Propellantless deorbiting of space debris by bare electrodynamic tethers

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1. Catastrophic Collisions in Space

* The LEO region (below 2,000 km) is filled with debris from Space activity. It may end unusable

Using films, ground/space lasers to de-orbit untrackable (< 10 cm) debris ??? Unpractical

$\Rightarrow$ Just <u>catastrophic</u> collisions matter (over 40 KJoules *Impact* energy per kilogram of *Target*)

* At relative speed of up to twice orbital velocity v_{orb}, kinetic energy per unit mass

is much greater than energy per unit mass from TNT explosions

* Two events account for 36 % of all catalogued (> 10 cm) debris

and for 68 % of all big-debris conjunctions with derelict satellite *Envisat*:

Missile hit satellite *Fengyun*-1C in 2007 / *Cosmos* and *Iridium* satellites collided in 2009

One catastrophic collision might occur every 6 to 12 years

* Collision probability increases with frontal area, number of fragments with satellite mass

$\Rightarrow$ **Large satellites at high-inclination, 800-1,000 km orbits are critical**

2. Debris Mitigation Actions

* Mission design with minimum release of subsystems

* Immediate de-orbiting of *Launcher Upper-Stages* / *Multiple Payload Dispenser Systems*

* *Post-Mission Disposal* (PMD) of satellites

Just one technology, *De-orbiting*, is needed

* Debris population models suggest, however, that

the population would grow nonetheless uncontrolled (*Kessler cascade*) :

Debris-fragmentation would dominate debris elimination by re-entry into the atmosphere

over most of the 11-year Solar Cycle

* *Active Debris Removal* (ADR) is needed: Cleaning what debris already exists.

But… it requires a 2nd (*Capture*) technology, tougher than de-orbiting, raising legal issues

⇒ **Furthermore, once space is cleaned, just one technology, PMD, need be kept on**

3. An issue stands against de-orbiting heavy space-debris

* A repeatedly proved *PMD* technology could move the *InterAgencyDebrisCoordinatingCommittee* to implement *Active Debris Removal*

Testing de-orbit technology has thus become a priority matter

* But there is one issue standing against any technology other than rockets:

Small satellites (well below 1 ton, say) fully burn at reentry…

but 10% to 40% of mass of large satellites (those of critical interest) survives reentry

* It may result in damage to people if impact energy exceeds 15 Joule.

* Uncontrolled reentry only allowed if probability of damage on ground is less than 0.0001

Uncontrolled Reentries in 2012 accounted for over 100 metric tons

Risk level may be small, but re-entry would need rockets to end de-orbiting of heavy satellites

⇒ **This could make other technologies, possibly better than rockets in de-orbiting, useless**

4. The *Design for Demise* solution

* Uncontrolled reentry is shallow (1 degree incidence) like a pebble skipping over a pond

Major break up occurs at about 80 km altitude

Place of impact is unpredictable and the footprint is thin but long

* If reentry is controlled with rocket, incidence is about 20 degrees

Footprint is small, and impact, predictable, is carried into the Pacific Ocean

<u>But fuel is needed</u>

* Recently introduced *Design for Demise* has eliminated that issue:

It involves analysis of materials, structures, configuration

Regarding processes of fragmentation, ablation, fusion

Passivation of power and propulsion subsystems

$\Rightarrow$ **Rockets are <u>now</u> essential for <u>neither</u> de-orbiting nor <u>reentry</u>**

5. Requirements on any de-orbit technology

(i) Bring de-orbit time below some threshold

25 years maximum for initial orbit at critical altitudes

800-1,000 km (and 1,400-1,500 km)

(ii) Allow scalable design, reaching into multi-ton mass range

(iii) (Being economically and scientifically unproductive)

be a small mass fraction of its satellite

(**iv)** Allow maneuvers in case of long de-orbiting (to avoid large trackable debris)

(v) Be reliable: Lying dormant for years,

be ready to start operating with minimum support

There exist passive, dissipative systems, based on air drag or magnetic drag

and active propulsive systems, whether chemical – rockets - or electrical

6. Air drag / Propulsion

* Time for air-drag de-orbiting is proportional to inverse frontal area and inverse air density

Density is extremely low for altitudes of interest

Deploying a sail increases that area, reduces time, but extremely large sails would be required

for masses and altitudes of interest

* Actually, below 600 km, de-orbiting under 25 years hardly requires sail

* Rocket propulsion de-orbiting requires too much fuel mass,

fuel exhaust velocity being limited by chemistry

There are reliability issues on most propellant choices

Required “green” combustion reduces propellant choices

*** Electrical propulsion, though allowing “unlimited” exhaust velocity**

may require too large a power subsystem, and attitude control over long operations

7. Conductive *Tethers*

* A Space tether is a thin, multi-kilometers long conductive wire,

It joins satellite and some end-mass, keeping vertical by the gravity-gradient in orbit

The ambient plasma, being highly conductive, is equipotential in its own moving frame

* In the tether frame, in relative motion, there is in the plasma, <u>however</u>,

a *motional* electric field $\boldsymbol{E_m} = \mathbf{v}_{\rm orb} \times \mathbf{B} \sim 100\text{V/km}$

* This allows *Plasma Contactor Devices* to collect electrons at one (anodic) end

and eject electrons at the opposite cathodic end

to establish a current along a fully insulated (standard) tether

* The *Lorentz* force by the geomagnetic field **B** on the resulting current is always drag

A Space Tether could also work efficiently at Jupiter though not at Saturn

It relies on just thermodynamics, like air drag

8. The bare-tape optimum

* A *bare tether* concept was introduced in 1992 at Universidad Politécnica de Madrid

It takes away the standard-tether insulation

and has electrons collected over a segment coming out polarized positive (*anodic*)

It rests on advantages of 2D *Langmuir probe* current-collection in plasmas over 3D collection

* It was later shown that a tape cross-section bare tether de-orbits much faster

than a (*corresponding*) round bare tether of equal length and mass

* Tethers being long and thin, they are easily cut by abundant small space debris.

It was recently shown that the tape has a probability of being cut per unit time

smaller by more than one order of magnitude than the corresponding round tether

Further, the tape collects much more current, and de-orbits much faster,

than a multi-line "tape" made of thin round wires cross-connected to survive debris cuts

9. Requirements satisfied by Space Tethers

* They use dissipative mechanism quite different from air drag.

$\Rightarrow$ De-orbit time may be just a few months

* The 3 disparate tape dimensions allow easily scalable design

* Tape tethers are much lighter than round tethers of equal length and perimeter,

which can capture equal current

* Switching the remaining cathodic *Plasma Contactor* off-on allows maneuvering

* Lorentz braking, being just thermodynamics, is as reliable as air drag

* Tethers are still effective at high inclinations, where the $\boldsymbol{E_m}$ *field* is small and changes direction

because **B** is not a dipole along the Earth polar axis

The tape-tether can survive debris comparable to its width, which is much less abundant than debris comparable to the radius of the corresponding round tether

10. BETs is the European Commission FP7/ Space Project 262972

- Financed by the *EC* in about 1.8 million euros
- Duration 36 + 3 months, from 1 November 2010
- It carries out *Research / Technology Development* on using Tethers to de-orbit space debris
- Coordinated by Universidad Politécnica de Madrid
- Partners:
- Università di Padova
- ONERA
- Colorado State University
- *Emxys*
- DLR – Bremen
- Fundación Tecnalia

11. In-orbit demonstration ??

* BETs carried out work: On designing, building, and testing basic subsystems hardware:

Cathodic Plasma Contactor

Tether Deployment Mechanism

Power Control Module

Tape with cross-wise and longitudinal structure

* On testing current collection. On verifying tether dynamical stability

* On preliminary design of length, width, thickness of the conductive segment in a generic mission, conducive to low both system-to-satellite mass ratio <u>and</u> probability of tape cut by small debris

* On determining an ohmic-effects regime of tether current that reduces the probability of catastrophic collision of big debris and the S/C being de-orbited

$\Rightarrow$ **At Technology Readiness Level 5, BETs appears ready for in-orbit demonstration**