CHAPTER 51

BETs: Propellant less deorbiting of space debris by bare electrodynamic tethers

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ABSTRACT

As a fundamental contribution to limiting the increase of debris in the Space environment, a three-year project started on 1 November 2010 financed by the European Commission under the FP-7 Space Programme It aims at developing a universal system to be carried on board future satellites launched into low Earth orbit (LEO), to allow de-orbiting at end of life The operational system involves a conductive tape-tether left bare of insulation to establish anodic contact with the ambient plasma as a giant Langmuir probe The project will size the three disparate dimensions of a tape for a selected de-orbit mission and determine scaling laws to allow system design for a general mission It will implement control laws to restrain tether dynamics in/off the orbital plane and will carry out plasma chamber measurements and numerical simulations of tether-plasma interaction The project also involves the design and manufacturing of subsystems electron-ejecting plasma contactors, an electric control and power module, interface elements tether and deployment mechanisms, tether tape/end-mass as well as current collection plus free-fall, and hypervelocity impact tests

ACHIEVED RESULTS

The BETs project focuses on an activity explicitly recommended in the topic 'preventing generation of **new** debris **after mission completion**', based on the FP7- Space 2009 Call The project thus ignores mitigation measures and surveillance programmes such as ESA's Space Situational Awareness, as well as debris already accumulated in space Work to be carried out would be **Research and Technology Development** of a de-orbit system, which, in the near future, should be carried on board every spacecraft launched into LEO A dedicated system is needed because satellites naturally orbit at ionospheric altitudes where air drag is very weak

The system considered will deploy a conductive thin-tape bare-tether to collect electrons as a giant Langmuir probe, requiring no propellant and no power supply, and thus generating power on board The system involves magnetic drag on current flowing along the tether Like air drag, magnetic drag is a dissipative mechanism arising from the orbiting-tether motion relative to the co-rotating magnetised plasma, which induces a so-called motional electric field $\bar{E}_m$ at the ambient plasma, in the frame of the tether That field drives current into the tether, and the geomagnetic field then exerts a Lorentz force on the current-carrying tether Tether drag is passive like air drag and propulsive like rockets and electrical thrusters

The scientific/technological objectives of the project are to prove that a tether system capable of de-orbiting could beat alternative systems (air-drag enhancing sails, rockets, electrical thrusters) in simplicity and the combined basic metrics Frontal area x de-orbit time and system-to-satellite mass ratio The project was to consider de-orbit altitudes from 800 to 1 000 km, for a range of orbital inclination and satellite mass A prototype tether would be designed, built and tested on the ground, for de-orbiting a representative mass/orbit satellite Approximate scaling laws would then be determined to adapt results to a broad range in those satellite parameters

NASA tethers TSS1, TSS1R were fully insulated round wires that carried anodic and cathodic contactors at corresponding ends The cathodic device was a hollow cathode, a type of highly efficient, electron ejecting plasma contactor The anodic contactor was a large spherical conductor of a radius of 0 8 m that is very large compared to both Debye length and electron thermal gyroradius, which are about 5 mm and 30 mm respectively This makes the sphere highly inefficient in collecting ambient electrons

In the early 1990s the **bare tether** concept introduced collection with two characteristic lengths (Ref 1) The tether itself, left un-insulated, was to collect electrons in a 2D-OML regime over some segment coming out positively biased A characteristically small radius $R \sim 1$ mm allows efficient collection in cylindrical geometry In turn, a quite large tether length L provides a big collecting area The 2D-OML current-collection rate is proportional to L, to cross-section perimeter $p = 2\pi R$, and to the square root of bias With bias varying along the tether, collection rate varies too

For *R larger* than some value R_{om} comparable to the Debye length, current collection drops below the OML value Also, the current inside the tether can actually be limited by ohmic effects For dominant such effects, the length-averaged tether current approaches the short-circuit value $\sigma_c E_m A_t$, where σ_c is the electric conductivity, At = πR^2 is the cross-section area, and E_m the motional-field component along the tether Ohmic effects are dominant under condition L >> $l^{1/3} (2A_t /p)^{2/3} = l^{1/3} R^{2/3}$, where $l \propto \sigma_c^2 E_m / N_e^2$ is a certain ambient-dependent characteristic length

A fundamental result from Langmuir probe theory shows that 2D-OML current collection is equal for all non-concave cross sections of equal perimeter (Ref 2) This allowed introducing collection with three characteristic lengths Consider in particular a thin-tape tether of width w and thickness $h << w$, thus having $A_t = why$ and $p \approx 2w$ (and an 'equivalent' radius $R_{ed} = w/4$ with regard to OML collection validity) A 'corresponding' round tether of equal length and mass would have a radius of $R = \sqrt{wh/\pi}$ Collection will thus be greater for the tape in the large factor $\sqrt{w/\pi h}$ Also, the ratio $2A_t /p$ ° h for the tape is much smaller than its value R for the corresponding round wire, typically, the wire does not reach the ohmic-dominated limit

Results

The work package (WP) breakdown consists of four large primary WPs

PWP10 **System Analysis and Trade-off** (work packages 11 through 15),

PWP20 **System Design** (WP21 (subdivided in WP211 through WP213), 22, and 23),

PWP30 **System Manufacturing** (WP31 (subdivided in WP311 and WP312), 32 and 33),

PWP40 **System Tests** (WP41 through WP44)

Furthermore there are also three simple primary work packages

PWP50 **Analysis of Results** (WP51 and WP52),

PWP60 **Management** (WP61), and

PWP70 **Other Activities** (WP71 through WP73)

So far just work on PWP10 and PWP20 was carried out over the first year of the project

System Analysis and Trade-Off (PWP10)

WP11, 12:

Two significant results from analysis showed ED tethers in a very positive light for de-orbit operations First, detailed de-orbit calculations using a full geomagnetic field model showed that tether performance at high inclination orbits is much better than usually estimated from using simple field models This proves critical to tether use as considered here because of the large number of satellite missions at inclination higher than 80 °

Second, the probability of survival from impacts by space debris can also be much higher than usually estimated Impact by a piece of debris may cut a tether, if its size is large enough The fatal impact rate for a thin-tape tether, which involves two widely different cross-section lengths, was proved much lower than the rate for a round tether of equal length and mass Both ESA (MASTER) and NASA (ORDEM) debris-flux models were used in the analysis Since de-orbit duration will also be shorter for the tape because of current collection being generically greater due to its larger perimeter, the fatal impact count may be smaller by over two orders of magnitude

This will allow to stick to a single-line tether-system design Furthermore, possible material degradation due to multiple impacts by (abundant) very small debris pieces, which are too small to cut the tether, was proved negligible All of the above allowed establishing convenient design ranges on de-orbit duration and **tether system-to-satellite** mass ratio If the duration is too long, corresponding to very low mass ratio, survival to debris might be in danger If the mass ratio is too high, corresponding to very short de-orbit operation, a rocket system might be lighter

Two basic effects in cathodic and anodic contact are being considered New materials having work function as low as 0 6 electronvolts allow for tether systems that are fully passive, with no need for a hollow-cathode plasma contactor The wire itself, if conveniently coated, would act as both anode (collecting electrons in the **bare-tether** concept along the segment coming out positively biased) and cathode, ejecting electrons by thermionic emission along the segment negatively biased In turn, simple estimates of adiabatic electron trapping in electron collection, when the ion ram motion relative to the orbiting tether is considered, are being studied as complement to the numerical simulations and laboratory experiments

WP13, 14:

A CPU-efficient tether dynamics model (LIBRA) has been developed to analyse stability limits of a tether during de-orbit and to subsequently develop control strategies to stabilise the system, which, without control, exhibits a librational instability that manifests itself after a few days of de-orbiting at representative values of system parameters Stability limits have been identified vs key system parameters, such as orbital inclination and ratio between gravity-gradient and tether-drag forces

Three different options of control strategies have been analysed (a) tether current control, (b) using a stabilising inert tether, and (c) adding a libration damper at the tether attachment point Each option, if suitably implemented, could provide stability for a complete de-orbit of the system for different orbital inclinations These encouraging results are to be verified with a more refined computer code that includes tether flexibility (FLEX) This code was validated through test cases and frequency analysis of vibrational modes Both computer codes incorporate up-to-date environmental models gravity field, magnetic field, ionospheric density model, and atmospheric density model

Orbital scenarios that represent large classes of spacecraft that will need to be deorbited were identified and this served as the basis for parametric analysis (Ref 3) The CPU-efficient code has been used to study parametrically the de-orbit rate for representative scenarios The two computer models have been used, whenever appropriate, to carry out these analyses The three control options derived were also coded into the FLEX code to simulate the control options under more realistic dynamical conditions

WP15:

Both numerical simulations using the SPIS code developed at ONERA (Ref 4) and experimental measurements using its JONAS plasma chamber were carried out to determine current collection by a positively biased cylindrical tether moving relative to plasma under LEO environmental conditions A first measurement campaign yielded current-voltage tether characteristics for different LEO conditions, varying plasma density, and ion ram energy To compare the results with the OML theory, a second experimental campaign monitored the spatial evolution of plasma properties around the tether using Langmuir probes and a triple probe (developed in the frame of this project and successful in determining low plasma density). Probe measurements showed tether current oscillations at the electron plasma frequency and oscillations of both tether current and ambient plasma density at the ion frequency.

Results from SPIS simulations for the current-voltage response of three different Langmuir probes yielded plasma parameters and allowed to compare the OML theory to current-voltage characteristics from the first experimental campaign. First results currently do not show a significant deviation from the OML theory. SPIS simulations were also carried out to understand the origin of the oscillations above.

Unsuccessful simulations led to code improvement with enhanced boundary conditions, and a time scenario to rapidly enhance ion convergence while keeping possible electron oscillations. This permitted simulating current collection by a tether in LEO at high positive bias. First results show oscillations at the electron plasma frequency but it is presently not yet clear whether their origin is numerical or physical. At the moment, no significant deviation from the OML theory has been found. Additionally this work does not impact other work packages.

System Design (PWP20)

WP 22:

The task of designing the control system in charge of electrically driving the tether involves both power electronics and control issues, as such a system must deal with a changing load impedance and extremely high external potentials in the plasma-tether interface during the de-orbit operation. During this first year, the most suitable architectures for the power stage and their appropriated control topologies were identified after a deep trade-off survey (Ref.5). A complete system level layout has been designed down to component-level, mostly involving the power stage, where extensive simulations were performed to validate the design concepts. Final implementation details remain to be defined in rounding up the design process, such as those concerning the control loop.

A first approach for mass and volume estimations has been performed, considering identified power semiconductors and estimated requirements of the magnetic components. This approach will be refined to a definitive set of requirements during the second period. An important effort was made to adapt electrical parameters coming out from tether physical processes to the requirements of the electrical system, mostly in terms of output impedance and bias voltage at the tether connector. This task is relevant to the goal of identifying and properly defining the operational requirements of power supply in terms of maximum voltage/current.

WP23:

Experience in the reliability and lifetime of hollow-cathodes was reviewed, although most experience relates to use in electric propulsion, where they are at the core of generated thrust or drag. For tethers, they just act as 'neutralisers', and could actually disappear as subsystems in case low work function coating is available. Furthermore, in EP the HC requires both neutraliser and power supply, which is not the case for tethers The anticipated maximum lifetime of the BETs plasma contactor is ~ 300 days or 7 200 hrs Hollow cathodes have operated for over 1 200 days The BETs HC will utilise porous tungsten inserts impregnated with barium-calcium aluminate

The key aspects of a Hardware In the Loop (HIL) evaluation scheme were defined that would combine any number of Hollow-cathode Assembly (HCA) sub-systems as well as a simulated tether in a variety of potential operating circumstances Once all subsystems have been independently developed and tested, they will be combined in a realistic testing environment, evaluating and verifying their interdependent operation During HIL testing, electrical signal interference, on/off transients, power supply performance and interaction, proper HCA start-up and operation, verification of measured plasma parameters, control analysis and scaling and tether operation impact on the HCA system, will be considered

HCA design and analysis include structural design of a hollow cathode and a discharge chamber that utilises a ring-cusp magnetic field to enhance plasma production and reduces the impedance between plasma contactor and low density ionospheric plasmas (Ref 6) The plasma contactor also requires an expellant storage and delivery (ES&D) subsystem that can deliver xenon gas to the cathode and discharge chamber for the duration of the mission Components include the HCA with a ring-cusp discharge chamber, the ES&D subsystem, and the power controller system (PCS) A flight PCS would operate the plasma contactor and the flow control valves It would also include data collection capability, a controller as well as communication links to the spacecraft bus

WP213:

A state of the art survey was carried out to provide an overview of already existing deployment mechanisms, in particular completely passive mechanisms that could be adapted to every satellite system Deployment would start at the end of satellite life with just one signal and no control from the satellite, such as data handling and power supply, which would be required during the unreeling process Next, effects from environmental parameters on the functionality of the deployment mechanism were theoretically analysed This showed that passive deployment is both very hard to realise and highly dependent on environmental parameters

In a second step several deployment concepts were developed based on the existing experience at DLR (Ref 7) They differed in how the tether is stored, in unreeling basics, and in end-mass separation All those concepts have been realised in bread-board units for deployment tests under different conditions These tests were carried out to study tether unreeling behaviour, to compare different storage possibilities, and to record and analyse the required pull force at tether release and during its deployment Based on test results, an evaluation of the concepts was done This evaluation showed that deployment from a reel presents the best characteristics for a passive deployer as well as the lowest risk in tether behaviour during deployment, such as tether entanglement or twisting

The best rated deployment mechanism was chosen for final design in CAD The mechanism consists of end mass, which will be ejected smoothly with separation springs that pull the tether from the reel, the separation springs, the reel on which the tether is reeled, a centrifugal break to ensure that the unreeling speed does not exceed a predetermined value, a launch lock and a shell for the entire mechanism

WP211:

Work has been carried out in defining the tether design concept, both with regard to cross-section and lengthwise structures Tape tether materials have been preselected and tensile tests performed The cross-section structure of the tape core is made of ALPET 102510 (Ref 8) Samples of this material have been mechanically tested and analysed by means of SEM images It comprises three different layers the core, which is 25–28 µm thick and manufactured in PET (a thermoplastic polymer resin), is sandwiched by external aluminium layers of 10–12 µm thickness and tape width of 25 mm Material procurement has started

The connectors of the tape tether with both end-mass and satellite have been designed and tested Tape tether insulation in the segment next to the satellite and in the triple-point junctions has been carefully studied The lengthwise structure is as shown in the figure (from the first BETs Periodic Report)

CONCLUSIONS

Important basic results for tether deorbiting already established are (i) performance at high-inclination orbits proves much better than usually estimated, and (ii) survivability to debris impacts greatly increases in moving from round tethers to thin-tape tethers of equal length and mass, this applies both to a single-impact tether cut by large enough debris and to material degradation due to nearby multiple impacts by abundant, very small debris

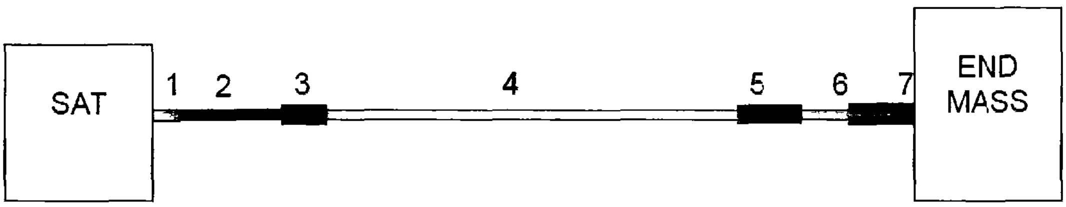

Figure 1.

1. Conducting joint between Al connector — ALPET, shielded/reinforced by Kapton
2. ALPET(w25 mm) insulated by Kapton/Mylar/Coating(w35–40 mm) Length 220 m (ProSEDS) Coating to avoid ATOX problems CCOR
3. Triple point Aerodag G Length 150–300 mm
4. Bare ALPET, Length 5 km
5. Insulation Al removing + CCOR Length 30–40 mm Triple point Aerodag G Length 150–300 mm
6. ALPET, non conducting Length 300 mm
7. Same as at 1

High tether survivability will allow use of single-tether systems It will also allow establishing broad ranges for **tether system-to-satellite** mass ratio and de-orbit duration If the mass ratio were too low, it would lead to long duration and high debris risk, if it were too high it could make the tether-system heavier than a de-orbit rocket system This has a deep effect on designing a tether system, which is made of the tether itself and auxiliary subsystems (deployer, power module, hollow cathode) A **rule of thumb** would require total system mass not to be larger than three times the tether mass This places constraints on the mass of subsystems

A de-orbit mission representative in satellite mass, altitude and inclination orbit, had been first searched for in order to carry out detailed design, manufacture, and tests of an optimum de-orbit tether system Finally, however, focus has moved to a de-orbit mission at 1 300 km altitude, 65 degree inclination, and mass of order of 500 kg (similar to GMES **Jason cs**, planned by ESA for the near future, with a commitment to de-orbiting within some limited span of time from end of life) This will conveniently force critical assessment in evaluating subsystems, and will require some degree of systems integration A light demo flight will be considered in parallel

Both dynamic modelling and simulations/chamber tests of current collection are well advanced Design is continuing in the first half of the second year

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