# Sustainability of Drag-Augmentation Devices

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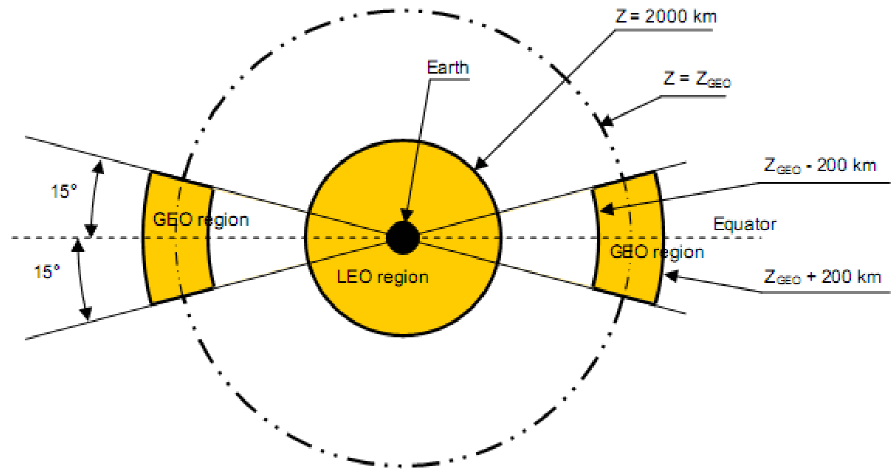
# Overview

- Introduction
- Orbital Lifetime
- Collision Risk
- Aspects to be Considered
  - Impact flux
  - Impact Effects
- Summary and Conclusions

# Introduction

- ESA's space debris mitigation requirements
  - ESA/ADMIN/IPOL(2014)2
  - ECSS-U-AS-10C, 2012
  - ISO 24113:2011
- LEO protected region
- 25 year rule
- Various possibilities to ensure compliance
  - electrical propulsion system
  - chemical propulsion systems
  - solar sails
  - tethers
  - drag-augmentation devices




Source: DLR

# Introduction

- Question:

**What is the impact of drag augmentation devices on the space debris environment?**

- 25 years rule shall reveal minimisation of the collision risk after the end of mission
- Collision risk: determined by the number of impact during the disposal phase
- 25 years with large area vs. longer decay with small area

# Orbital Lifetime

- Simple equation (King-Hele)

$$T_L = \frac{H_P}{\sqrt{\mu \cdot a} \cdot \rho_P \cdot F \cdot B} \qquad F = \left(1 - \frac{r_p \cdot w}{v_p} \cos i\right)^2 \qquad B = c_D \cdot \frac{A}{m}$$

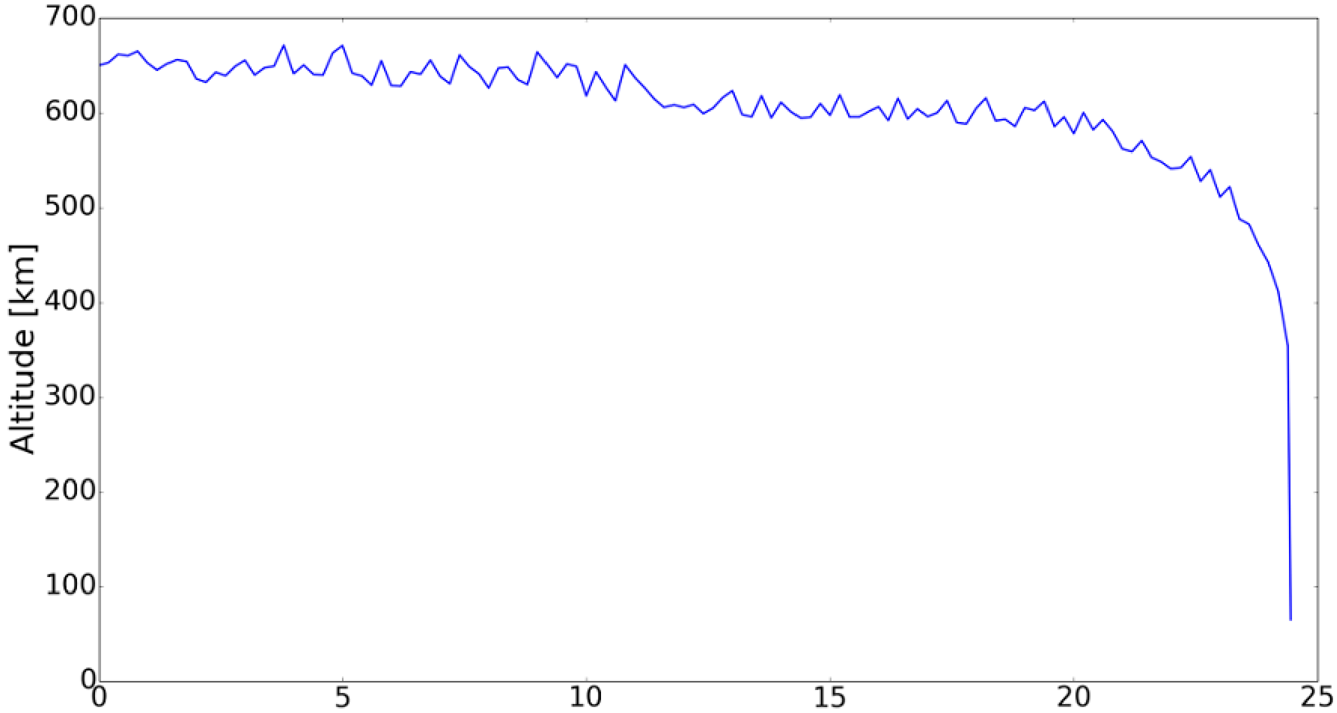
| | | | | | |
|---|---|---|---|---|---|
| $T_L$ | orbital lifetime | $F$ | wind factor | $B$ | ballistic parameter |
| $H_p$ | scale height | $r_P$ | perigee radius | $c_D$ | drag coefficient |
| $\mu$ | gravitational constant of the Earth | $w$ | angular velocity | $A$ | cross-section |
| $a$ | semi-major axis | $v_P$ | perigee velocity | $m$ | mass |
| $\rho_P$ | atmospheric density (perigee) | $i$ | inclination | | |

  - valid for near-circular orbits ($e < 0.01$)
  - atmospheric drag is the main perturbing force
- Main dependencies
  - initial orbital altitude -> atmospheric density
  - ballistic parameter: cross-section and mass

Reference: King-Hele, D. G., Satellite Orbits in an Atmosphere: Theory and Applications, ISBN 0-216-92252-6, 1987

# Orbital Lifetime (Altitude vs. Time)

- ADEO case (25 m² membrane); analysis with STK




Source: HPS

- Spacecraft remains in regions of high space debris flux for most of the orbital lifetime

# Number of Collisions

- Equation $N_C = F_{M/OD} \cdot A \cdot T_L$

  $F_{M/OD}$ impact flux, $A$ exposed area, $T_L$ orbital lifetime/exposure duration

- Combination of both equations (orbital lifetime in collision risk equation)

$$N_C = F_{M/OD} \cdot \cancel{A} \cdot \frac{H_P \cdot m}{\sqrt{\mu \cdot a} \cdot \rho_P \cdot F \cdot c_D \cdot \cancel{A}}$$

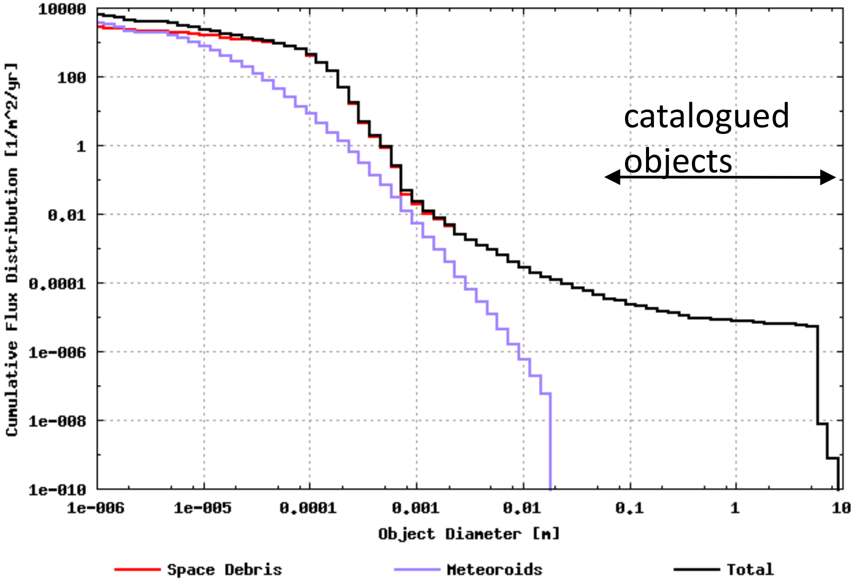
- Result: collision risk is independent from the area
  - nor positive neither negative effect
  - valid for drag area = exposed area

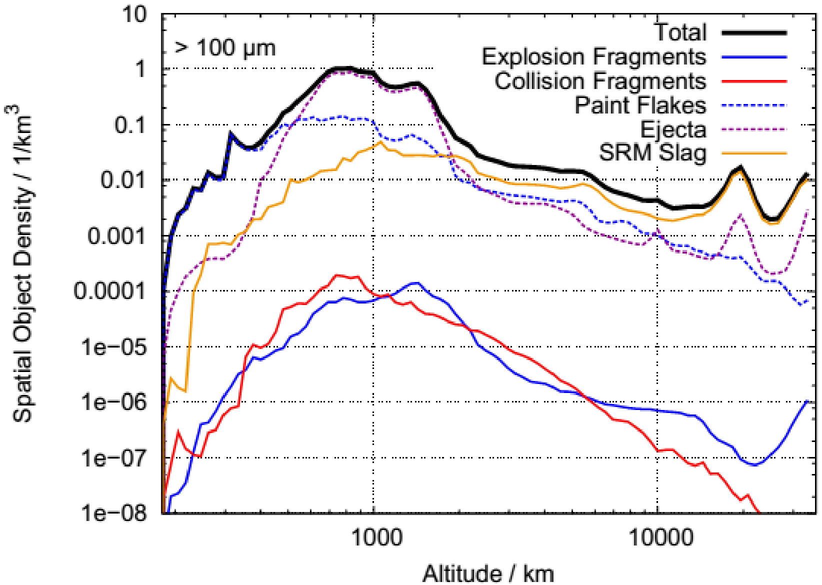
# Aspects to be Considered/Analysed

- Effective drag-area (cross-section)
  - attitude stabilisation, deviations from the nominal attitude
  - loss of drag area, e.g. as a consequence of impacts
- Collision area (exposed area)
  - impact flux accumulated over the mission duration (with/without drag augmentation)
  - flux signatures on the different parts of the exposed area
  - impact angle, impact velocity
- Cross-section vs. exposed area
  - example: plate, perpendicular to the velocity vector:
  - exposed area = 2 x cross-section (but small number of impacts on the rear side)
- Effects of impacting particles
  - suitable damage equations
  - effects of grazing impacts
  - identification of the critical particle diameter
  - impacts of large objects/catastrophic impacts
    - on the membrane and booms
    - on the spacecraft
  - debris cloud generated by an impact -> environmental effect
- Effects on the number of required collision avoidance manoeuvres

# Impact Flux (1)

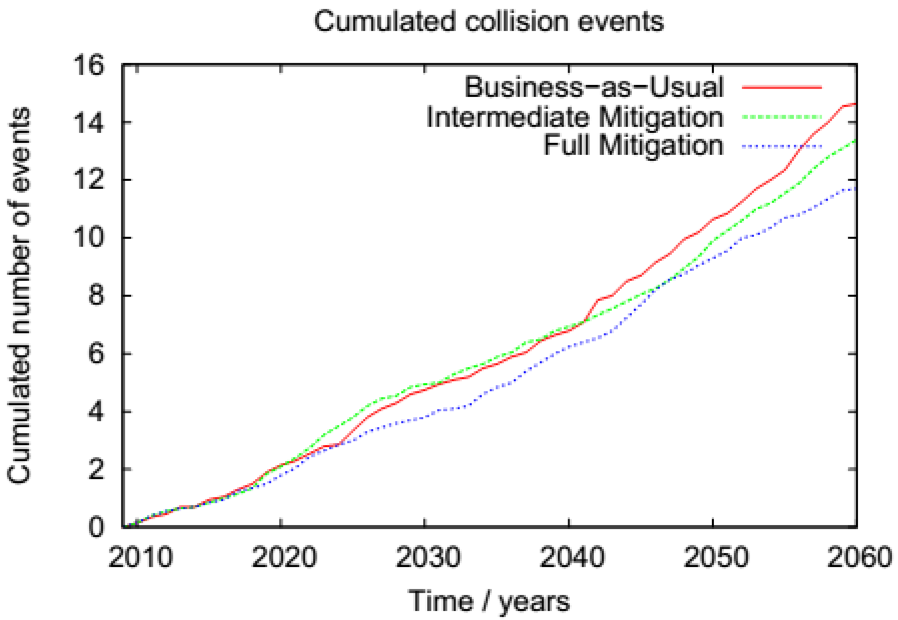
- Flux vs. particle diameter
  - MASTER-2009
  - 800 km SSO
  - large number of impacts of small particles to be expected
- Flux vs. altitude
  - highest spatial density in the 600 km to 1000 km altitude band



# Impact Flux (2)

- Flux vs. time
  - will increase, mainly due to further collisions
  - mainly in LEO




Source: MASTER-2009 Final Report

- Simplified flux and "cratered" area estimation for ADEO
  - affected area is small: < 0.1% of the membrane area
  - but: crack propagation needs to be considered (detailed assessment ongoing)

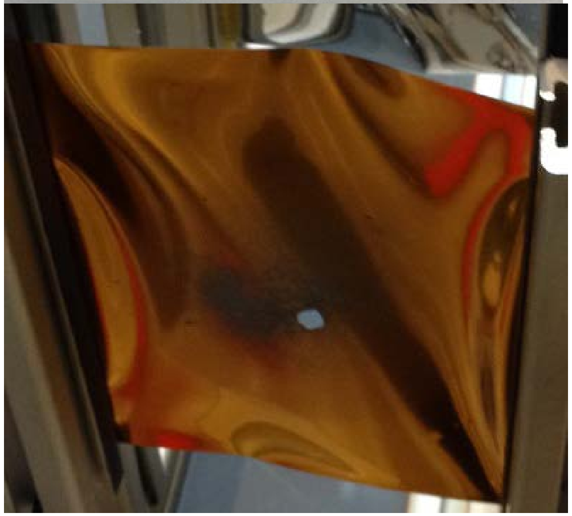
# Impact Effects (1)

- Membrane damage assessment
  - HVI tests
    - performed as part of the “Deployable Membrane” study at TU Munich
    - ca. 4 mm, 3.7 km/s, impact angle 0°
  - Damage equation (hole size equation)

$$D = \left\{ K_0 \cdot \left( \frac{t_s}{d_p} \right)^{\lambda} \cdot \rho_p^{\beta} \cdot v^{\gamma} \cdot (\cos\alpha)^{\xi} \cdot \rho_s^{\nu} + A \right\} \cdot d_p$$

| | | | |
|---|---|---|---|
| $t_s$ | foil thickness | $v$ | impact velocity |
| $d_p$ | particle diameter | $\alpha$ | impact angle |
| $\rho_p$ | particle density | $\rho_s$ | foil density |

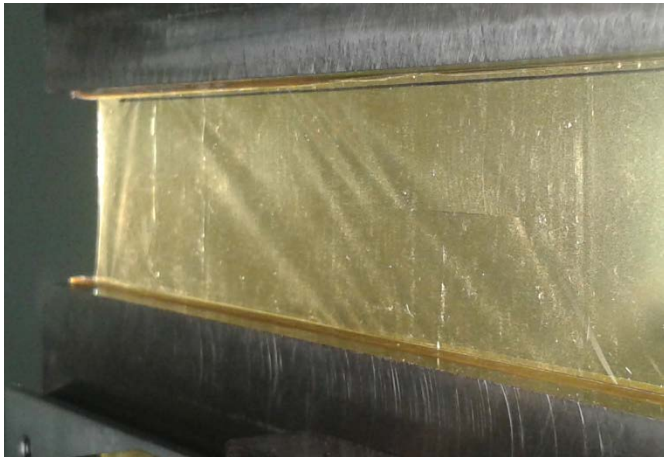
constants $K_0$, $A$ and exponents are used to adapt the equation to specific materials

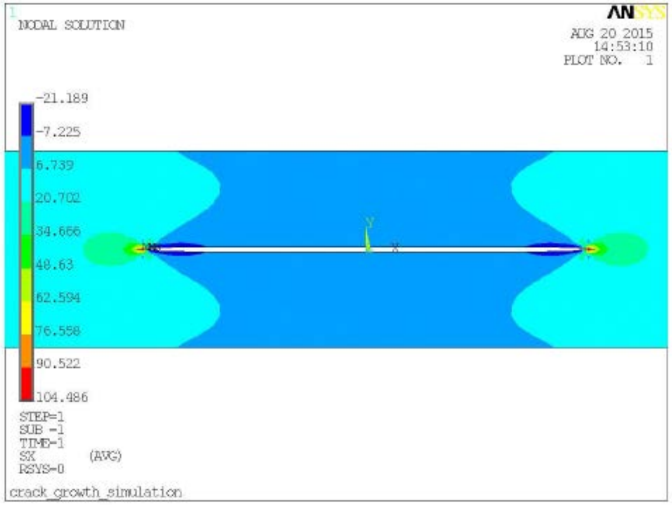


Source: HTS, HPS

# Impact Effects (2)

- Membrane damage assessment
  - Grazing impacts cause slit shaped damage
  - Crack propagation
    - tensile test of pre-damaged membrane material
    - derivation of material related parameters
    - correlation with FEM analyses
  - Objective
    - assessment of the membrane stability based on the damage estimation

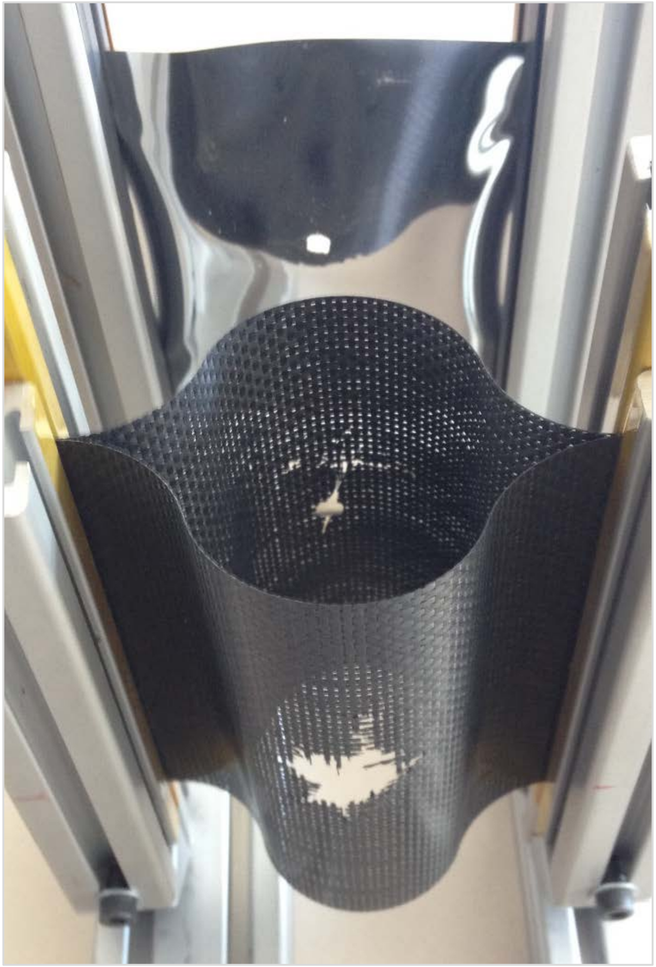





Source: HTS

# Impact Effects (3)

- Boom damage assessment
  - HVI tests
    - at TU Munich
    - ca. 4 mm, 4.1 km/s, impact angle 0°
  - Failure and damage equations
    - adaptation of the parameters of existing double wall CFRP equations required
    - alternative: derivation of new equations
    - probably further testing necessary
  - Objectives
    - estimation of the damage
    - assessment of the boom stability



Source: HPS

# Summary and Conclusions

- Further detailed investigation required to answer the question raised

- Also required for other active or passive de-orbiting methods and for ADR methods

➢ Comparison of the sustainability of all proposed technologies to comply with the standards

➢ Comparison of the sustainability of all ADR technologies
  - Application of methods such as FTA, FMEA, etc.
  - Consideration of technical and environmental aspects

- The application of methods which are counterproductive from the environmental point of view cannot be justified!

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