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PERFORMANCE ANALYSIS OF BARE ELECTRODYNAMIC TETHERS AS MICROSAT DEORBITING SYSTEMS

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It has recently been proposed to use bare electrodynamic tethers (EDTs) in connection with micro- and nano-satellites, either to provide a cheap test of OML current collection theory or to devise a lightweight deorbiting system for cubesats experiments. In the present article we investigate the orbital evolution of small satellites (2 kg) equipped with electrodynamic tethers of different lengths (100 m to 300 m) different ionospheric conditions and focusing on a nominal VEGA polar orbit of 700 km altitude. Issues of tether integration in the microsatellite system and tether deployment are also addressed. Results show that, given sufficient power availability and once a safe and effective deployment strategy is devised, a small dedicated experiment involving two cubesats is feasible in favorable conditions with tether length of 100-300m.

INTRODUCTION

In spite of the limited mass and volume resources cubesats are a very attractive option to perform space experiments at a considerabily reduced budget. Several cubesats designed by research institutions including universities and small companies have been launched into orbit giving the possibility to students around the world to be directly involved with space missions.

Among the different possible experiments which can be carried on board of a cubesat/microsat it has been suggested to include the operation of a small electrodynamic tether (EDT) [1]. An Electrodynamic tether (EDT)[2] is a space apparatus which can supply power and/or propulsion to a spacecraft by exploiting the electromagnetic interaction of a conducting cable orbiting around a planet with a magnetic field and reasonable plasma density. As such interaction occurs without the need of expending fuel EDTs can be used as propellantless propulsion systems of great interest in space technology. Since EDTs can work in passive mode, i.e. without the need of onboard power supplies* for deorbiting a satellite to which they are connected, it is reasonable to think that they could work onboard cubesats provided that efficient contact with the plasma is established and a simple and safe tether deployment mechanism is devised. It is in fact crucial, when dealing with EDTs to be able to deploy a sufficiently long tether, being the performance in terms of deorbiting acceleration dependent on the 5/2 power of the overall tether length neglecting ohmic effects.

In addition to the aforementioned experiment it has even been proposed to adopt relatively short (100m) bare electrodynamic tethers as deorbiting devices for cubesats carrying their own experiments [3]. In the proposed design the limited mass and volume availability drove the design towards

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*when short tethers are considered, however, a minimum power is required in order to drive electrons through the cathodic plasma contactor for ejection a floating tether assembly, i.e. an EDT without cathodic plasma contactors hence reducing the extent of the anodic section of the tether and providing orders of magnitude smaller current. Unfortunately for both the aforementioned applications the results listed could not be reproduced.

In an attempt to provide a more comprehensive -although still preliminary- analysis of such mission typologies we have performed a broad simulation campaign considering different tether lengths, cross section shape, and orbital conditions. The current collection in the bare electrodynamic tether has been modeled with orbital motion limited (OML) theory. In order to reduce computation time the analytical approximation for the EDT current provided by reference [4] has been employed. The plasma electron density was computed according to the IRI2007 model while an IGRF95 model for the Earth magnetic field has been employed. Orbital perturbation due to geopotential harmonics and atmospheric drag were not included and will be considered in a more refined analysis in the future. Issues of tether integration with the spaceraft and possible deployment strategies including tether librational motion stability and influence on the deorbiting performance of the system are discussed.

One point which has been, for the time being, left out from the analysis, is the issue of limited power availability for the cathodic plasma contactor. We here assume that the potential drop at the cathod is entirely compensated by a power supply available on the cubesat. In reality, it is reasonable to expect that this will not be the case, and the maximum tether current will be power-limited. As miniaturized hollow cathod have not yet been developed for cubesats it is still difficult to precisely assess the influence of such constraint.

EDT CUBESAT MISSION DESIGN ISSUES

Mass, volume and power availability is limited on a cubesat, which makes the design and integration of a cubesat payload particularly challenging. For every cubesat employed in the experiment a volume of 1 liter, a 1 kg of mass and not more than 2-3 W of power are available. A thin aluminum tape of 1-5 cm width having the smallest possible thickness and the largest possible length makes best use of tether mass and offers orbital motion limited (OML) or quasi-OML[†] current collection. Taking 0.05 mm as a reasonable lower bound for tape thickness and dedicating 750 g of mass budget to the tether alone we obtain a maximum of 111, 185 and 277 m length for a tape tether of 5, 3 and 2 cm width, respectively. Longer tethers may be too difficult to deploy with a cubesat where controlled deployment systems flown on previous tether missions would be very hard to integrate in the satellite. For this reason we suggest deploying a folded tape tether (as proposed for the upcoming JAXA experiment [5]) in an open-loop fashion and having the required momentum provided by a spring. In order to increase the performance on high inclinations orbits as well as for redundancy reasons we propose to include two cathodic contactors (miniaturized hollow cathods or field emission systems can be used) one at each tether end.

One important issue revolves around the tether attitude stability and control. Simplicity of design and operation favours a gravity gradient stabilized system with the tether constantly lying along the local vertical. This configuration provides maximum electrodynamic drag performance for systems in equatorial orbit, while for high inclination orbits the situation is more complex. Reaching a minimum-oscillation local-vertical-stabilized system at the end of the deployment is unfeasible with a simple open loop deployment strategy although it might be possible to limit the magnitude of the libration motion with properly selected initial conditions and/or to later damp the residual librations

[†] strictly speaking the tape width should not exceed 4 times the Debye length of the surrounding plasma

by proper modulation of the electrodynamic torque. Libration electrodynamic instability during operation is also critical as it is known that Lorentz torques along inclined orbits gradually deposes energy in the tether in- and out-of-plane pendulum motion. As the restoring gravity gradient torque is very small for a light and relatively short cubesat tether system it might be very hard to stabilize the system. A self-balanced tether design with an accurate placement of the system center of mass can solve the problem for single-cathode systems but not when two cathods are used as the center of application of the Lorentz force changes according to the direction of the current. These issues will not be dealt with in the present article where we will make the assumption the the tether is contantly lying on the local vertical. Future studies will be needed to assess the magnitude of the librational motion and the implications for the deorbiting capability of the system.

DYNAMIC MODEL

After indicating with m the total spacecraft mass the time evolution of the orbit semimajor axis a under the tangential perturbing force F_t obeys Gauss equation:

$$\frac{da}{dt} = \frac{2a^2 v_{sc}}{\mu_E}\frac{F_t}{m} \tag{1}$$

where μ_E is the earth gravitational constant and v_{sc} the spacecraft velocity. If we assume that the orbit evolves while remaining almost circular (typical CubeSats missions employ circular orbits of different inclinations) Eq. (1) can be replaced by:

$$\frac{dr}{dt} = \frac{2r^{3/2}}{\mu_E^{1/2}}\frac{F_t}{m}$$

Besides, since the electrodynamic drag is expected to be the dominant perturbations all others will be neglected.

When correct contact with the surrounding plasma is established[‡] the Lorentz force $\boldsymbol{F}$ generated by the electrodynamic tether obeys:

$$\mathbf{F} = I_{av} L(\mathbf{u}_t \wedge B) \tag{2}$$

where L is the tether length, I_{av} the current averaged over the tether length, $\mathbf{u}_t$ the tether line unit vector and $\boldsymbol{B}$ the local magnetic field.

Following the work of Bombardelli et al. [4] the maximum[§] average current flowing through an EDT with tether under orbital motion limited current collection, can be written, in the hipothesis of small ohmic effects, as:

$$I_{av} = \frac{3}{5}\eta_{th} I_{ch} \tag{3}$$

[‡]other than bare tether anodic contact this requires that a hollow cathod be placed at each tether end

[§]this corresponds to the assumption of zero potential drop at the cathod where I_{ch} is the characteristic tether current and η_{th} is the thrust ohmic efficiency . For a thin tape tether of width w the former is equal to:

$$I_{ch} = \frac{4w}{3\pi} N_e \sqrt{\frac{2E_t}{m_e} q_e^3 L^3}, \tag{4}$$

where N_e is the local plasma electron density, q_e and m_e the electron charge and mass, respectively, and where E_t is the projection of the local motional electric field along the tether line[¶].

$$E_t = |[(\boldsymbol{v}_{sc} - \boldsymbol{v}_{pl}) \wedge \boldsymbol{B}] \cdot \boldsymbol{u}_t| \tag{5}$$

with $\boldsymbol{v}_{sc}$ and $\boldsymbol{v}_{pl}$ indicating the spacecraft and plasma velocity vectors, respectively, and $\boldsymbol{u}_t$ the tether line unit vector. For small ohmic effects, as in the present case, the thrust ohmic efficiency can be accurately evaluated with the following formula:

$$\eta_{th} \simeq 1 - \frac{3}{8}\epsilon, \tag{6}$$

Where ϵ is the ratio between the tether ohmic impedance and the equivalent plasma impedance:

$$\epsilon = \frac{4}{3\pi} \sqrt{\frac{2q_e^3}{m_e}} \frac{N_e L^{3/2}}{\sigma h E_t^{1/2}}, \tag{7}$$

with σ indicating the tether conductivity and h the tether thickness.

Eq. 2 can be compacted in one formula by use of Eq.s (3-6):

$$\boldsymbol{F} = \frac{4\eta_{th} w}{5\pi} N_e B \sqrt{\frac{2q_e^3 E_t L^5}{m_e}} \left(\boldsymbol{u}_t \wedge \boldsymbol{u}_B\right), \tag{8}$$

with $\boldsymbol{u}_v$ and $\boldsymbol{u}_B$ indicating the instantaneous velocity and magnetic field unit vectors, respectively.

Finally, in the hypothesis that the tether is constantly aligned with the local vertical ($\boldsymbol{u}_t \equiv \boldsymbol{u}_r$) the orbit decay equation yields:

$$\frac{dr}{dt} = -\frac{8}{5\pi} \frac{\eta_{th} w N_e B_\perp r^{3/2}}{m \mu_E^{1/2}} \sqrt{\frac{2q_e^3 E_t L^5}{m_e}} \tag{9}$$

where $B_\perp$ is the modulus of the local magnetic field component orthogonal to the orbit. The motional electric field E_t for our tether constantly aligned with the local vertical can be developed as:

$$E_t = \left|\boldsymbol{B} \cdot (\boldsymbol{v}_{sc} \wedge \boldsymbol{u}_r) + \boldsymbol{B} \cdot (\boldsymbol{v}_{pl} \wedge \boldsymbol{u}_r)\right|, \tag{10}$$

which, neglecting the plasma velocity, yields:

[¶] we assume that two hollow cathodes, one at each tether end, are used

$$E_t \sim B_\perp v_{sc} = B_\perp \sqrt{\frac{\mu_E}{r}} \tag{11}$$

Eqs. (12-11) shows that a sufficient and necessary condition to produce electrodynamic drag for a local-vertical-stabilized EDT is that there exist a non-zero component $B_\perp$ of the magnetic field orthogonal to the orbit. After substituting Eq. (11) into Eq. (9) the final orbit decay equation yields the simple form:

$$\frac{dr}{dt} \sim -\frac{8}{5\pi}\sqrt{\frac{2q_e^3}{m_e}} \times \frac{\eta_{th} w L^{5/2} N_e B_\perp^{3/2} r}{m\mu_E^{1/4}} \tag{12}$$

CUBESAT CARRIERS

Vega

The VEGA launcher program is a response of the European Space Agency to the need of placing small size satellites in Low Earth Orbit and its qualification flight (maiden flight) is scheduled for early 2011. The VEGA mission range spans across orbits with altitudes up to 1500 km and inclinations of 5 degrees up to sun-synchronous. The reference orbit is a polar circular 700-km-altitude orbit although the maiden flight orbit will be a 71 deg inclination elliptic orbit with 354 km and 1447 km perigee and apogee altitudes. VEGA is suitable for launching CubeSats as secondary payload. This capability will be demonstrated in the qualification flight when nine CubeSats built by European Universities will be flown. The CubeSats, each of them weighting no more than 1 kg, will be accommodated in three Poly-Picosatellite Orbital Deployers (P-POD) which are to be mounted on the payload interface of Vega's upper stage (AVUM). Each CubeSat will be deployed into a high inclination, low Earth orbit, and is expected to operate in orbit for up to one year using a small ground station based at its respective university. As it is expected that CubeSats arrays will fly as VEGA secondary payload on a regular basis, we will take the nominal VEGA orbit as a main reference for our simulations.

Polar Satellite Launch Vehicle

The Indian Polar Satellite Launch Vehicle ha already placed CubeSats into orbit. In the first cubesat launch, on April 28 2008, 6 CubeSats were launched in a sun-synchroundous 720 km altitude 98.5 deggree inclination orbit. Another batch of CubeSats was successfully launched in a similar orbit on September 23 2009 while two more CubeSats will be launched later this year.

Minotaur-I

The U.S. Minotaur-I launcher has successfully placed 4 Cubesats in circular orbit with about 460-km altitude and 40 degrees inclination on May 19th 2009.

Dnepr

The Russian DNEPR launcher has carried out only one succesfull launch involving CubeSats on April 17th 2007. The final orbit was a sun-synchronous circular orbit with about 700 km altitude and 978 degree inclination

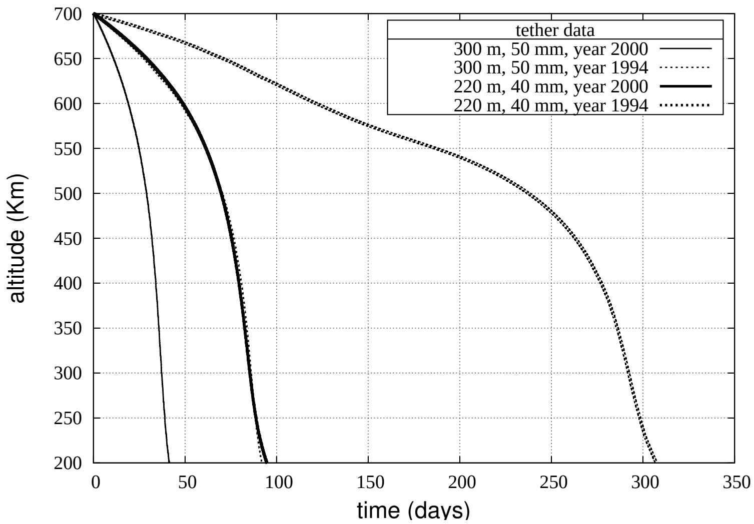

Figure 1. Deorbiting performance of two different EDT designs on a 700 km circular polar orbit under maximum and minimum solar illumination conditions

DEORBITING PERFORMANCE

Eq. (12) has been integrated numerically with different tape electrodynamic tether designs and different orbital conditions. The total system mass is always set to 2 kg, that is two CubeSat are employed. A typical EDT orbital decay curve is depicted in Figure (1) for a VEGA-like polar orbit and considering tethers of different lengths and width. Note that in this as in the following plots as aerodynamic drag is not included in the present model the last part of the decay curve does not accurately represent the cubesat dynamics. Nevertheless, since this has a small influence on the system orbital lifetime the model simplification is reasonable. Figures (2) and (3) show the influence of the tether design parameter on a polar orbit CubeSat lifetime. Finally Figures (4) and (5) highlight the influence of orbital inclination.

CONCLUSIONS AND RECOMMENDATIONS

We have evaluated the performance of a dual-cathode tape electrodynamic tether system as a 2-CubeSat deorbiting system. In our preliminary analysis only circular orbits were considered and the tether was assumed constantly lying on the local vertical. Tether length, orbital inclination and solar illumination conditions were seen to greatly influence the system orbital lifetime. Future studies will be focused on the key issue of cathodic contactor design and power requirement as well as tether attitude stability and deployment dynamics. It is expected that the limited availability of power on board the cubesat will considerably reduce the cathodic contactor performance which, in turns, will provide less available current with consequent degradation of the actual deorbit performance. For this reason, the development of efficient and low-bias cathodic emission devices remains a crucial point towards the development of a successfull cubesat EDT mission.

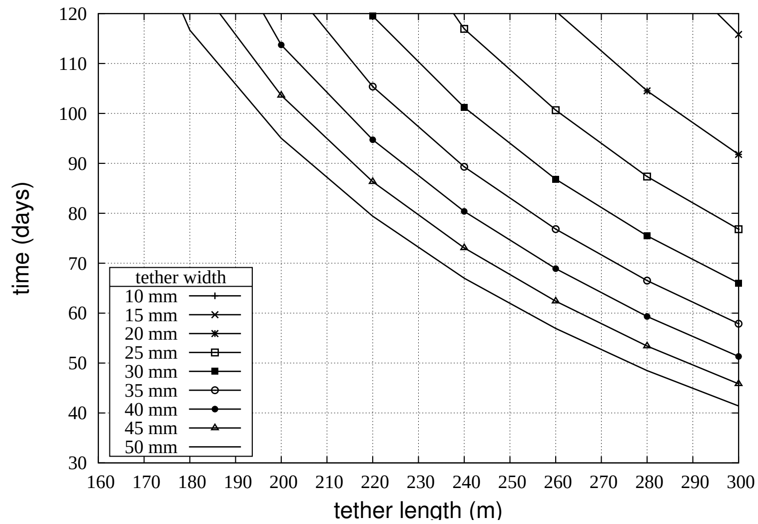

Figure 2. Influence of EDT design parameters on the deorbiting performance under maximum solar illumination conditions

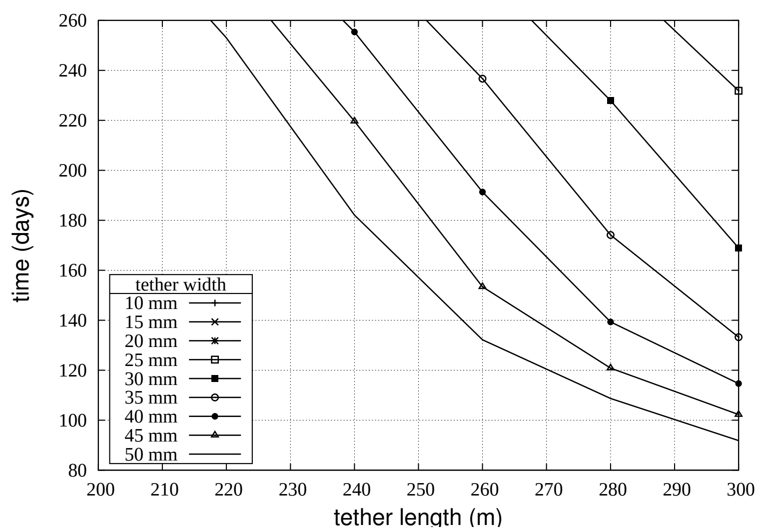

Figure 3. Influence of EDT design parameters on the deorbiting performance under minimum solar illumination conditions

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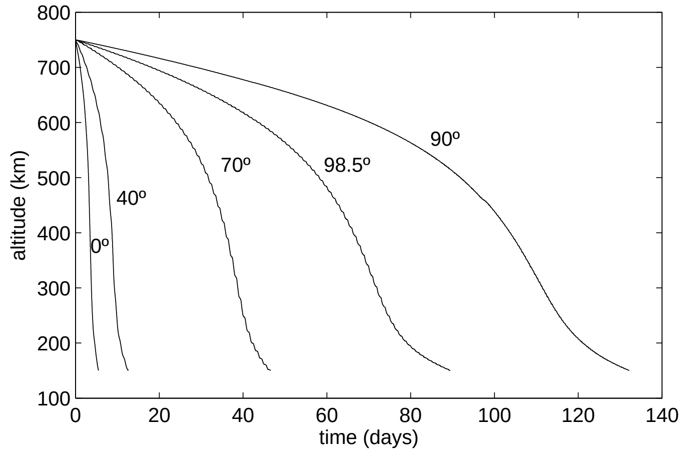

Figure 4. Orbital decay curves for a 200 m tape tether of 3 cm width on circular orbits of different inclinations and during maximum solar activity

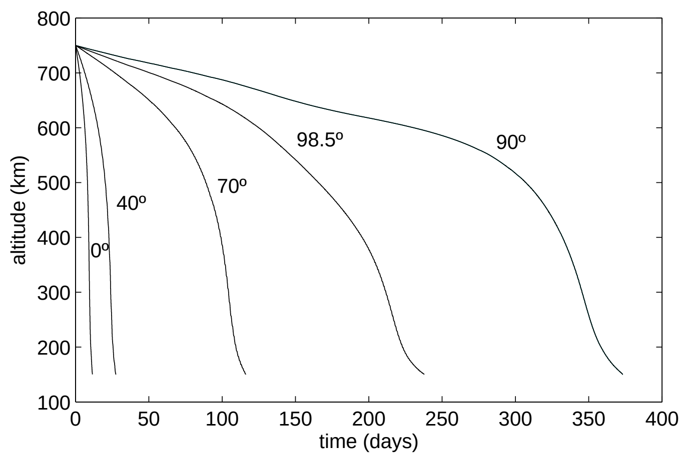

Figure 5. Orbital decay curves for a 200 m tape tether of 3 cm width on circular orbits of different inclinations and during maximum solar activity

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