



E.T.S.I. Aeronáuticos
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SPACE DEBRIS REMOVAL with ELECTRODYNAMIC TETHERS

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2010 BEIJING ORBITAL DEBRIS MITIGATION WORKSHOP. Beihang University, PRC. 18-19 Oct 2010

Presentation outline

- Understanding the debris removal problem
- Large LEO debris 'taxonomy'
- Debris removal options
- Deorbit time and maneuverability
- Electrodynamic tethers
 - working principles, design & performance
- conclusions

Debris Removal: The Key Point

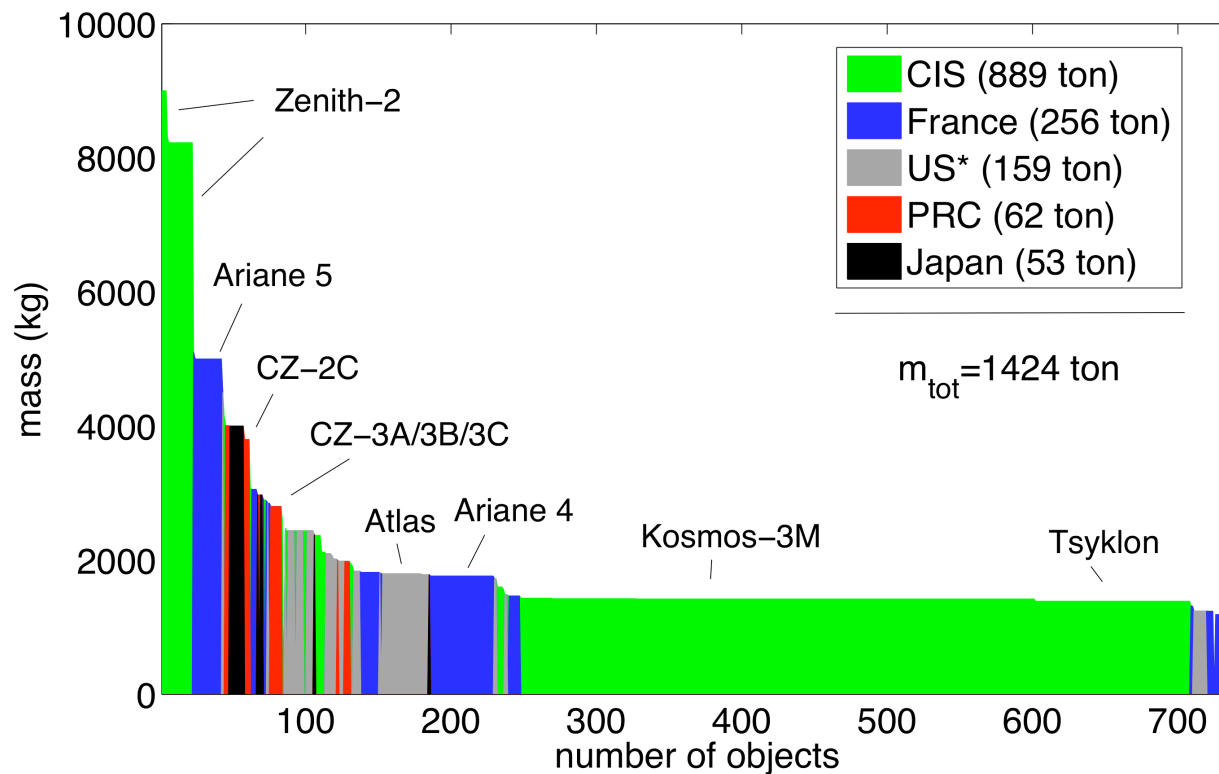
- We need a device that gets **big-size** upper stages and dead satellites down as **quickly** as possible, as **cheaply** as possible, while minimising the threat to the rest of our space assets

Why Big-size debris ?

- 1) Higher collision probability (due to large cross section)
 - 2) Higher post-collision debris mass yield (due to large mass)
- Liou and Johnson's IAC-07 paper: **debris removal selection criterion** based on cross section, mass and orbit crowding
 - As a result their "5-debris-per-year campaign" is dominated by objects larger than 1 ton (Fig.6 of that paper, IAC-07 A6.3.05)

How Big is "Big" ?

LEO UPPER-STAGES WEIGHING MORE THAN 1-TON



Currently more than 700

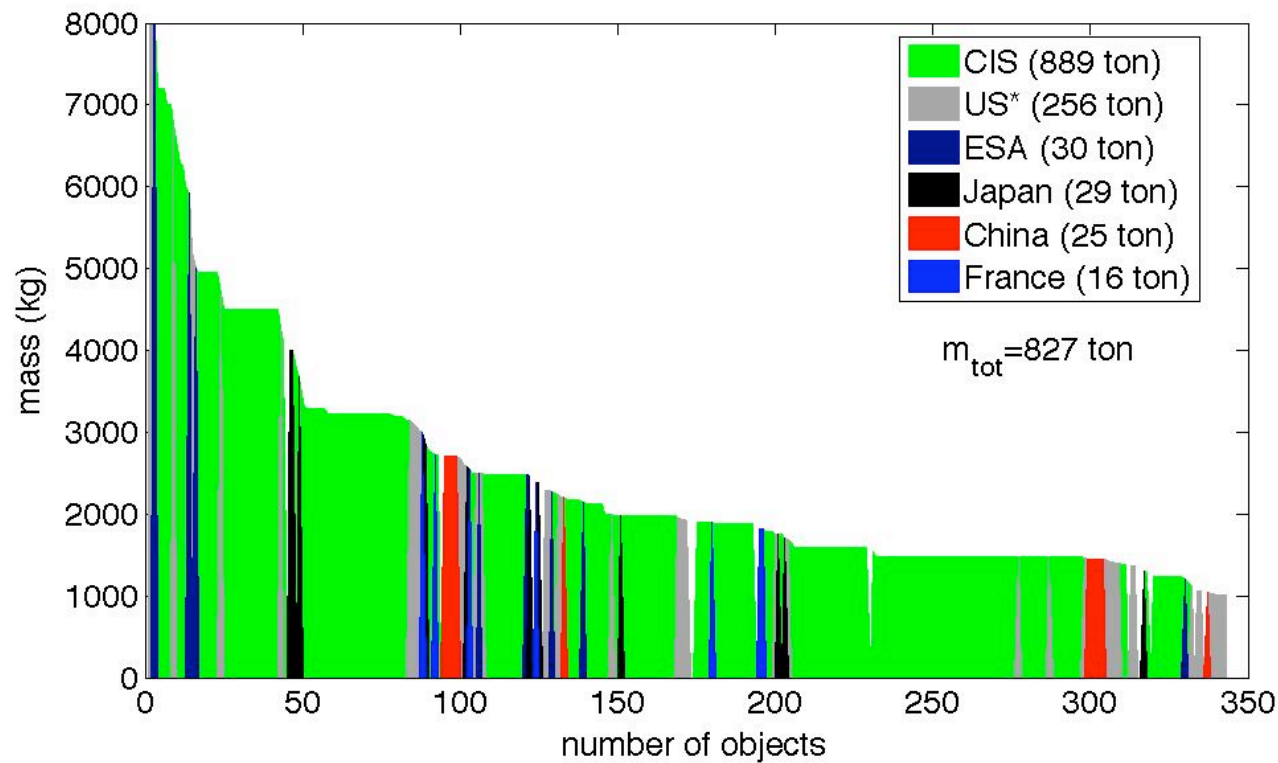
Mostly Russian and French

Mostly clustered
In a few altitude-
inclination bands:

800-1000 km altitude
Sun-synchronous
inclinations

Almost **1500 tons** of debris mass. More than 1/4 of the total catalogued mass in Earth orbit!

LEO PAYLOADS WEIGHTING MORE THAN 1-TON



All active satellites
 included except ISS

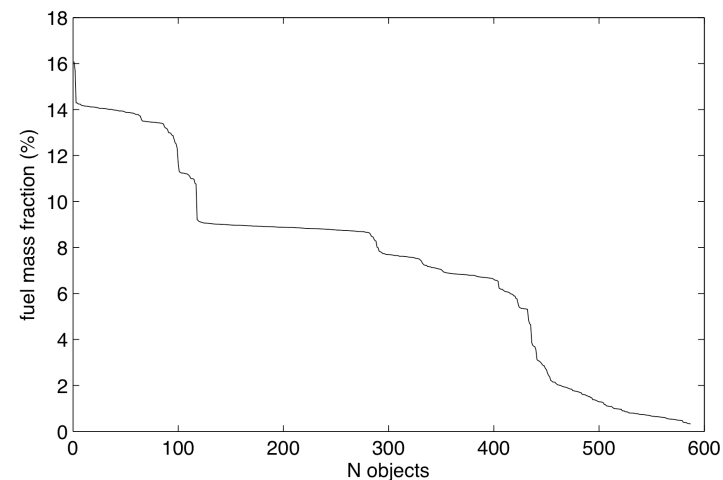
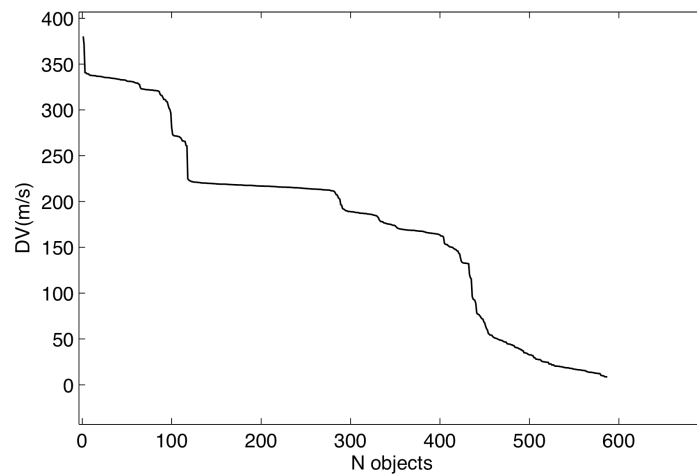
Mostly Russian and
 American

Less numerous and
 massive than upper
 stages

all-chemical removal campaign

- Consider DV cost of **direct deorbiting** with one apogee burn to lower perigee to 150 km altitude:

$$\Delta V = \sqrt{\frac{2\mu}{r_a}} \left(\sqrt{\frac{r_{pi}}{r_a + r_{pi}}} - \sqrt{\frac{r_{pf}}{r_a + r_{pf}}} \right)$$



- On average 150-200 m/s ΔV cost with 6-10% propellant mass fraction ($I_s=260$ s)
- ~79 tons of hydrazine in orbit needed to deorbit all upper stages > 1ton

Low thrust options

LOW-THRUST* ($10\text{mN} < F < 500\text{ mN}$)

- **Electric Propulsion (EP):**
 - High-specific impulse needed for (optimum) long duration removal campaign
 - Reusable up to fuel exhaustion
- **Electrodynamic Tethers (EDT):**
 - Propellantless and fully reusable
 - Lighter than EP for long-enough required thrust time
 - Collision avoidance more critical (needs maneuverability)

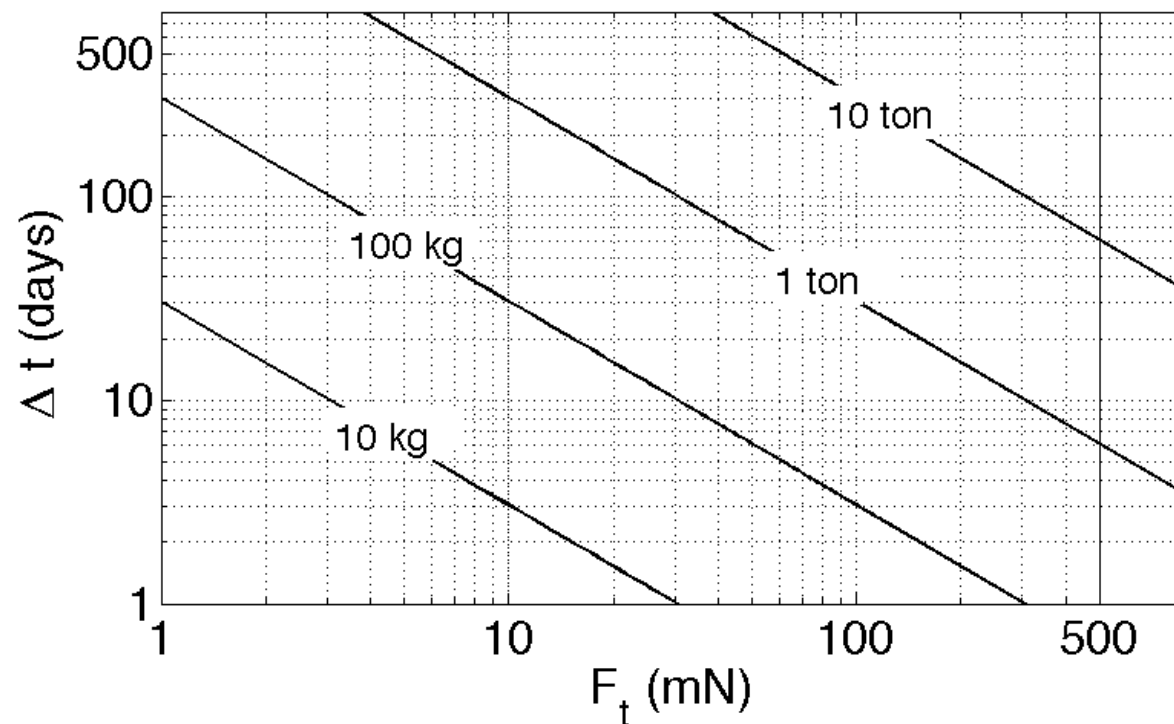
VERY LOW-THRUST* ($< 10\text{ mN}$)

- Laser ablation
- Parachutes
- Solar sails

* For reasonable values of power availability, mass and size of device at orbital altitude of interest

Deorbit time for constant thrust

- Assume constant tangential thrust F_t and quasi-circular orbit evolution
- Maneuver from 1000 km to 500 km altitude orbit

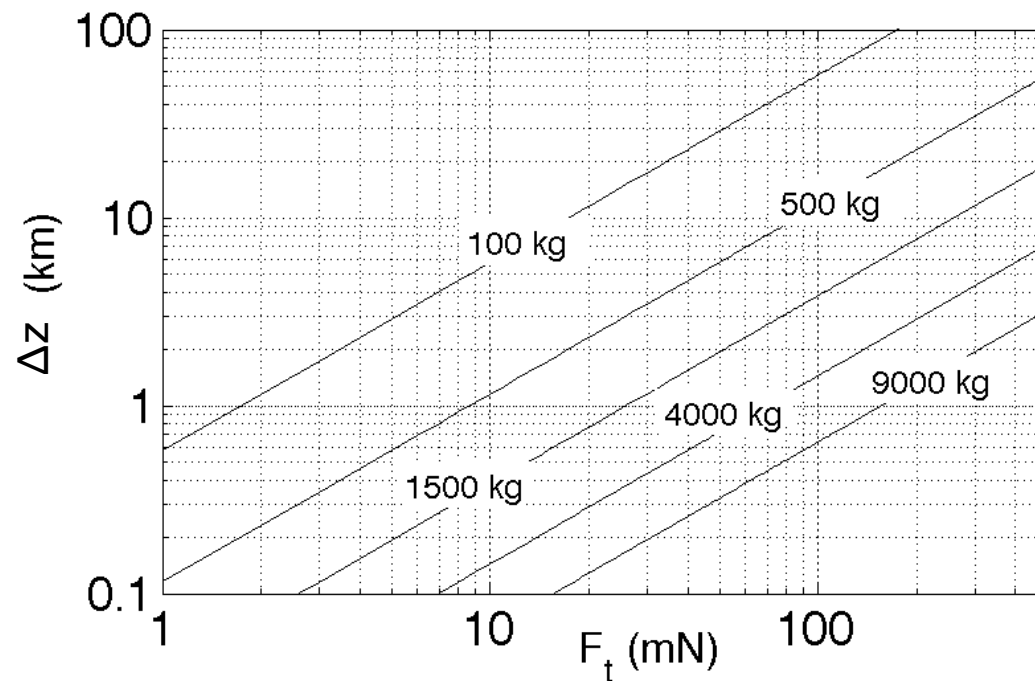


$$\Delta t \simeq m_d \frac{\sqrt{\mu}}{F_t} \times \frac{\sqrt{R} - \sqrt{r}}{\sqrt{rR}}$$

~100 mN of thrust (or more)
required for dealing with
large-size debris in a
reasonable time (i.e. less
than a year)

Maneuverability for constant thrust

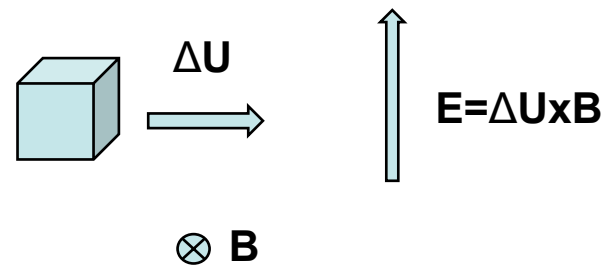
- Assume predicted (ballistic) collision between two objects in circular orbits with 1000 km altitude and 180 deg inclination difference (worst-case scenario)
- Constant tangential drag is activated for a time-span $\Delta t_{ca}=8$ hours
- Minimum Orbit Interception Distance computed for different values of S/C mass



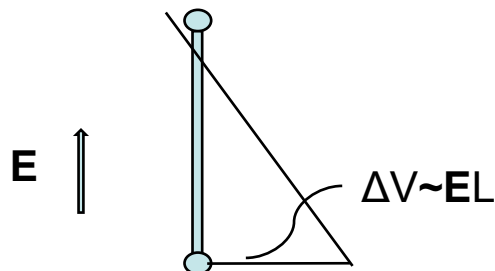
Again, ~100 mN of thrust (or more) required for dealing with large-size debris

Bare Electrodynamic Tethers basics (1)

- 1) A S/C moving at relative velocity $\Delta \mathbf{U}$ wrt plasmasphere in the presence of a Magnetic field \mathbf{B} sees a motional electric field $\mathbf{E} = \Delta \mathbf{U} \times \mathbf{B}$ in its own frame



- 2) If the S/C physical size is extended by a length L along \mathbf{E} a large potential difference ΔV between the S/C and the surrounding plasma can be achieved



To get high-enough potential difference in LEO we need km-long structures: that is a **space tether!**

Bare Electrodynamic Tethers basics (2)

3) Once we have a high ΔV how do we get **current** flowing through the tether?

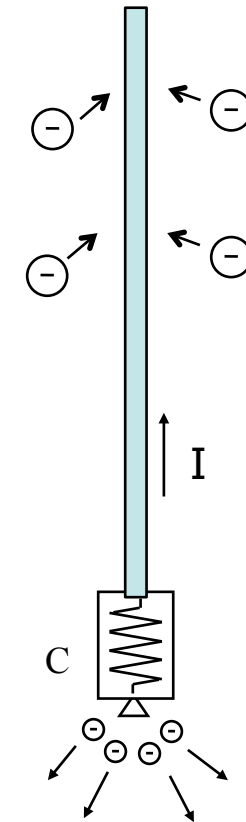
By collecting plasma electrons at one side (ANODE) and giving them back to the plasma at the other (CATHODE).

At present, the most efficient way to do that is to have the tether itself collecting the electrons and conducting them towards a hollow cathode that ejects them back to the plasma.

This is called the **bare electrodynamic tether** and was proposed in 1991 by prof J.R. Sanmartin (Madrid University).

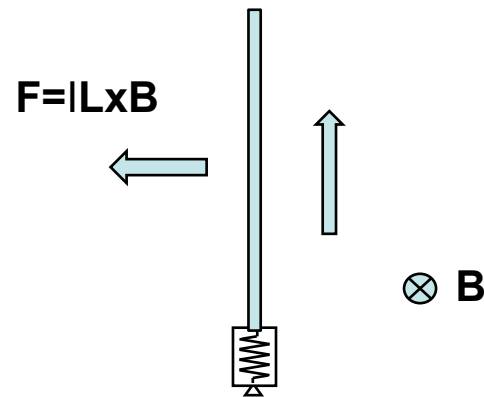
A conducting wire has the most efficient collection capability, which obeys the Orbital Motion Limited (OML) theory, as long as its size is small compared to the local plasma Debye length.

In LEO such length ranges from a few mm to a few cm.



Bare Electrodynamic Tethers basics (3)

4) Finally, the current will interact with the magnetic field to generate a Lorentz force which for a passive system (no power given to the tether) will be a **drag force**.



- The drag force can be used to deorbit satellites without using propellant and is currently considered among the best solutions for orbit debris removal

A preliminary EDT model

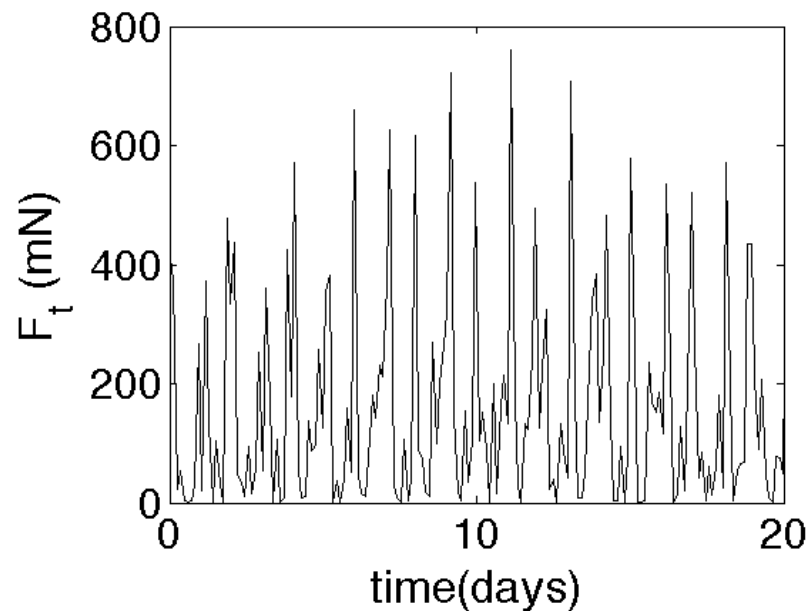
- Tether assumed constantly stabilized along the local vertical (high eccentricity debris excluded)
- Dual cathode system (important for high inclination orbits) **constantly on**
- Tether is a thin aluminum tape with smallest possible thickness (0.05 mm) and width (3-cm) inside OML validity range
- Tether length of 20km (80kg) are considered
- IRI 2007 and IGRF95 plasmasphere model used
- MSIS-90 atmosphere and EGM-96 gravity model

EDT tangential force profile

- For a 'hanging' EDT in circular orbit Lorentz drag proportional to the 3/2 power of magnetic field projection along the orbit plane

$$F_t \propto B_{\perp}^{3/2}$$

- In high-inclination orbits this makes F_t oscillating with main frequencies corresponding to orbital motion (~ 2 hours) and Earth rotation (1 day)



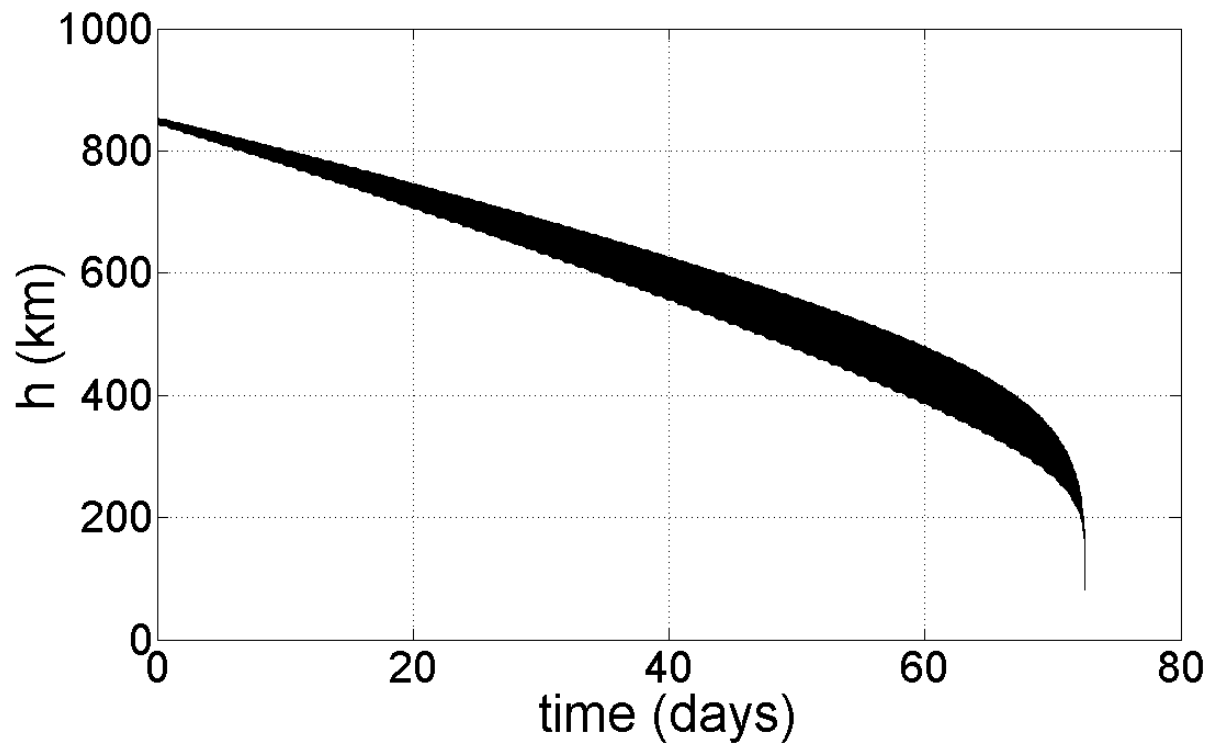
Tangential Lorentz force for a 20-km tape
EDT in circular orbit of 1000 km
altitude and 98 deg inclination



Deorbiting performance evaluation needs ad-hoc numerical sims for each case

Zenit-2 upper stage family

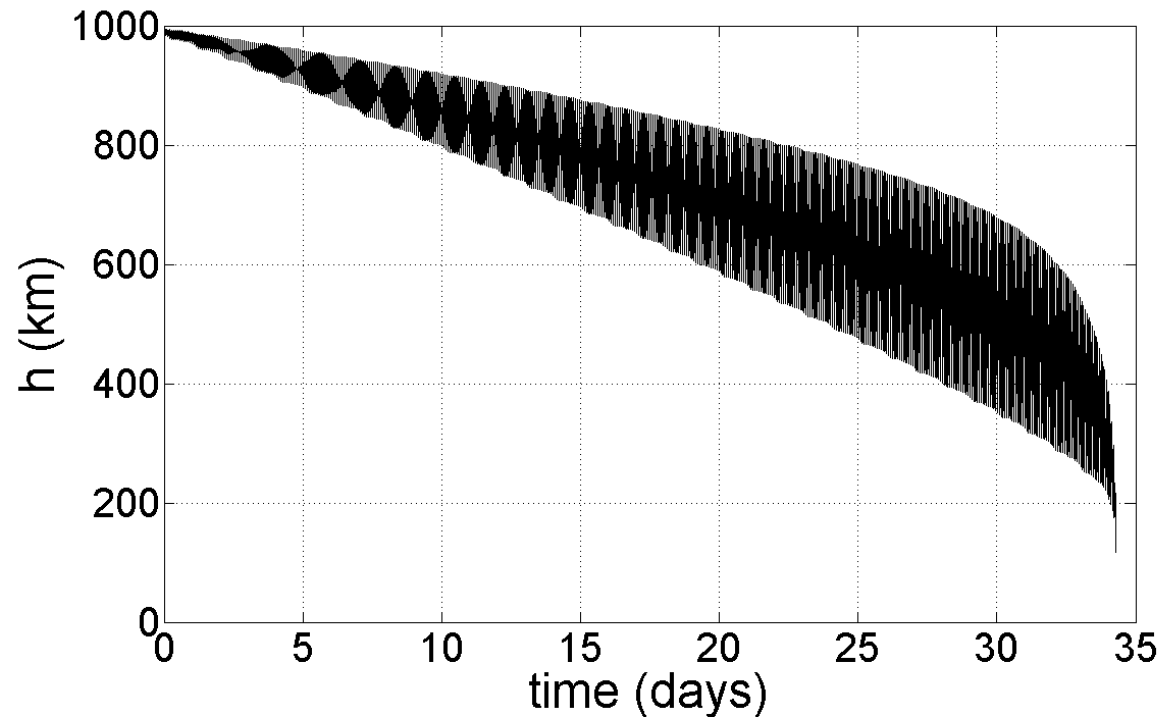
- Heaviest 2nd stage (**9 tons**)
- All members ~circular high inclination (~71 and ~98 deg) orbits with altitude around 850 km.



Zenit-2 at 845 km
altitude and 71deg
inclination, attached
to a 20-km tape EDT

Kosmos-3M upper stage family

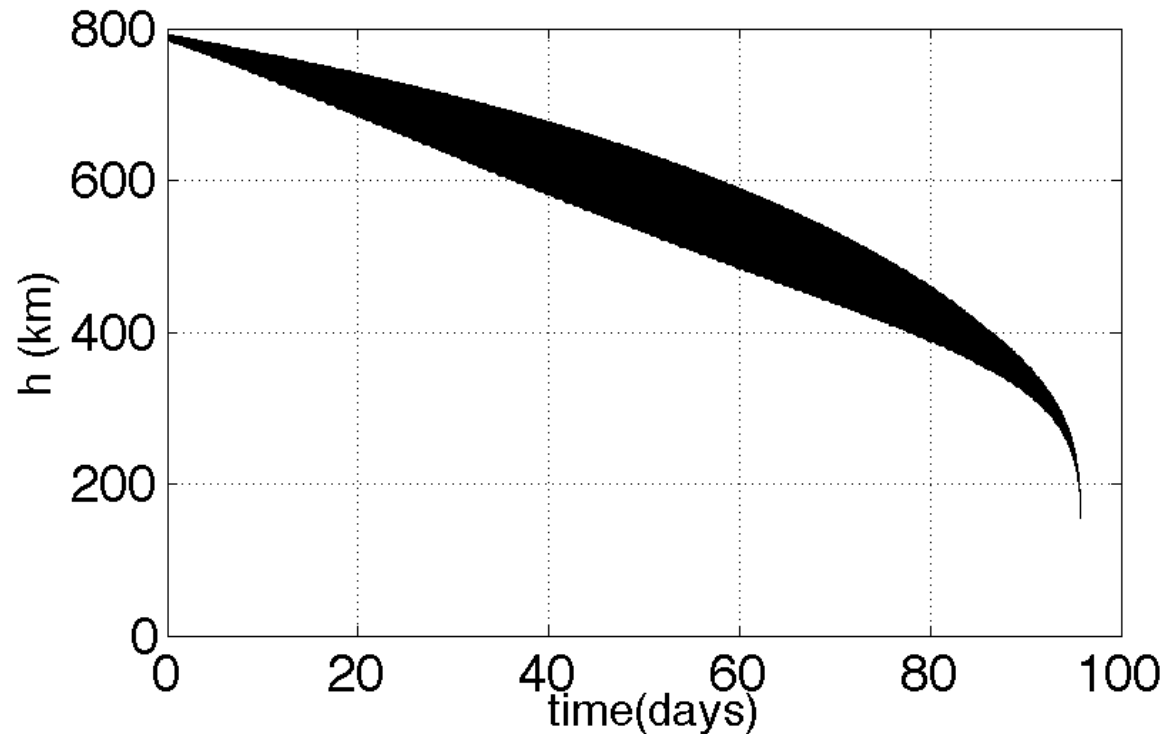
- **Most numerous** upper stage family (more than 260 members!) with **1.4 ton** mass
- All members ~circular high inclination (~74,~92 deg) orbits with altitude 700 to 1000 km.



Kosmos-3M at 986-
km altitude and
71deg inclination,
attached to a 20-km
tape EDT

Envisat

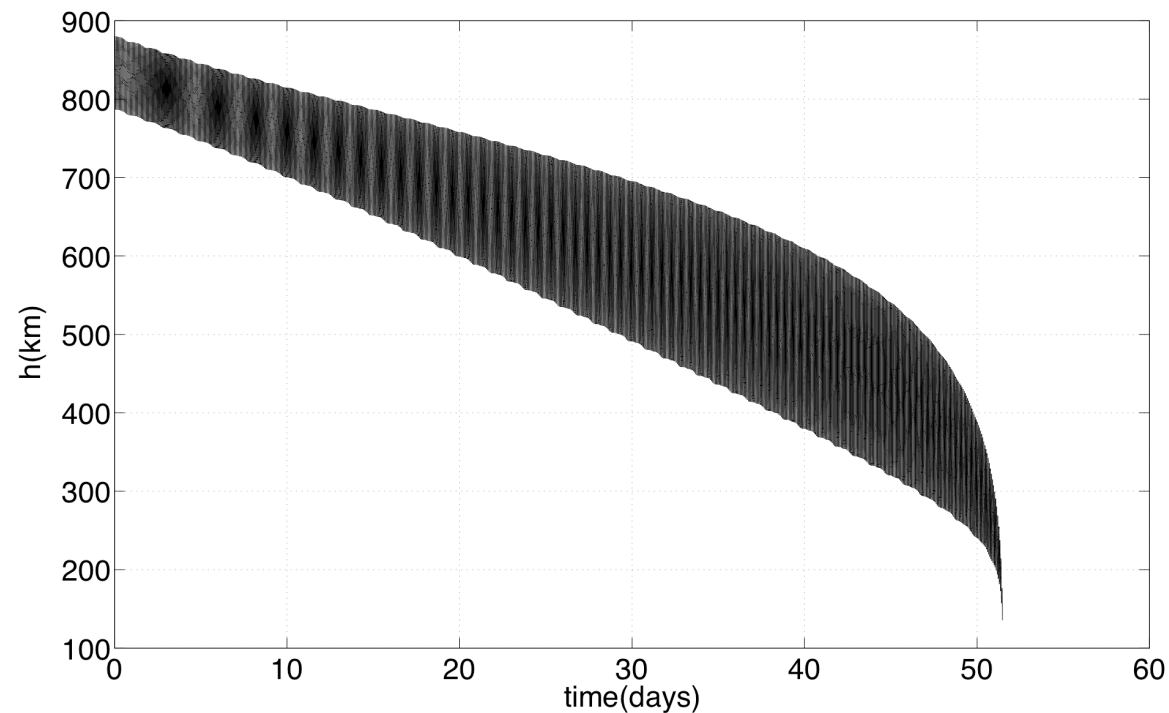
- Envisat twice-extended mission will end in 2013 with virtually no hydrazine left.
- Active removal is the only deorbiting option for this **8-ton 26x10x4.5m** spacecraft



Envisat at 784 km
altitude and 98.5deg
inclination, attached
to a 20-km tape EDT

Long March upper stage (CZ)

- China's upper stage family. Can reach up to 3.8 tonne.



CZ-2C (3800 kg)

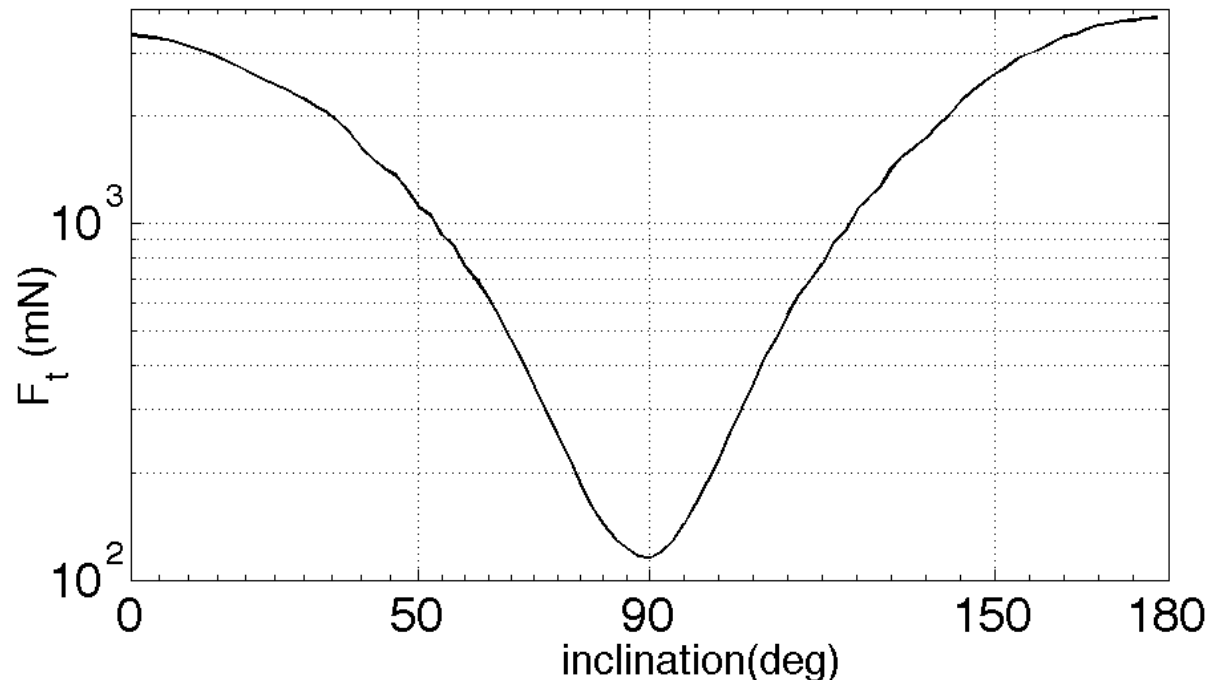
~830 km altitude

98.25 deg inclination

attached to a 20-km tape EDT

EDT Performance vs inclination

- Gravity-gradient stabilised EDT's exhibits lower performance at higher inclination ($F_t \propto B_{\perp}^{3/2}$)
- Even so performance remains competitive with low-thrust electric propulsion



Orbit-Average
tangential thrust for
a 20km EDT on a
1000-km altitude
orbits of different
inclinations

Tether collision risk

1) MICROMETEOROIDS

High survivability of tape tether achieved by a cm-wide tape with tear-stop reinforcement to stop crack propagation after μ -meteoroid impact.

2) “TECHNOGENIC” OBJECTS

- Km-size tether adds a non-negligible cross section area
- TimeArea product dramatically reduced thanks to fast deorbit capability
- However, collision risk with large-size objects demands **high maneuverability**

For a 20-km 80-kg tape tether ~ 150 mN average thrust is available in polar orbit.

This is enough to give a $\Delta z > 2\text{km}$ to a **9-ton** debris given $\Delta t_{ca} = 8\text{h}$ in LEO

Other issues

- **STABILITY:** EDTs along inclined orbits can exhibit libration instability (energy pumped into tether attitude through out of plane libration mode) eventually leading to rotation. Self-balanced EDT configurations can greatly reduce this effect but they need further investigation.
- **DEPLOYMENT:** Tethers successfully deployed in a few missions. Devising a consolidated low-risk deployment strategy will need additional effort.
- **RENDEZVOUS and DOCKING:** It is one of the main challenges of many debris removal concepts in general. A tethered structure could make things more complicated (structural oscillations) but or more simple (spacecraft sensitive parts tethered at safe distance from the target).

Conclusions

- Big size objects should be given higher priority in any effective debris removal strategy
- An average 100 mN of thrust seems to be a reasonable lower bound for dealing with the largest LEO debris
- A 20-km aluminum tape tether (80 kg tether mass) can deorbit any LEO debris in reasonable time and can be properly maneuvered in case of collision
- Performance degrades with higher inclinations but remains reasonably good compared with other strategies (eg EP)
- Issues of attitude stability and rendezvous/docking need further investigation