Deorbiting / Reorbiting of Space Debris with an Ion Beam Shepherd Satellite

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Outline

- **Active Debris Removal (ADR)**
  - LEO large debris taxonomy
  - Priority targets
  - ADR Performance metrics

- **The IBS Concept**
  - Basic principle
  - technological aspects

- **Deorbiting Performance**

- **Beam Modelling**

- **Proximity Formation Flying**
  - Generalized C-W equations
  - Stability issues
  - Control strategies
  - Numerical simulations

Big-Size Debris in LEO

Debris removal selection criterion based on <u>cross section</u>, <u>mass</u> and <u>orbit crowding</u> prioritizes active removal of **big-size debris from crowded orbits in LEO:**

- Higher collision probability
- Higher post-collision debris mass yield

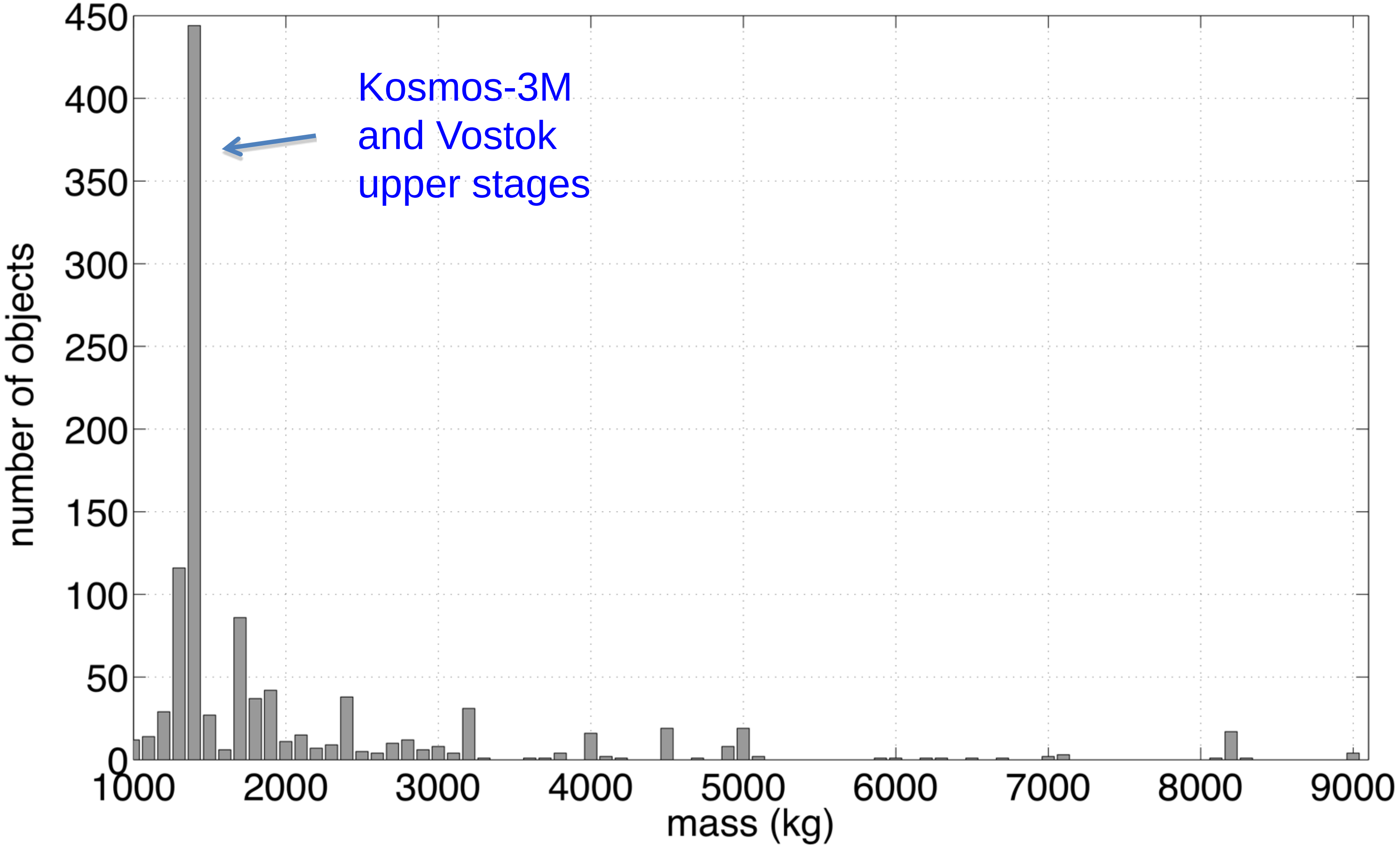
Liou , J. C., Adv. Space Res, Vol 47, No 11, June 2011, pp 1865-1876.

Kosmos-3M
~1.5 tons (upper stage)
More than 260 of them in LEO!

Upper Atmosphere Research Satellite (UARS)
~5.9 ton

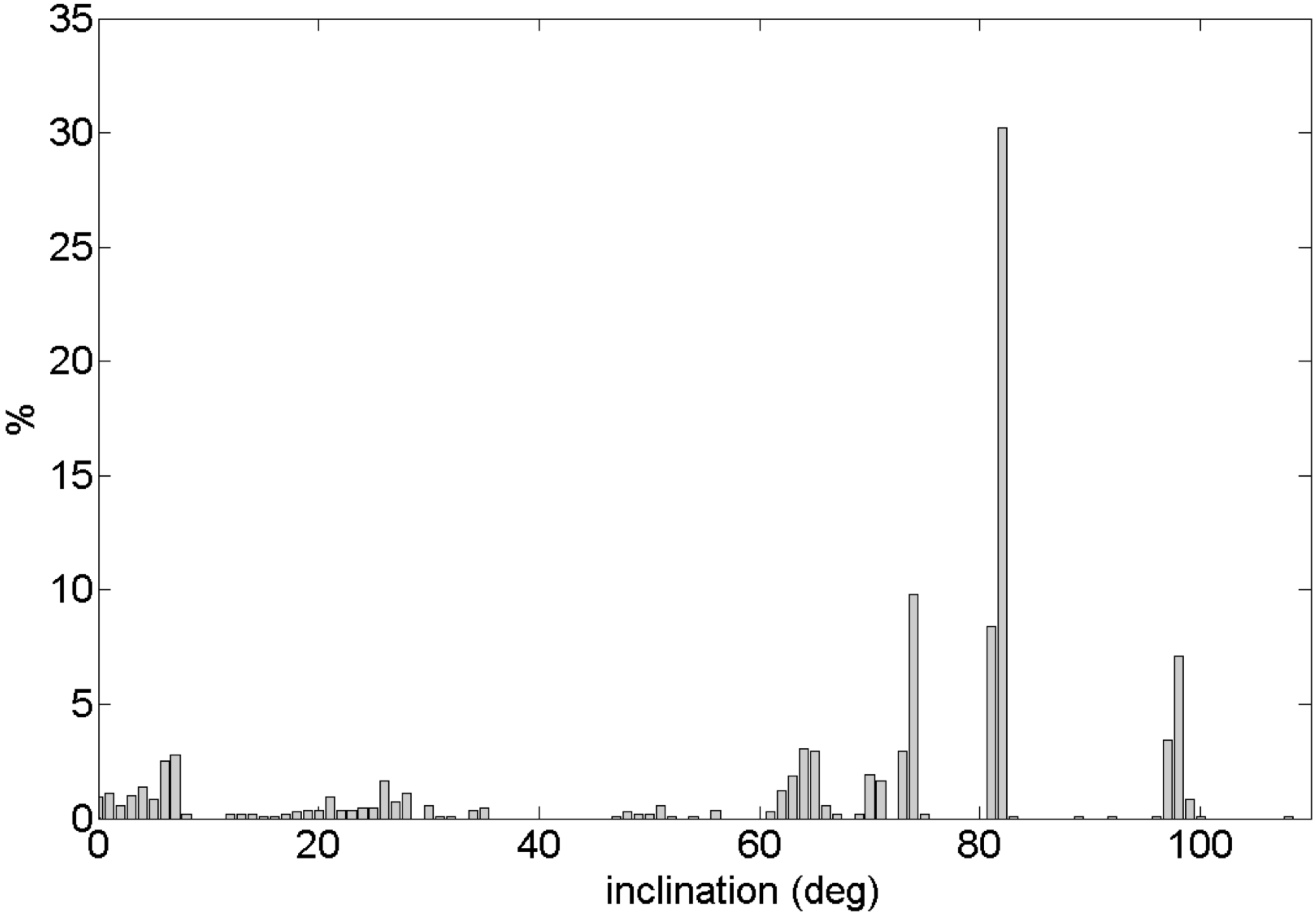
Envisat
~8.2 tons

Big-Size Debris in LEO: mass distribution

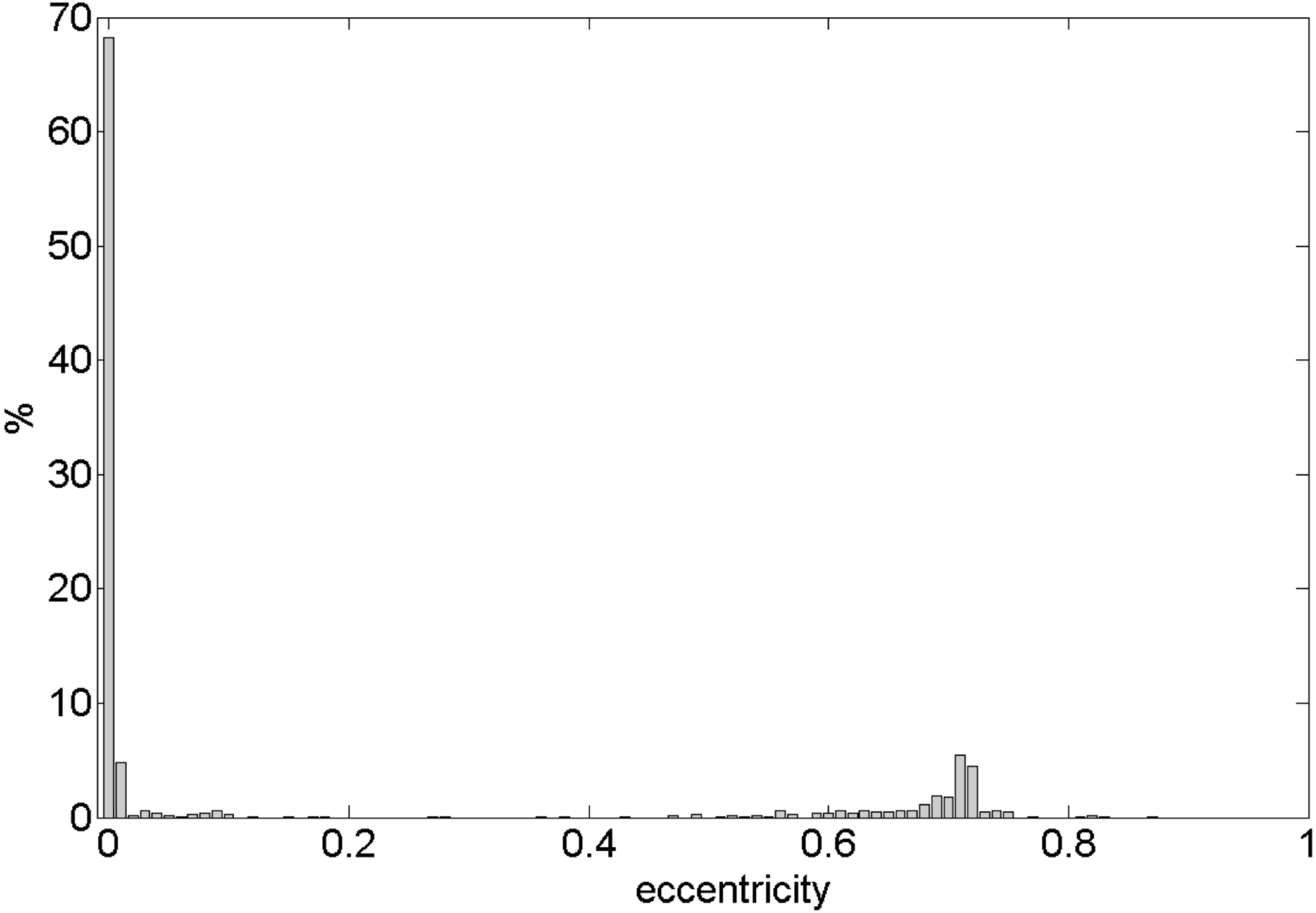


Kosmos-3M
and Vostok
upper stages

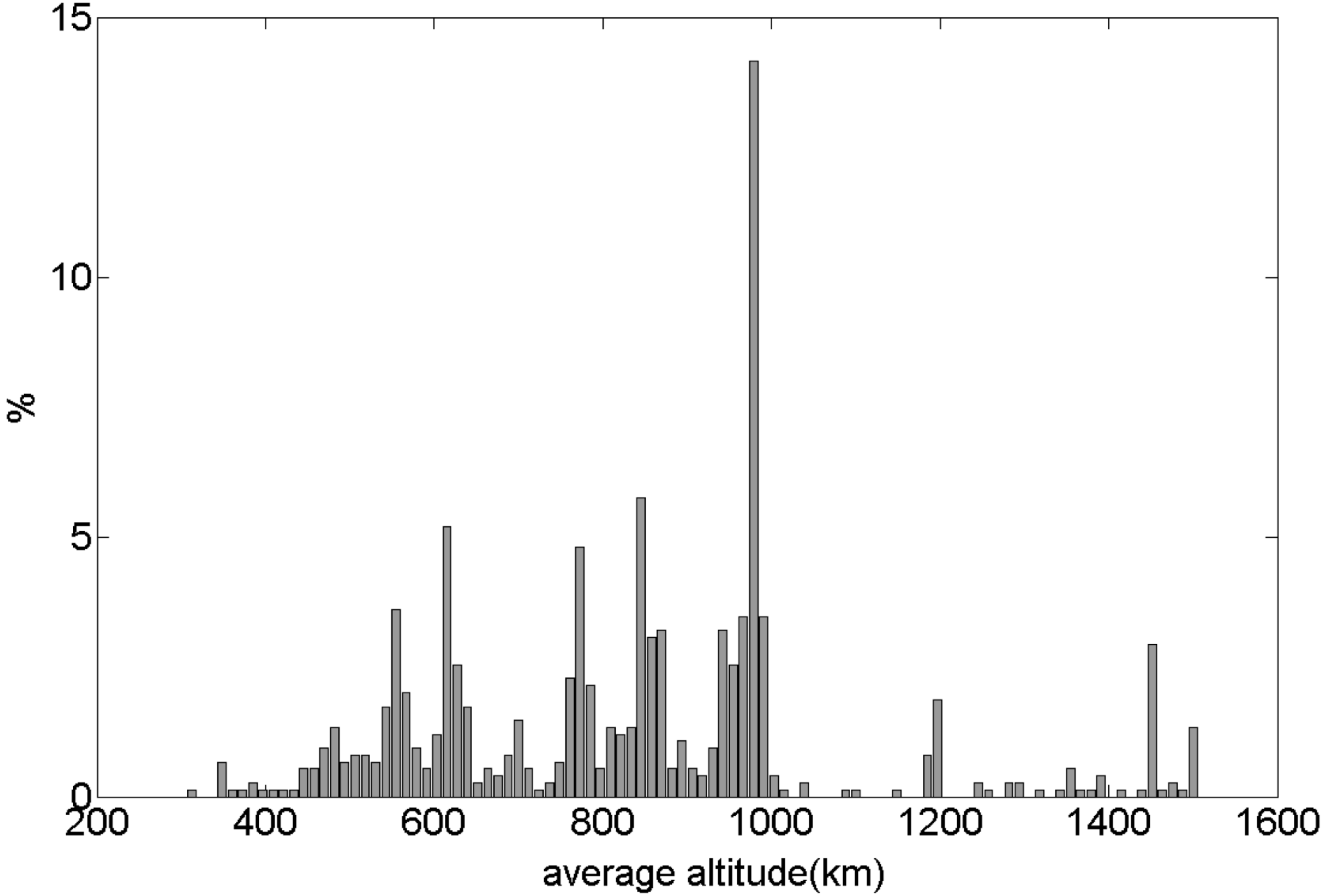
Big-Size Debris in LEO: inclination



Big-Size Debris in LEO: eccentricity



Big-Size Debris in LEO: altitude



The 7 ADR Metrics

- Different methods for ADR have been proposed (impulsive, low thrust, tethers, sails, parachutes, lasers, nets…)

- There is a need for <u>quantitative</u> and <u>qualitative</u> **metrics** for a fair comparison

1) SPECIFIC MISSION IMPULSE

$$p = \frac{F \cdot \Delta t}{m}$$

$F \cdot \Delta t$ → *deorbit force x deorbit time*

m → *mass of deorbit device*

→ Favors leightweight systems with fast deorbit capability

2) TIME AREA PRODUCT

$$\phi = A \cdot \Delta t$$

→ *cross section x deorbit time*

→ Favors small cross section devices with fast deorbit capability

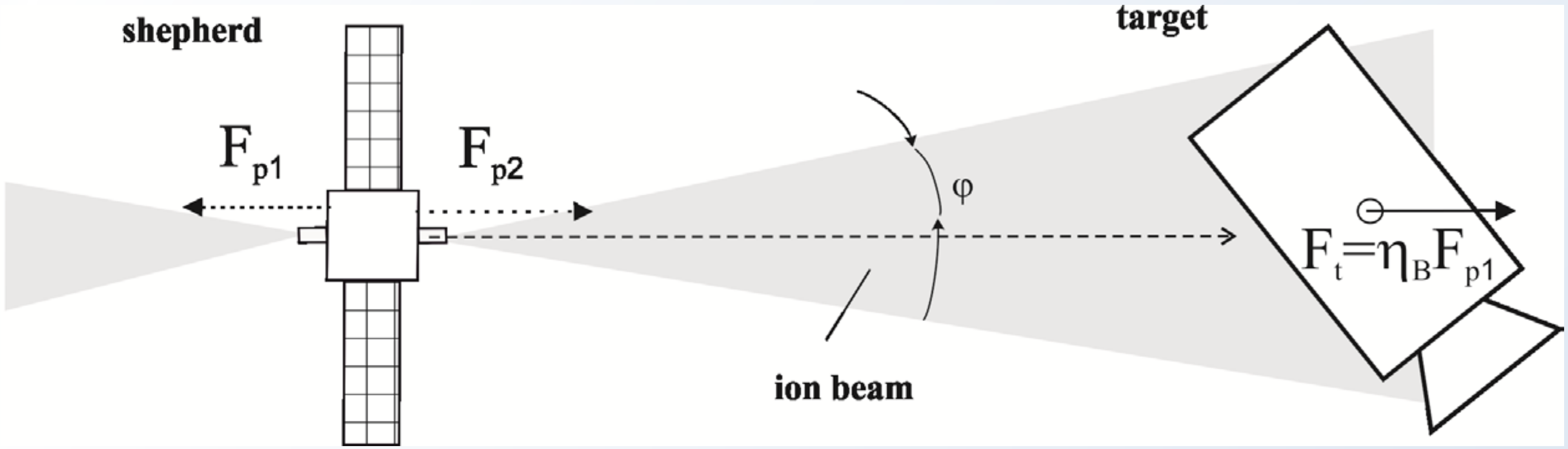
The 7 ADR Metrics (cont'd)

3) RELIABILITY	Accounts for docking/capturing issues, deployment collision with the target, etc..
4) TECHNOLOGY READINESS	Favors use of state of the art components
5) COLLISION AVOIDANCE CAPABILITY	Favors agile systems that can be controlled to avoid collisions with other targets during descent
6) REUSABILITY	Favors high specific impulse and propellantless Methods with reorbiting capability
7) ASAT POTENTIAL	Penalizes systems with remote deorbit capability (e.g. lasers)

The IBS Concept

- Point the ion-beam of an ion thruster towards the debris
- Ions reaching the debris surface penetrate the debris material substrate transferring their momentum (linear + angular)
- Need for a secondary propulsion system to compensate the reaction force on the shepherd

Advantage: **Contactless** momentum transfer



IBS Applications

- **CONTACTLESS DEORBITING/REORBITING**:
  - Transfer linear momentum without docking and increase/decrease orbit semimajor axis.
  - Contactless maneuvering of space debris, **asteroids**, payloads…

- **CONTACTLESS ATTITUDE “REEDUCATION”**:
  - Detumbling/despin of a space object before docking
  - Soft docking

- **SECONDARY ION MASS SPECTROSCOPY**:
  - Contactless in situ mass spectrometry of backsputtered material.
  - Interesting tool for asteroid science
  - Ongoing work at JPL/Caltech

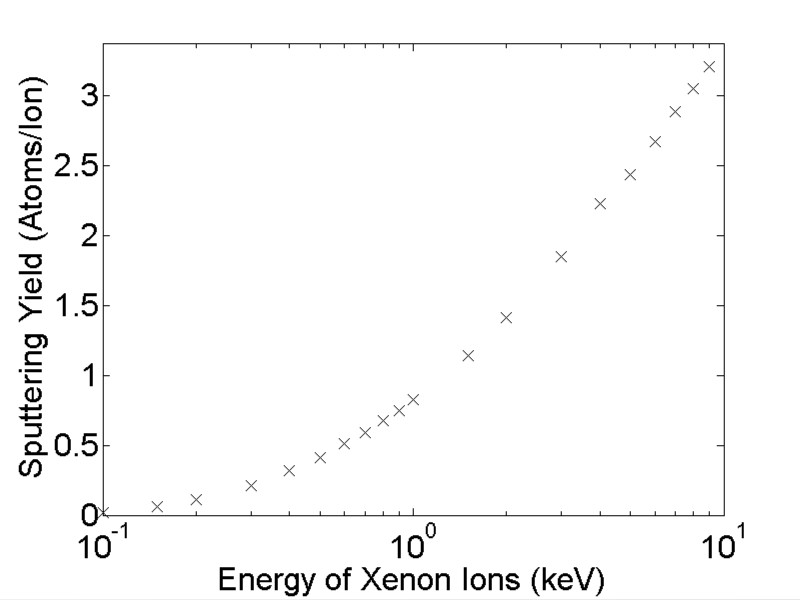
  - Amini et al. (JPL-Caltech) “Electric Propulsion Induced Secondary Mass Spectroscopy (EPI-SMS)”, conference on small

IBS Challenges

- **Proximity Formation Flying Control**:
  - Typical target-shepherd distance for almost full **beam overlap** is 10-15 m
  - Need for accurate metrology + control strategies to avoid collisions

- **Attitude Reeducation Control**
  - Attitude estimation and control from a few meters distance is challenging.

- **Backsputtering**:
  - Secondary emissions from debris surface following ion bombardment can drive neutrals into thruster nozzle and sensors
  - Increasing separation distance highly beneficial

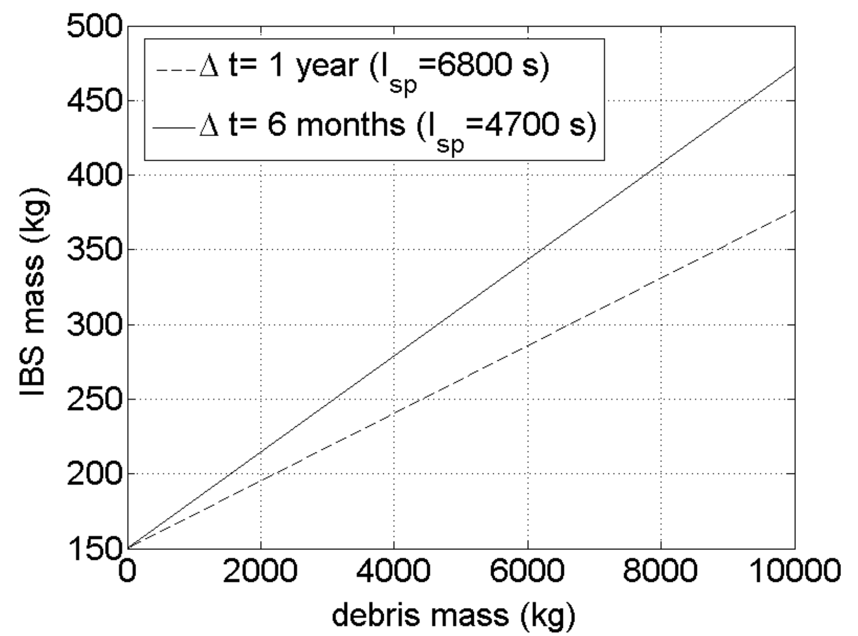


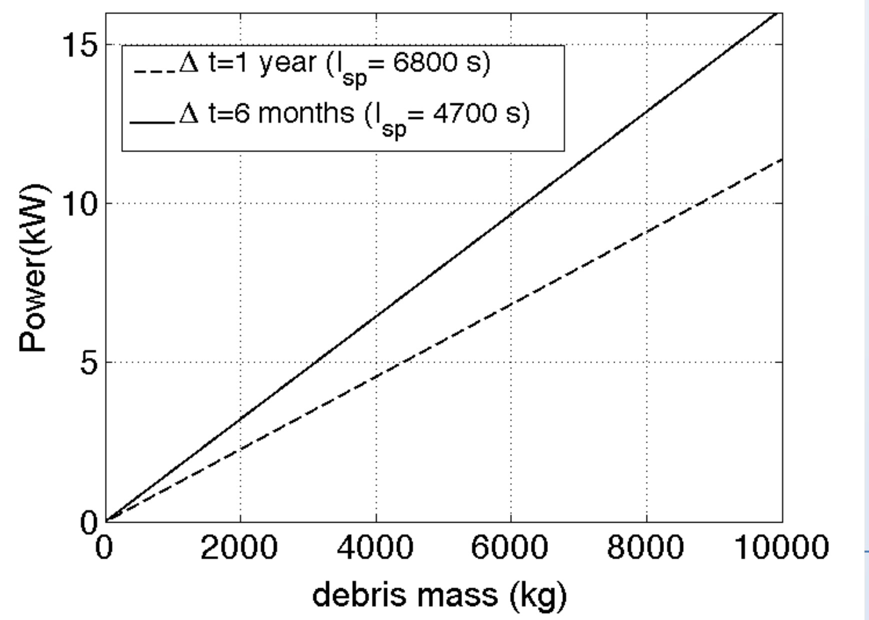
Simulations done with J F Ziegler SRIM (Stopping and Range of Ions in Matter).

IBS Performance in LEO

- One debris deorbiting
- Quasi-circular spiralling orbit from 1000 km to 300 km
- Thrust is constant & tangent to orbit
- Primary & secondary prop. systems are equal

- 70% ion thruster efficiency
- full momentum transfer eff.
- Power plant α= 10 kg/kW
- 150 kg structural mass (i.e. total mass w/o propellant and w/o power plant).





IBS mass ≈ 5% of the debris mass

Deorbit or Reorbit?

- Large debris containing highly resistant alloys (eg titanium) may partly survive reentry

- Fully **targeted reentry** with low-thrust <u>not feasible</u>

- Reorbiting to higher altitude cemetery orbits possible with a small increase in DV:

$$m_{IBS} \propto \frac{\sqrt{R}-\sqrt{r}}{\sqrt{Rr}}$$

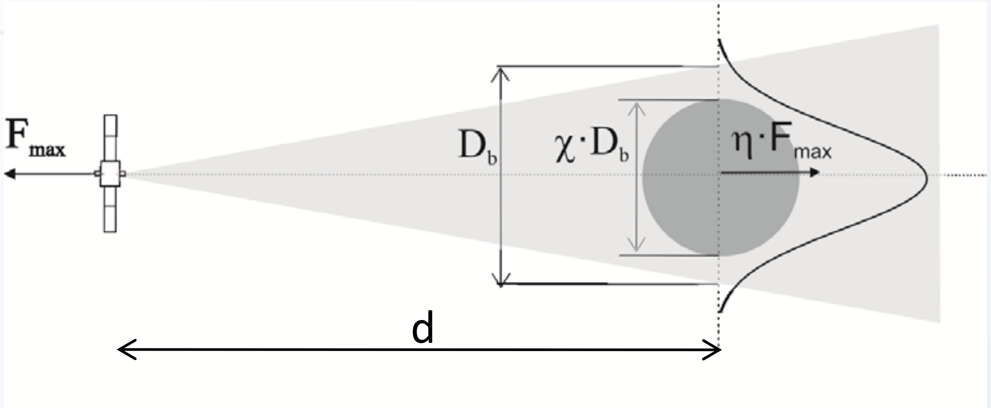
- Compare reorbit to "globalstar cemetery" (h~2000 km) with deorbiting at h=300 km
  +20% mass penalty when starting from h= 1000 km
  +76% mass penalty when starting from h=850 km

  Debris recycling?

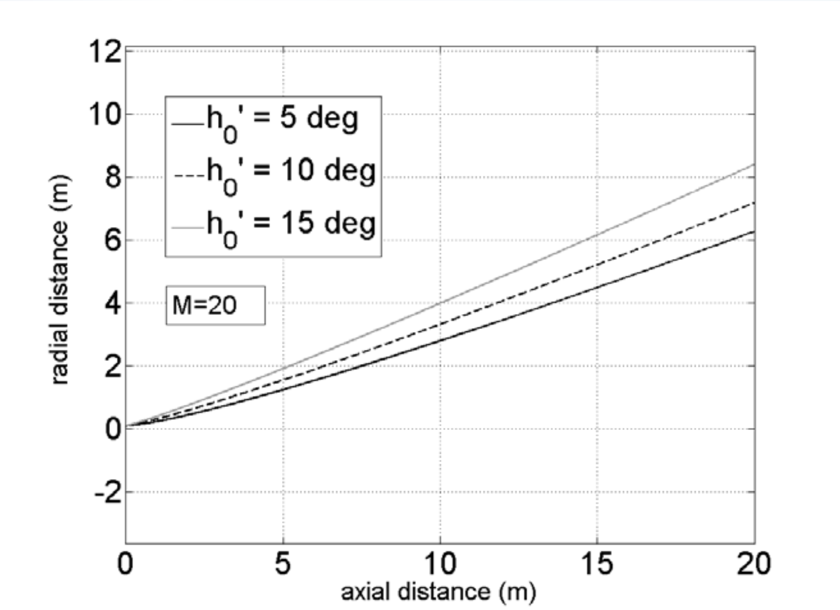
- Feasibility of reducing uncertainty ellipse by **shepherding at low altitude** is under investigation.

Ion Beam Modeling

- Low beam **divergence** is key in order to allow high efficiency at large separation



- Beam expands due to initial divergence (-> h0’) *and* electron pressure (-> plasma Mach number M)



- State of the art ion engines -> h0’=5-15 deg , M=10-30

A typical 4 m size debris can be handled at distance of 10 m with (almost) full efficiency

Beam-Perturbed Relative Motion

- IBS co-orbiting with the Debris with same semimajor axis (i.e. bounded separation)

Full Governing Equations:

Control Strategy

Beam-Debris Interaction

Debris-Shepherd Relative Dynamics

$$\ddot{\boldsymbol{\rho}} + \left(\boldsymbol{\Omega}\boldsymbol{\Omega} + \dot{\boldsymbol{\Omega}} - \mathbf{G}\right)\boldsymbol{\rho} + 2\boldsymbol{\Omega}\dot{\boldsymbol{\rho}} = \frac{\boldsymbol{F}_D}{m_D} - \frac{\boldsymbol{F}_S}{m_S},$$

Shepherd Orbit Dynamics

$$\ddot{\boldsymbol{r}}_S = -\mu\frac{\boldsymbol{r}_S}{r_S^3} + \frac{\boldsymbol{F}_S}{m_S},$$

→ Control Strategy

Debris Attitude Dynamics

$$\mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \wedge (\mathbf{I}\boldsymbol{\omega}) = \mathbf{N}_{tot}$$

→ Beam-Debris Interaction

- Generic orbit eccentricity can be handled
- J_2 perurbation included

Circular Orbit Approximation + Spherical Debris

- Key to allow analytical treatment of the relative motion
- Stability analysis
- Control design

$$\delta_x'' - 2\delta_y' - (3 + \gamma_r)\,\delta_x = 0,$$

$$\delta_y'' + 2\delta_x' + \gamma_y \delta_y = 0,$$

$$\delta_z'' + (1 - \gamma_r)\,\delta_z = 0,$$

- Linearize beam force around nominal equilibrium configuration and perform nondimensionalization

- Obtain CW-like relative motion equations with **additional terms** associated to **beam gradients**

$$\gamma_r = \frac{b_r F_0}{m_D \omega^2 R_B} = \frac{\epsilon r}{R_B} b_r$$

Radial **destabilizing** term

$$\epsilon = \frac{F_D r^2}{m_D \mu}$$

= Orbit tangential acc / local gravity

$$\gamma_y = -\frac{b_y F_D}{m_D \omega^2 \lambda} = -\frac{\epsilon r}{R_B} b_y$$

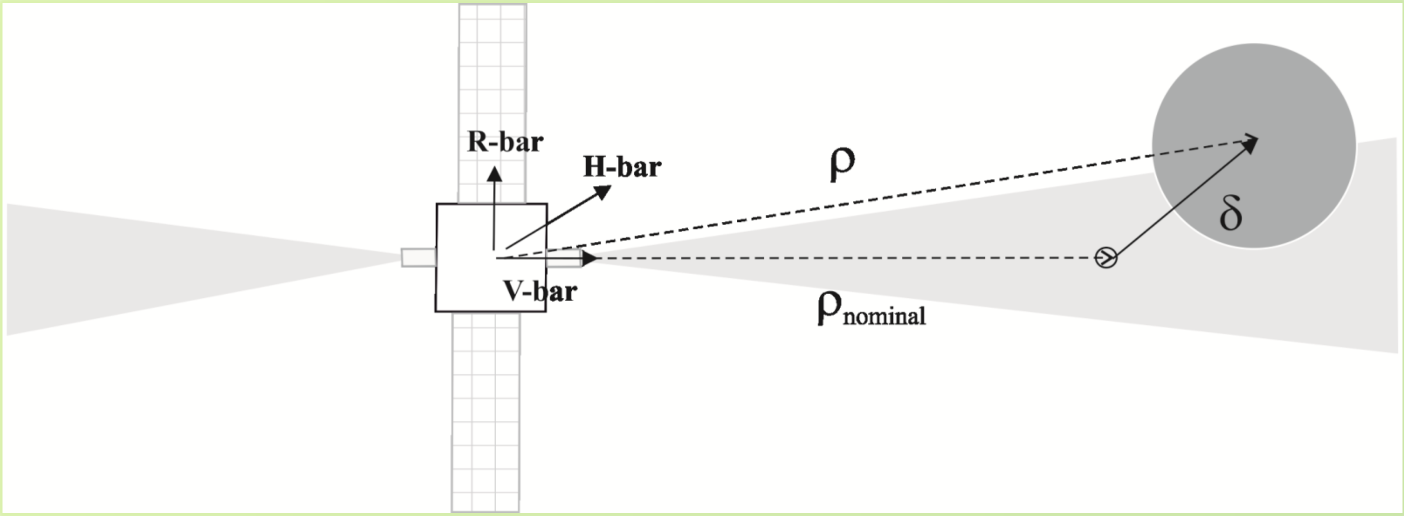
Along-track **stabilizing** term

Relative Motion Control

- Control strategy needed to eliminate real-posiive eigenvalue along R-bar direction

- Thrusters act on shepherd CoM to control relative position in R-V-H-bar directions

- Error vector δ (and time derivative) wrt to nominal position $\rho_{nominal}$ is **assumed available to the controller**



PD Feedback Controller

- Simple **3-axis** PD control strategy developed
- **Control gains optimized** depending on debris geometry and beam characteristics
- Controller tested with position and velocity initial offset
- **Robustness** wrt small eccentricity orbits ($e < 0.1$) and J_2 perturbation verified
- **Feedforward** control part added to deal with strong non-linearities associated with large displacement
  - model embedded in the controller employs an "equivalent spherical target" to deal with cylindrical debris

Numerical Simulations

Baseline Orbit:

- *circular i=82º h=700 km*

Baseline Target (Kosmos-3M upper stage)

- *Cylinder 6.5m hight by 4.8m diameter ; mass~1.5 tons*

Nominal equilibrium position:

- *On axis at 15 m distance from shepherd*

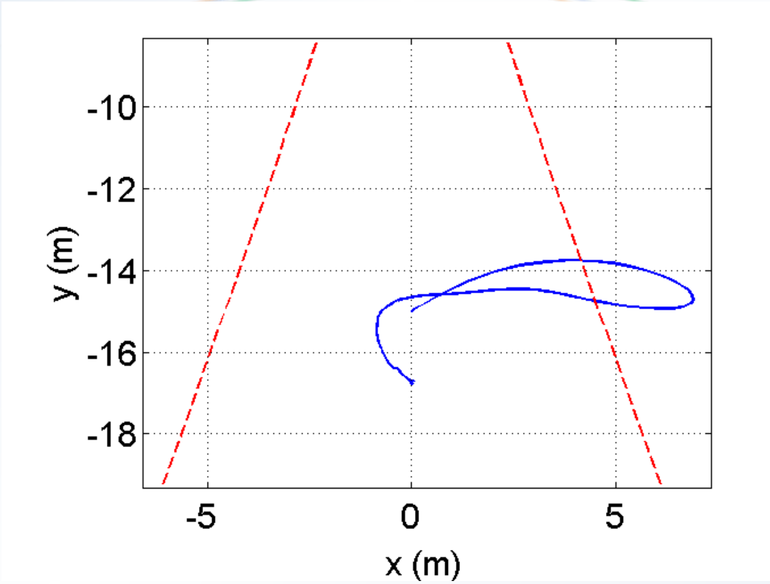
Thruster

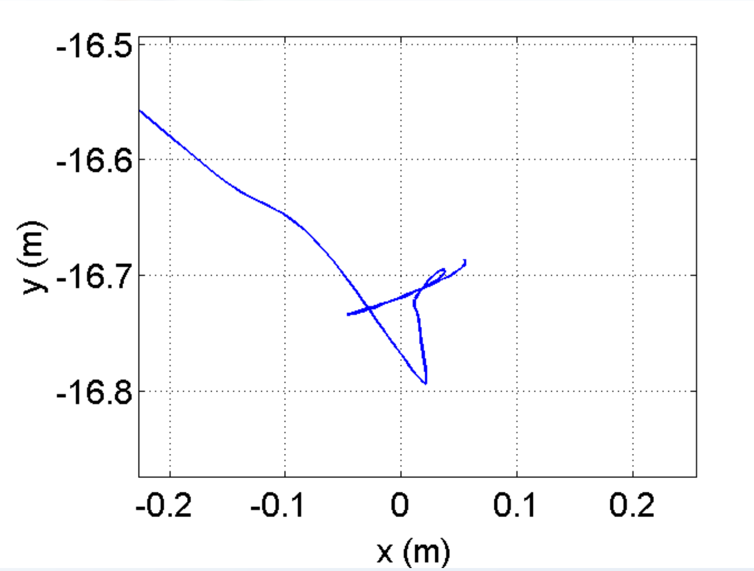
- *Nominal tangential thrust 100mN*
- *Divergence 6 deg half angle*
- *Plasma Mach number =20*

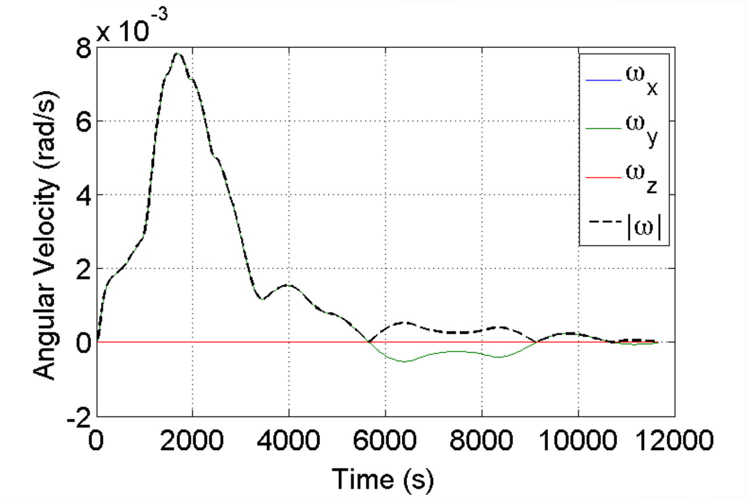
Shepherd Spacecraft

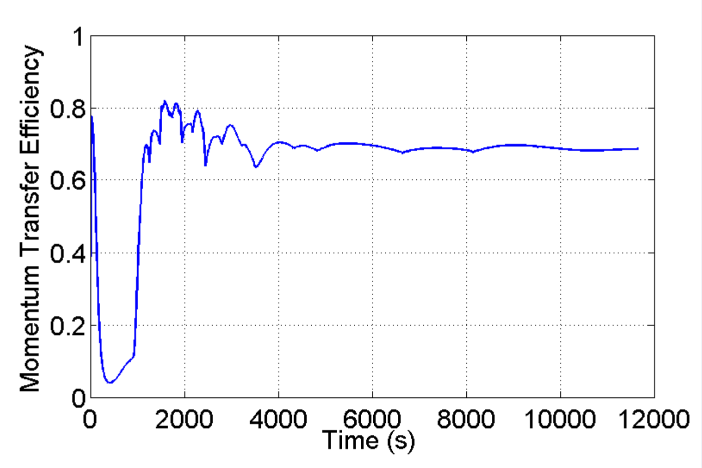
- *mass= 300 kg*

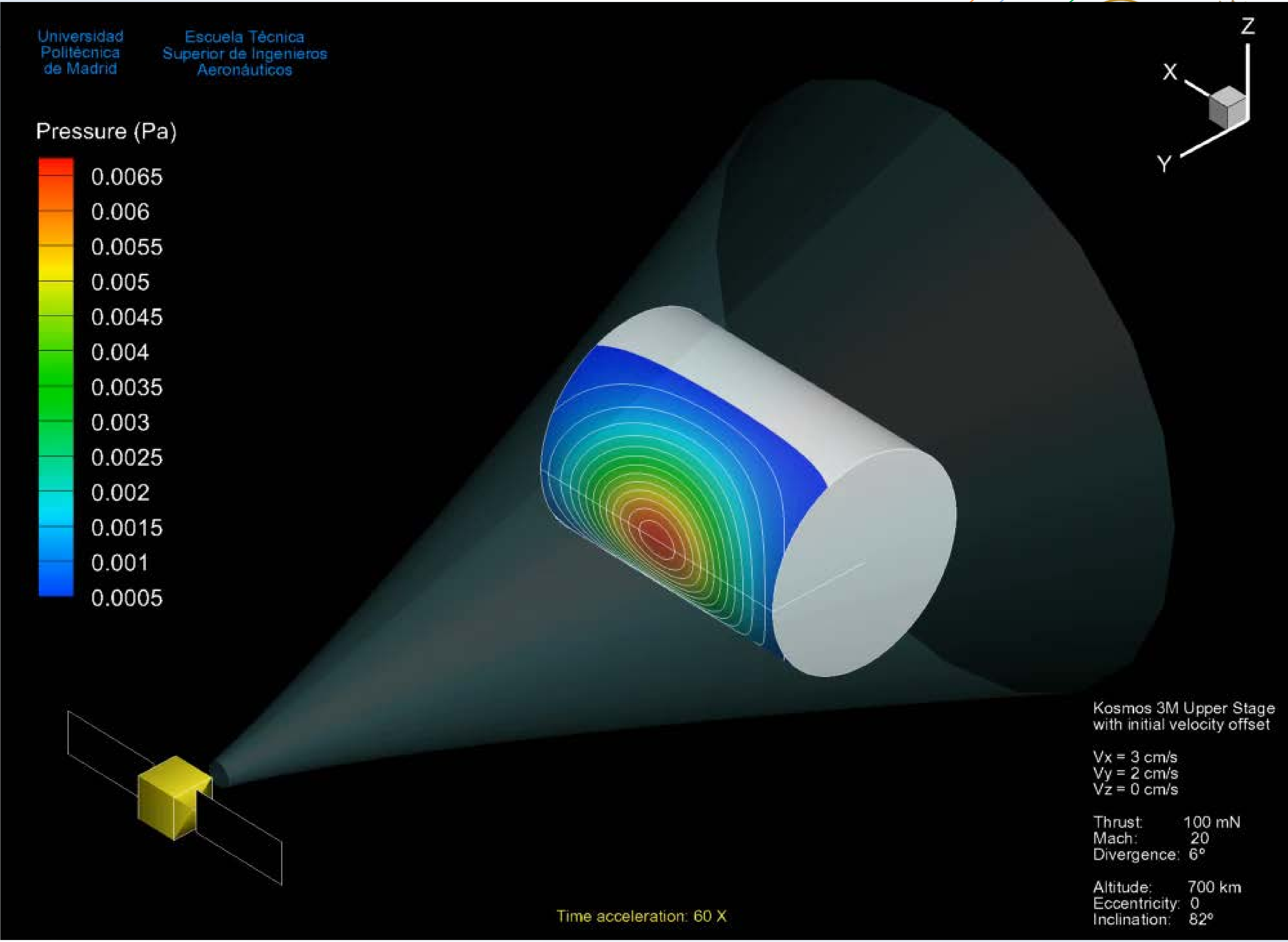
Numerical Simulations







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Pressure (Pa)
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Z
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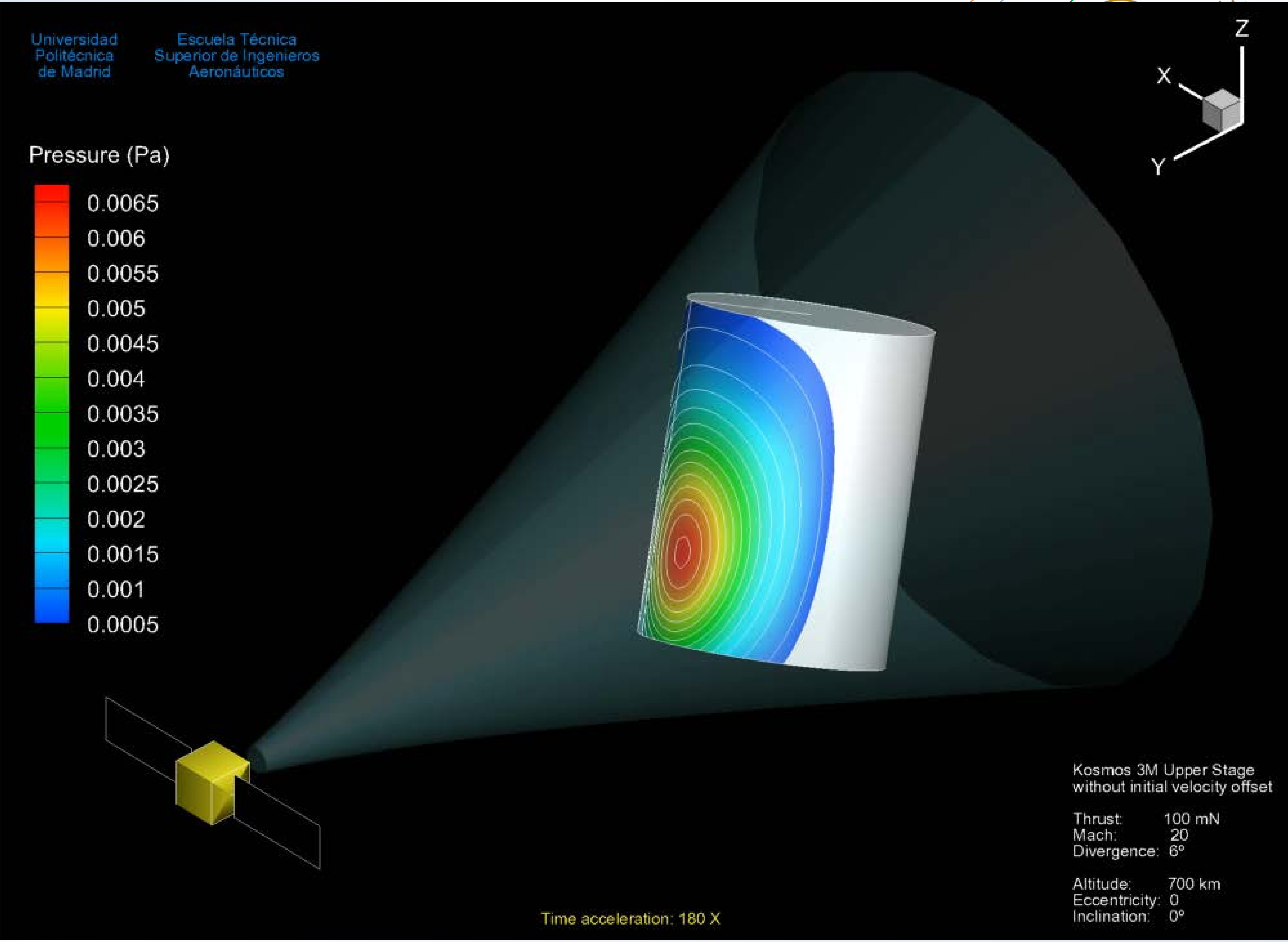
Y
Kosmos 3M Upper Stage with initial velocity offset
Vx = 3 cm/s
Vy = 2 cm/s
Vz = 0 cm/s
Thrust: 100 mN
Mach: 20
Divergence: 6°
Altitude: 700 km
Eccentricity: 0
Inclination: 82°
Time acceleration: 60 X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Pressure (Pa)
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0.002
0.0015
0.001
0.0005
Z
X
Y
Kosmos 3M Upper Stage
without initial velocity offset
Thrust: 100 mN
Mach: 20
Divergence: 6°
Altitude: 700 km
Eccentricity: 0
Inclination: 0°
Time acceleration: 180 X

Conclusions

- Active Debris Removal (ADR) is a necessary step for space sustainability and should target large debris in crowded LEO orbit
- ADR metrics were introduced to address efficiency, cost, complexity and risk for a generic ADR strategy
- The Ion Beam Shepherd (IBS) appears to be a promising technology to address key ADR challenges
- Key physical aspects of the IBS were identified and the dynamical interaction between beam and a target bodies reasonably well understood.
- IBS-Debris relative motion can be stabilized provided accurate **relative metrology** is available. Advances in relative motion guidance and control needed to make the concept feasible
- Other issues such as backsputtering contamination will also need to be addressed

The End

Thank you!

BACK-UP SLIDES

Non-dimensional quantities

Shape factors

$$\chi_i = \frac{R_i}{R_B(\rho)}; \qquad \chi_e = \frac{R_e}{R_B(\rho)}$$

= body internal and external envelope R / local beam R

Aspect ratio

$$\zeta = \frac{h}{2R}$$

= cylinder height / diameter

Dimensionless force & torque

$$\boldsymbol{f}_B = \frac{\left(\int_{S_b} d\boldsymbol{F}\right)}{\pi R_n^2 m_i n_n u_n^2} = \frac{\boldsymbol{F}}{F_0}$$

= transmitted force / thruster force

$$\boldsymbol{\tau}_B = \frac{\int_{S_b} (\boldsymbol{r} - \boldsymbol{r}_G) \times d\boldsymbol{F}}{R_e F_0} = \frac{\boldsymbol{N}}{R_e F_0}$$

= transmitted torque / thruster force X external envelope

Momentum transfer efficiency

$$\eta_B = \frac{F_z}{F_0}$$

= transmitted axial force / thruster force

Generalized beam gradient

Consider a nominal IBS-Debris relative equilibrium position $\bar{\boldsymbol{\rho}}$

Compute beam force gradient matrix:

$$\hat{\mathbf{B}} = \frac{R_B(\rho)}{F_0} \left.\frac{\partial \mathbf{F}}{\partial \mathbf{r}}\right|_{\boldsymbol{\rho}=\bar{\boldsymbol{\rho}}} = \begin{bmatrix} b_{xx} & b_{xy} & b_{xz} \\ b_{yx} & b_{yy} & b_{yz} \\ b_{zx} & b_{zy} & b_{zz} \end{bmatrix}$$

For a cylinder, add missing terms related to torque components and attitude angle (α = angle between beam axis and cylinder axis)

$$b_{x\alpha} = \frac{1}{F_0}\frac{\partial F_x}{\partial(\Delta\alpha)}; \quad b_{y\alpha} = \frac{1}{F_0}\frac{\partial F_y}{\partial(\Delta\alpha)}; \quad b_{z\alpha} = \frac{1}{F_0}\frac{\partial F_z}{\partial(\Delta\alpha)}$$

$$b_{\alpha x} = \frac{1}{F_0}\frac{\partial N}{\partial x}; \quad b_{\alpha y} = \frac{1}{F_0}\frac{\partial N}{\partial y}; \quad b_{\alpha z} = \frac{1}{F_0}\frac{\partial N}{\partial z}; \quad b_{\alpha\alpha} = \frac{1}{R_e F_0}\frac{\partial N}{\partial(\Delta\alpha)}$$

Generalized beam gradient

$$\mathbf{B} = \begin{bmatrix} b_{xx} & b_{xy} & b_{xz} & b_{x\alpha} \\ b_{yx} & b_{yy} & b_{yz} & b_{y\alpha} \\ b_{zx} & b_{zy} & b_{zz} & b_{z\alpha} \\ b_{\alpha x} & b_{\alpha y} & b_{\alpha z} & b_{\alpha\alpha} \end{bmatrix}$$