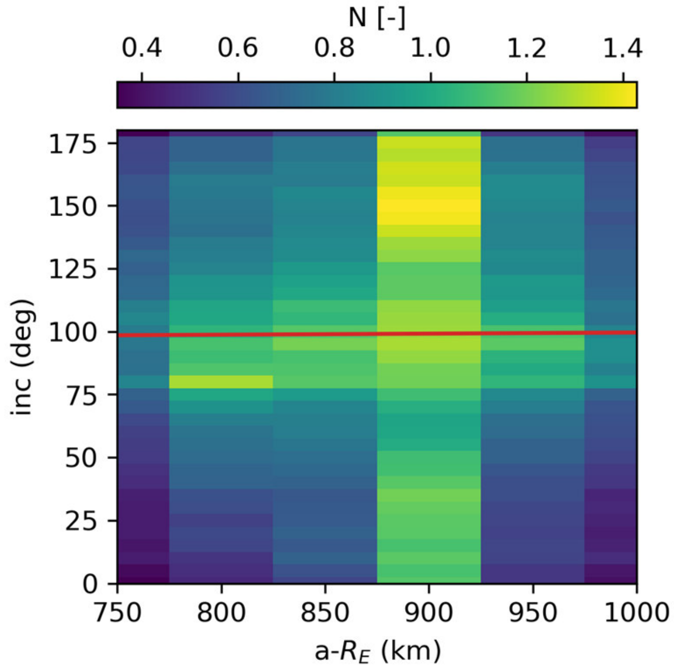
- $N = flux \cdot A_c \cdot year$
- Area: 100 m^2

Sun synchronous orbit

[0.01 – 0.1] cm



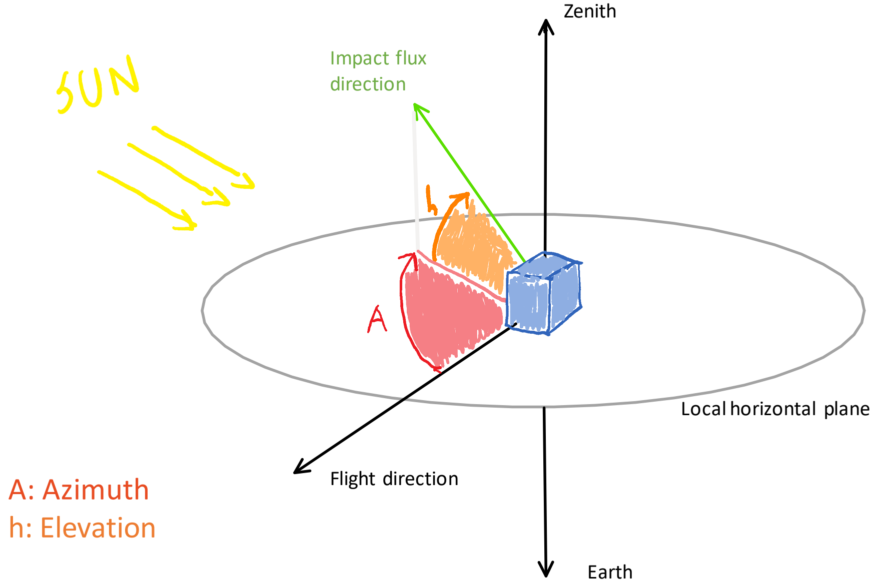
[0.1 – 5] cm



ORBIT AND ALTITUDE SELECTION

NUMBER OF IMPACTS WITH FLUX DIRECTIONALITY

- The directionality of the debris flux is directly extracted from MASTER
  - The three-dimensional distribution of **flux vs. impact azimuth vs. impact elevation** is considered
  - Impact elevation and azimuth are defined with respect to the local horizontal frame, with the impact azimuth measured clockwise from the projection of the spacecraft velocity onto the local horizontal plane
- If the impact speed is also required it can be extracted as follows:
  - Consider the MASTER distribution of **flux vs. impact speed vs. impact azimuth**
  - For each impact azimuth interval we have a distribution of impact speeds
  - Two options to extract the impact speed
    - The flux weighted average speed
    - The speed corresponding to the maximum flux
  - It is assumed that the impact speed varies mainly with the impact azimuth[4,5]
- A similar procedure can be followed if we want to associate a particle diameter

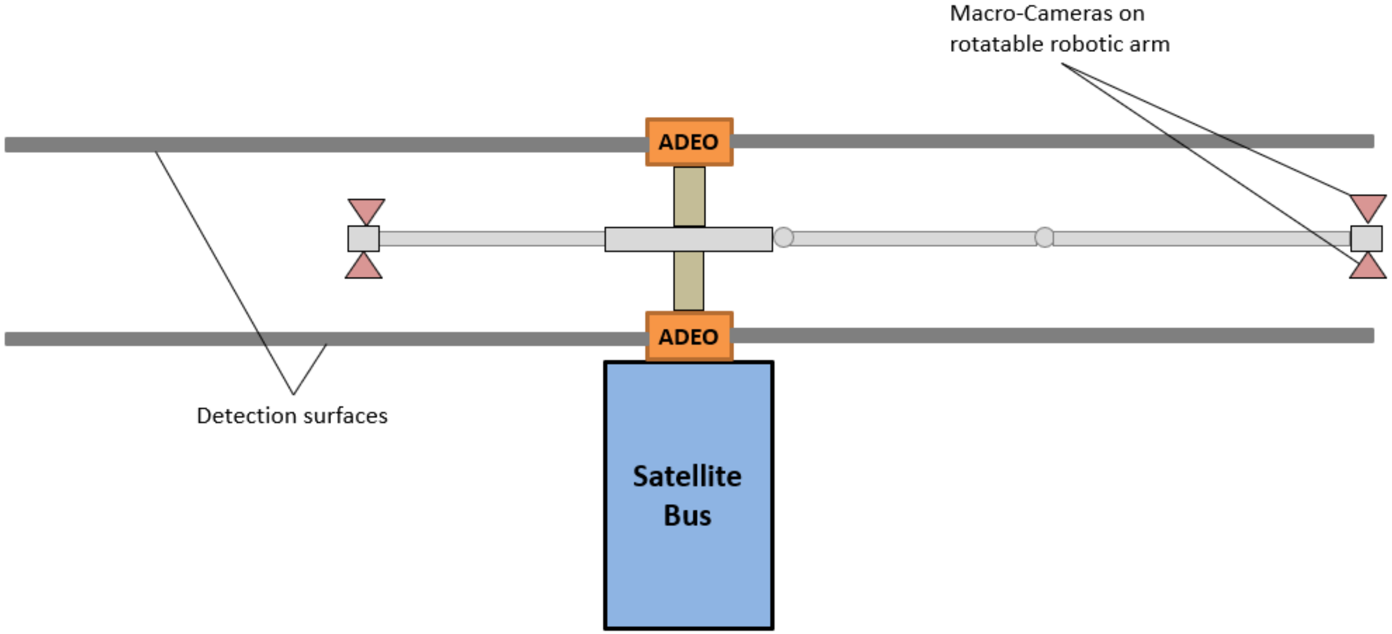


Refs:
[4] Trisolini M., Lewis H.G., Colombo C., “Predicting the vulnerability of spacecraft components: modelling debris impact effects through vulnerable-zones,” Advances in Space Research, 2020, Vol. 65, Issue 11, pp. 2692-2710
[5] 2.Welty, N., Rudolph, M., Scha¨fer, F., Apeldoorn, J., Janovsky, R., 2013. Computational methodology to predict satellite system-level effects from impacts of untrackable space debris. Acta Astronaut. 88, 35–43.

SPACECRAFT

PRELIMINARY DESIGN

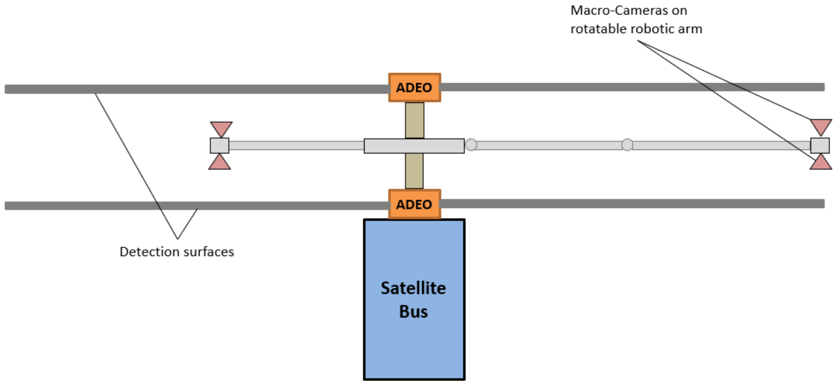
- Two layers
- Large-area membranes: 100 m2
- Detection system:
  - Optical instrument
  - Embedded Sensors

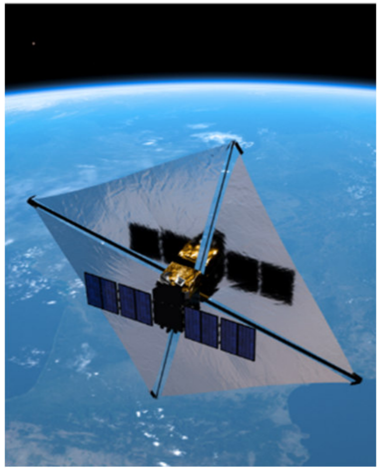


SPACECRAFT

PRELIMINARY DESIGN

- Deployment of membranes by ADEO-principle
- ADEO is a drag sail by HPS





OPTICAL IMPACT DETECTION CONCEPT

TRADE-OFF STUDY

- Usage of cameras as optical detection system for impact determination

- Observation of generated holes on the impact surface due to impact events

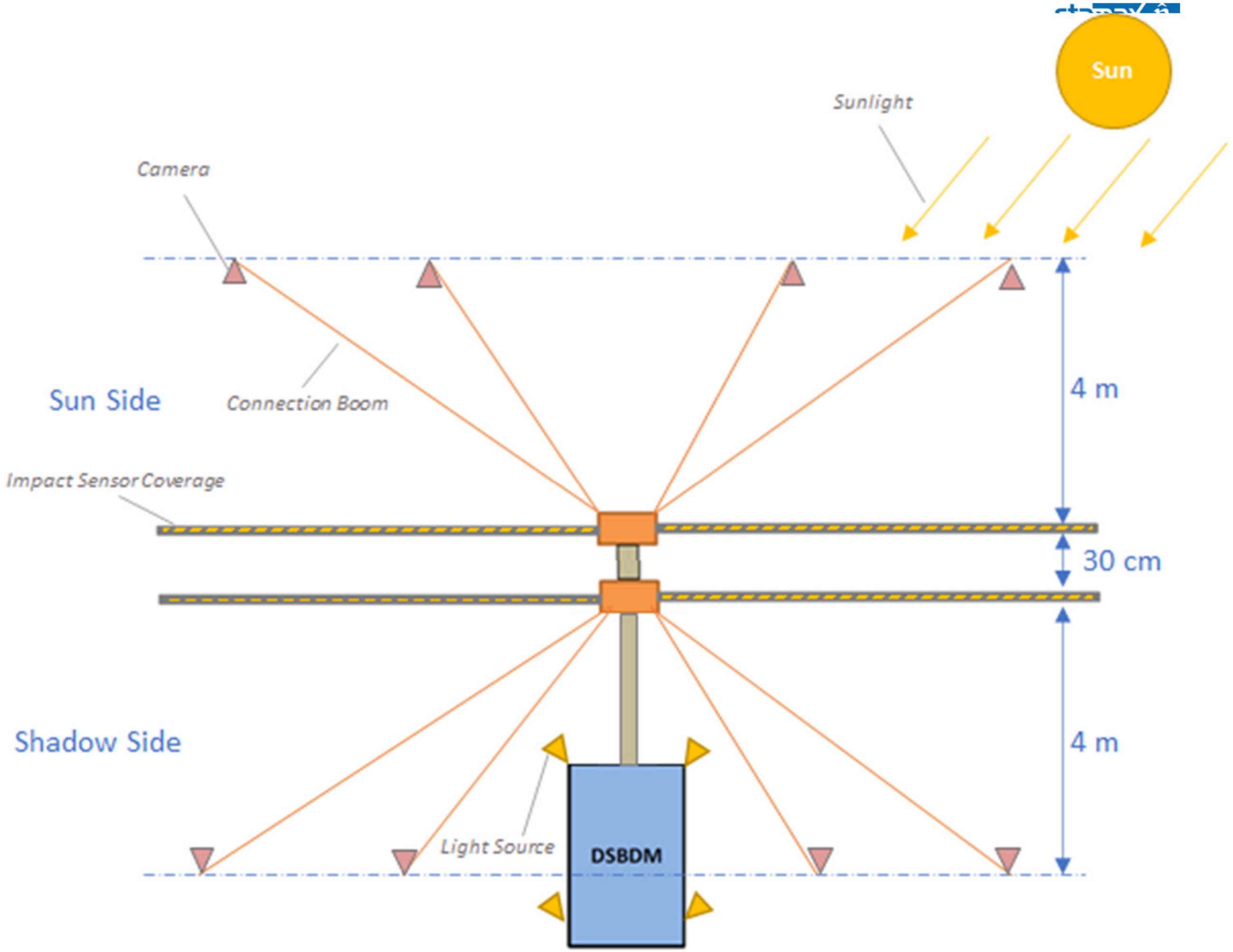
- Two trade-off studies were performed for the detection concept:
  I. Usage of static cameras
  II. Usage of moveable close-up cameras

- The illumination conditions for imaging were included in the trade-off study

OPTICAL IMPACT DETECTION CONCEPT

STATIC CAMERA CONCEPT

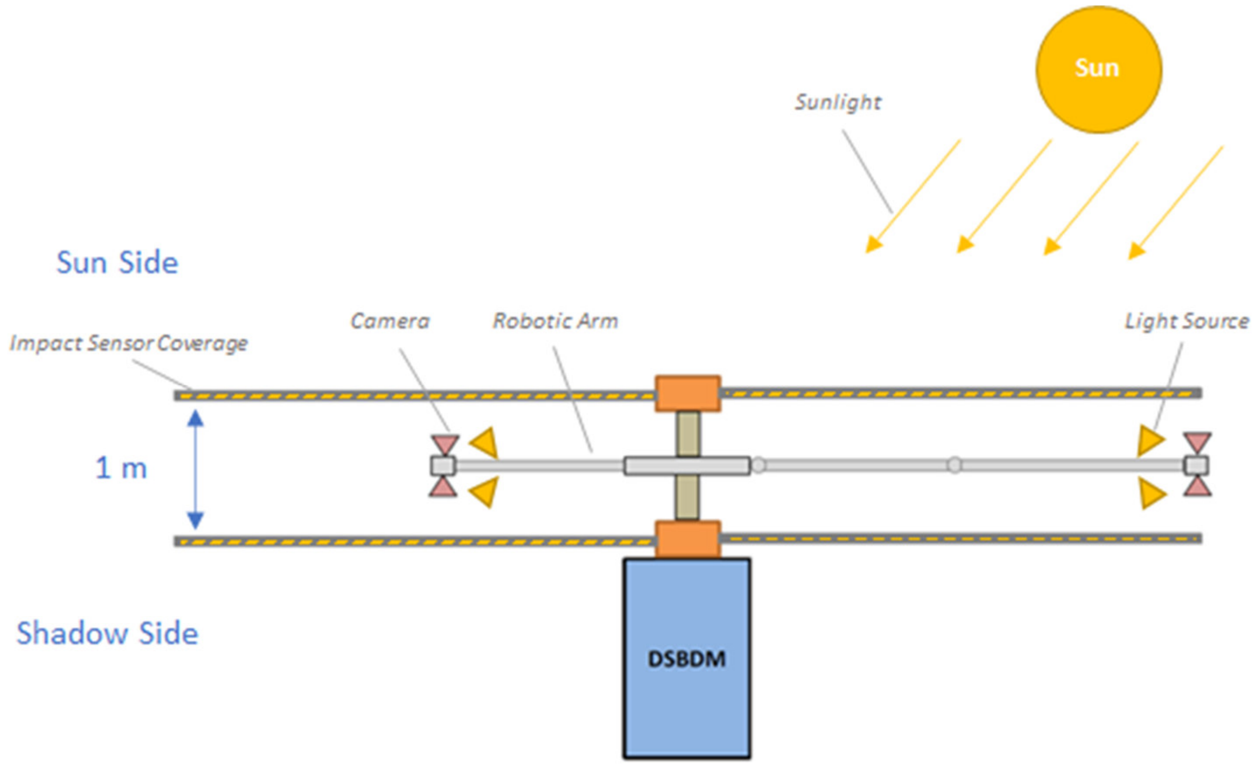
- Multiple cameras must be placed further away from the impact surface
- Has higher coverage area and can monitor the entire impact surface
- Does not need any moveable parts after deployment
- Impact surfaces are partially illuminated by sun and by artificial illumination for imaging
- Requires higher resolution per camera
- Observation of small holes (< 1 mm) potentially not feasible



OPTICAL IMPACT DETECTION CONCEPT

MOVEABLE CLOSE-UP CAMERA CONCEPT

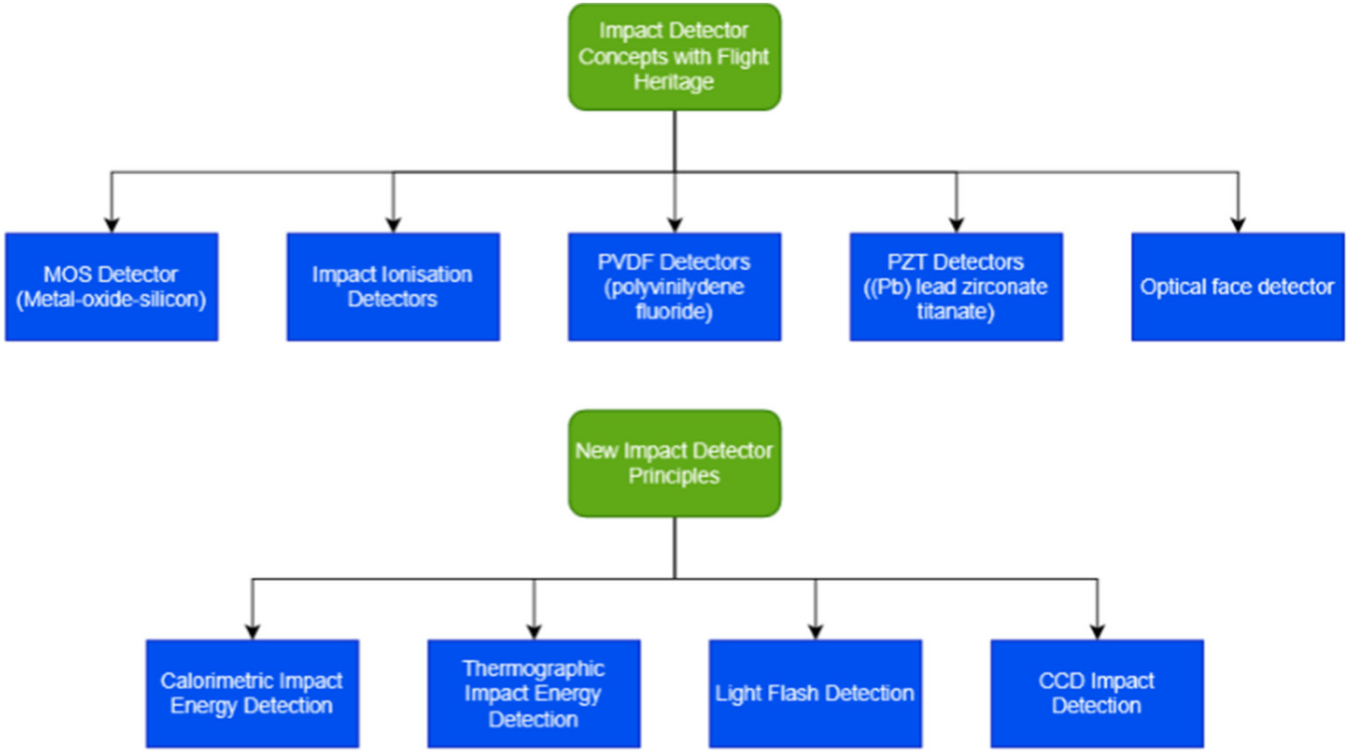
- Cameras are placed close to the surface
- Small coverage area. Moveable device required for pointing the camera
- Requires less resolution per camera
- Requires less number of cameras
- Observation of small holes down to submillimetre regime possible
- Observation of hole characteristics possible



IMPACT SENSOR CONCEPT

TRADE-OFF STUDY

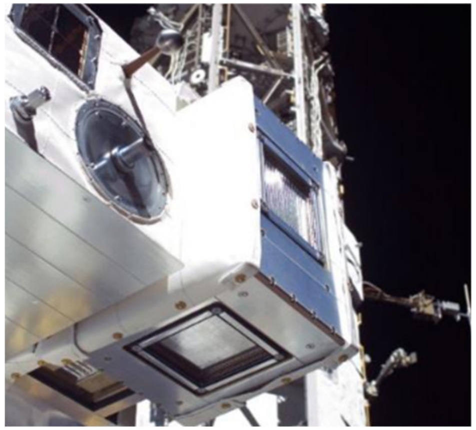
- Usage of impact sensors on the impact surface as complementary to the optical impact detection
- Review of impact sensors with flight heritage (space-proven) and new proposed concepts
- Four possible detection concepts identified based on their capabilities and applicability for the mission
- Suggested concepts comprise of a combination of complementary sensor types
- Following concepts are proposed:
    I. Impact ionization and PZT
    II. PVDF
    III. PVDF with PZT
    IV. PZT with electric grid



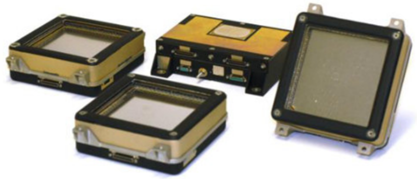
IMPACT SENSOR CONCEPT

PZT AND PVDF SENSORS

- **PZT (piezo-electric) Sensors:**
  - self-energising and provide a voltage output in proportion to the compression of a mechanical wave produced by an impact
  - 4 sensors distributed evenly on the surface leads to positioning of an impact on a surface

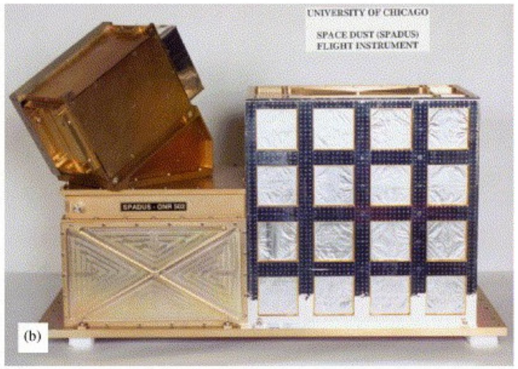


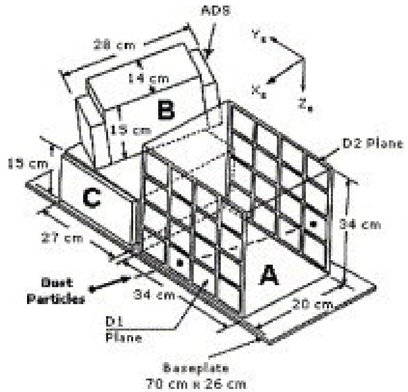
[1]



- **PVDF (polyvinilydene fluoride) Sensors:**
  - Comprises of a thin polymer film and a “frozen” electric field
  - Impact destroys the local electric field. Two electrodes detect the charge and provide as output
  - The impact characteristics can be determined from signal amplitude
  - High response rate to impacts

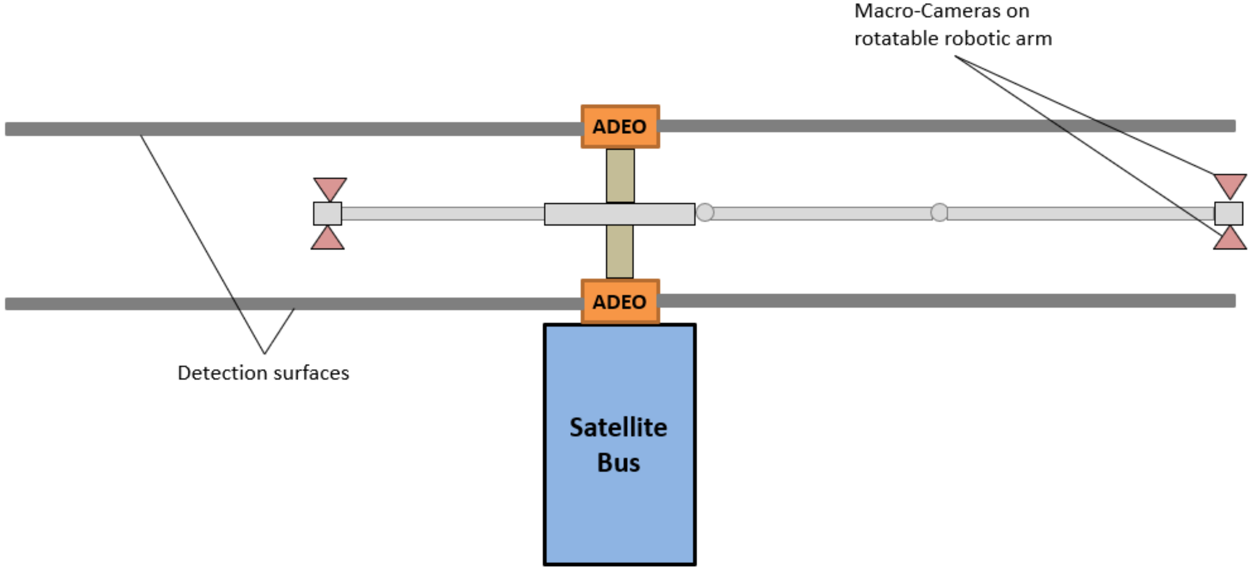
[2]





NEXT STEPS

- Selection of an altitude
- Selection of camera system
  - Static, or
  - Close-up
- Continue design activities
  - Spaceraft
  - Payload
  - Sensor architecture



THANK YOU FOR YOUR ATTENTION!

HPS GmbH
Hofmannstr. 27-29
81379 Munich
Germany

Phone: +49 89 452057647
Fax: +49 89 452057699
Contact ADEO sales: Stelzl@hps-gmbh.com
Web: www.hps-gmbh.com

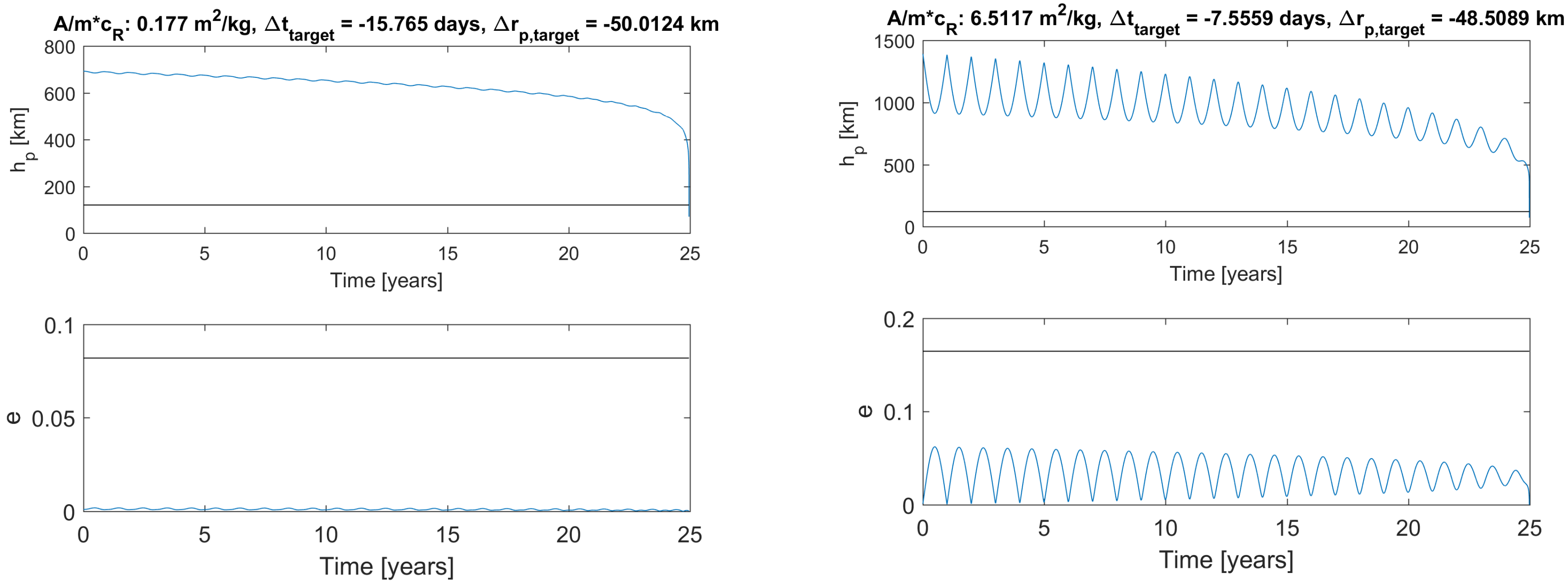
DEORBITING MAPS

SIMULATION SET-UP

- Set a desired deorbiting time $T_{\text{deorbiting}}$ for the spacecraft using a solar sail or a drag sail.
- Matrix of orbit altitudes $a - R_E$ (*a* being the orbit semi major axis and RE the radius of the Earth) and inclinations i has been defined. This is the operational orbit where the satellite deploys a sail once the deorbiting phase is initiated.
- For each initial condition and desired deorbiting time, the required drag or solar+drag sail is numerically calculated.
- Given a value of the effective area-to-mass ratio x and an initial orbit condition the orbit evolution is propagated with the semi-analytic propagator PlanODyn considering solar radiation pressure, atmospheric drag with a **Jacchia 77 exponential model** with **exospheric temperature of 750 K** and **no solar flux variation**, and the **effect of zonal harmonics up to order 6**.
- The orbit evolution is computed for a maximum time until deorbit is reached below an altitude of 70 km. The required effective area-to-mass ratio to deorbit in the desired deorbiting time is computed via a bisection method on x so that the two constrains are satisfied:
  - The minimum perigee achieved during the orbit evolution is below the critical perigee of 120 km
  - The deorbiting time is within the desired deorbiting time with a tolerance of ±20 days
- The initial right ascension of the ascending node and anomaly of the perigee for the simulation are set to 0.
- The initial orbit orientation with respect to the Sun position **makes a difference** in the requirements in terms of sail area in case only SRP and J2 are considered, but when the effect of drag is considered and deorbiting happens in more than 5 years, **the effect of drag smooths out the effect of solar radiation pressure**, therefore the initial orbit orientation is not anymore an important parameter for the simulation.

DEORBITING MAPS

Variable	Value
r_p [km]	[500:25:1000 1100:100:2500 3000:500:10000 11000:1000:15000]
e	[0.001:0.001:0.01,0.02:0.01:0.05,0.1:0.1:0.3]
i [deg]	[0.00001,2.5:2.5:130]

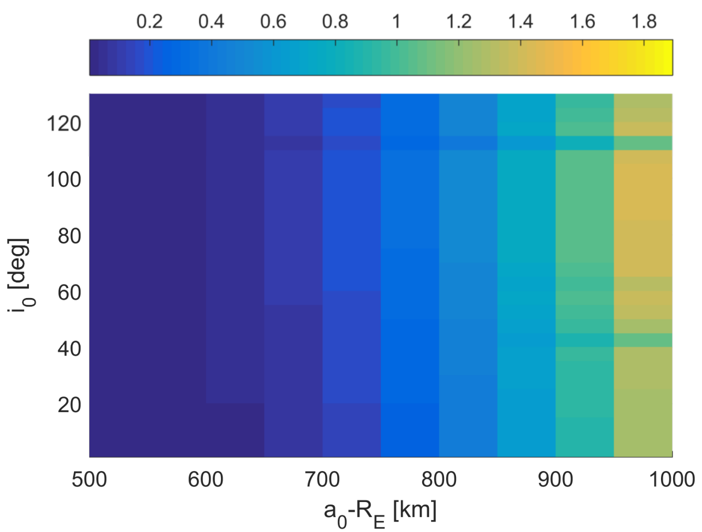


Deorbiting due to drag, solar radiation pressure and Earth's oblateness for **two initial conditions and two values of the area-to-mass**. Δttarget and Δrp,target correspond to the threshold used in the zero-finding algorithm to compute the required area to deorbit in a desired time

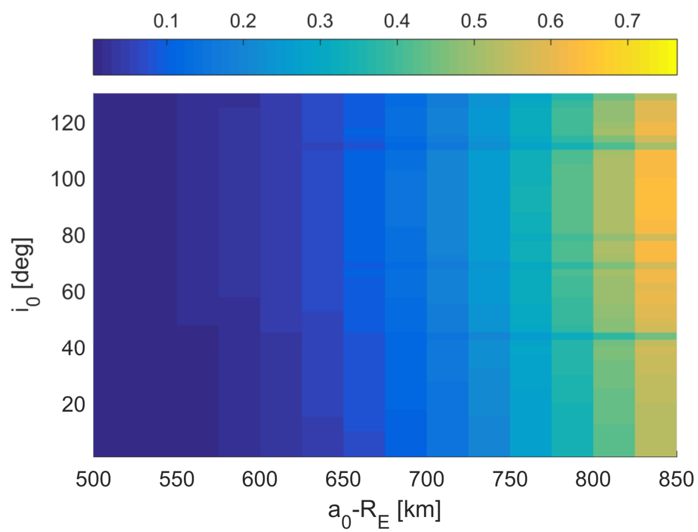
DEORBITING MAPS

REQUIRED A/M IN M2/KG

Initial eccentricity 0.001 and initial RAAN 45 deg. CR=1 and CD=2.1



Area-to-mass requirement for deorbiting in 10 years.



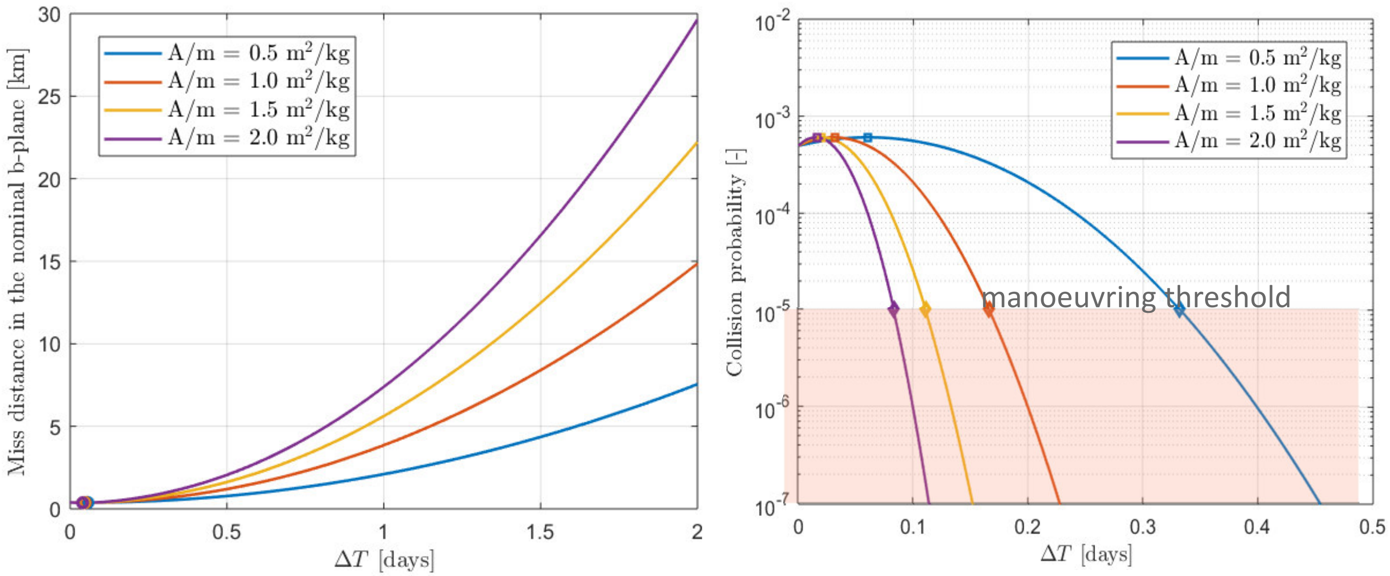
Area-to-mass requirement for deorbiting in 25 years.

- Colombo C., de Bras de Fer T., “Assessment of passive and active solar sailing strategies for end-of-life re-entry”, 67th International Astronautical Congress, Guadalajara, Mexico, IAC-16-A6.4.4.
- Dalla Vedova F., Colombo C., Gkolias I., "Preliminary End-of-Life Design Report", The Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies - ReDSHIFT, D. 4.6, European Commission H2020, Dec. 2017.

COLLISION AVOIDANCE MANOEUVRE BY SAIL

CONCEPT AND PREVIOUS STUDIES

- If the effective **area-to-mass of the sail is controllable**, a CAM can be implemented modifying it
- Equivalent to a tangential, low-thrust CAM
- Concept preliminarily studied in previous works [1,2]
- Main challenges:
  - Limited control authority
  - Longer lead times compared to propulsive CAMs
  - No control on CAM directionality



Sample test case for an on/off control law (i.e., A/m equal to nominal or 0), from [1]

Refs:

[1] J.L. Gonzalo, C. Colombo, P. Di Lizia, “Analysis And Design Of Collision Avoidance Maneuvers For Passive De-orbiting Missions,” AAS/AIAA Astrodynamics Specialist Conference, Snowbird (UT), USA, 19-23 August 2018

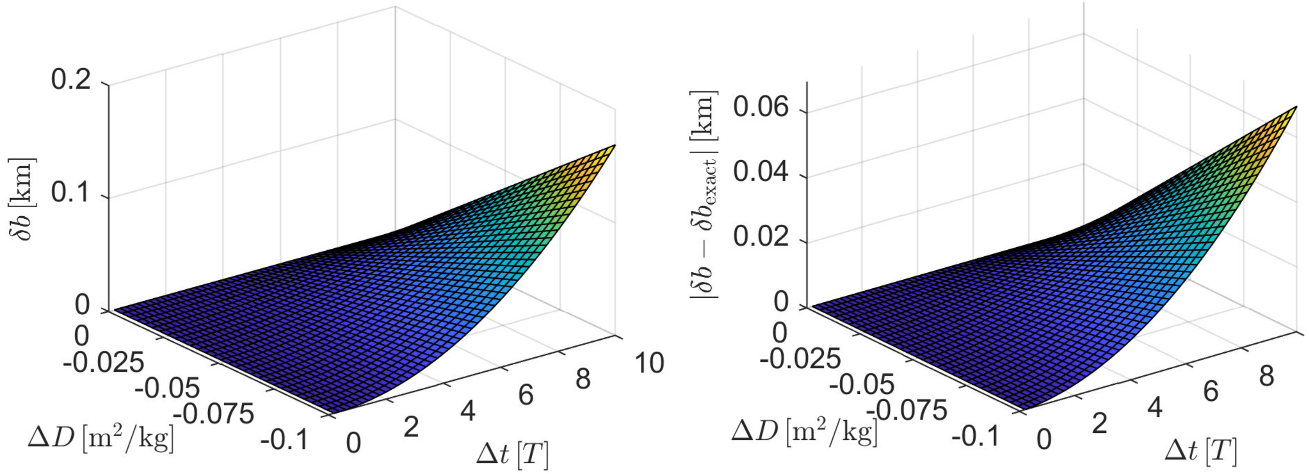
[2] C. Colombo, A. Rossi, F. Dalla Vedova, A. Francesconi, C. Bombardelli, M. Trisolini, J. L. Gonzalo, P. Di Lizia, C. Giacomuzzo, S. BayajidKhan, R. Garcia-Pelayo, V. Braun, B. BastidaVirgili, H. Krag, “Effects of passive deorbiting on the space debris environment”, *69th International Astronautical Congress 2018*, Bremen, Germany, 1-5 October 2018

COLLISION AVOIDANCE MANOEUVRE BY SAIL

ANALYSIS AND DESIGN THROUGH EXTENDED STATE TRANSITION MATRIX

- CAM design for sails can be costly, due to the high number of propagations involved.
- A first solution is proposed using an extended State Transition Matrix [3]:
  - Extended state includes sail parameters: $\boldsymbol{\beta} = [\ c_D,\ (A/m)_D,\ c_R,\ (A/m)_R\ ]$
  - A linear relation is reached between displacement at close approach and change in sail parameters $\delta\boldsymbol{b}(t_{CA}) = \boldsymbol{M}(\alpha_0, \beta_0; t_f, t_0)\ \delta\boldsymbol{\beta_0}$
  - STM only depends on initial state and lead time, not $\delta\boldsymbol{\beta_0}$
  - STM computed using the semi-analytical propagator PlanODyn (numerical integration of the single-averaged variational equations)
  - The model is linear, so valid only for small displacements

Nominal CA	a [km]	e [−]	i [deg]	Ω [deg]	ω [deg]	f_0 [deg]	c_D [−]	$\left(\frac{A}{m}\right)_D \left[\frac{\text{m}^2}{\text{kg}}\right]$	c_R [−]	$\left(\frac{A}{m}\right)_R \left[\frac{\text{m}^2}{\text{kg}}\right]$
Spacecraft	7200.00	0.000252	1.003	0	0	28.648	2.1	0.5	1.0	0.5
Debris	7444.28	0.313246	137.379	29.181	258.300	102.410	—	—	—	—



Displacement at close approach (left) and error of the linearized approximation (right) for a sample test case from [3]. Δt is the CAM anticipation, and ΔD the change in drag A/m

Refs:
[3] J.L. Gonzalo, C. Colombo, "Lightweight algorithms for collision avoidance applications," *11th ESA Conference on GNC Systems*, 22-25 June 2021