NEW ELECTRODYNAMIC TETHER TECHNOLOGY

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ABSTRACT

New Electrodynamic Tether Technology (NETT) is an experiment we proposed to ESA as part of the Columbus Precursor Flights. It was designed to fly as an exposed payload in the Spacelab carrier. Its primary objective is performance testing for the innovative bare tether concept. The experiment also includes two scientific objectives, specific for uninsulated tethers: i) detection of artificial auroral effects produced by secondary electron emission, and ii) detection of VLF wave emission. Additional objectives of the project are space performance of an electron-emitting hollow cathode and engineering verification of an open-loop deployment strategy.

1. THE BARE TETHER CONCEPT

Electrodynamic tether systems appear as promising devices for both high-power probing of the ionosphere and technical applications (Refs.1,2). The standard tether system (Fig.1, from Ref.1) consists of a vertical, gravity-gradient stabilized, *insulated*, conducting wire that exchanges electrical charges with the ionosphere through *plasma contactors* at its ends. As the system orbits the Earth with a velocity $\vec{v}_o$, it cuts across the geomagnetic field $\vec{B}$ lines. An electromotive force $E_m = |\vec{v}_o \times \vec{B}|$ is induced along the tether, generating a current I across any interposed useful load R_L. Typical motional fields ranging from 100 to 250 volts per kilometer of tether are available in a favourable (low latitude, F-layer altitude) orbit. The generated power $W_g = I^2 R_L$ comes, of course, from the orbital energy. The braking force is the Lorentz force $\vec{I} \times \vec{B}$, and the loss of mechanical energy is $W_m = |(\vec{I} \times \vec{B}) \cdot \vec{v}_o|$. (When the current I varies along the tether, as in a bare cable, W_m must be written in integral form).

Tether systems are being now experimented in their first flight missions. The most notorious example of an electrodynamic tether experiment is the italoamerican TSS-1 which consisted of a 20 km insulated cable with a 500 kg, 0.8 m radius, spherical satellite acting as anodic (electron collecting) contactor and an electron gun as cathodic (electron ejecting) contactor. TSS-1 flew in the american Orbiter in July 1992. Unfortunately the experiment will have to be repeated because jamming thwarted the deployment of most of the cable.

An efficient tether system requires a good electrical contact (little impedance) between the plasma contactors and the ionosphere. It is generally acknowledged that collection of electrons at the *anodic*, positively biased contactor is the most critical issue for electrodynamic power applications. The generic problem comes from the small ionospheric plasma density n_e, which attains a maximum value of $10^{12}\,\mathrm{m}^{-3}$ by day ($10^{11}\,\mathrm{m}^{-3}$ by night) in the F-layer ($\sim 250-300$ km altitude). Since, the plasma temperature T_e is about 0.1 eV, the typical electron

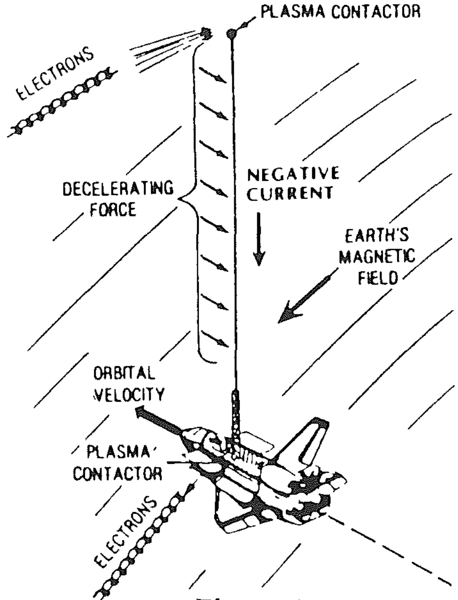

Figure 1

thermal current density J_e is of the order of 1 mA/m^2. The current collected by the anode can be expressed as

$$I = J_e \times (\text{anode area}) \times (\text{area gain})$$

It is clear that high power applications require large area gains. The natural way to increase the collecting area is the anode sustain some voltage drop, but electrostatic shielding makes this method inefficient for any anode with a typical length R much higher than the Debye length, $\lambda_D \sim 5$mm. For instance, applying a potential bias of 500 volts to a spherical anode with a radius of 0.8 m (anode area=8m^2), similar to the TSS-1's, would yield an area gain of about 2 (Ref.3) *if* the effects of the magnetic field are not considered. Since the electron thermal gyroradius l_e is about 30 mm in the geomagnetic field, the chanelling of the electrons restricts collection practically to one dimension, and the actual area gain for the above spherical anode could even be less than one.

The solution proposed to overcome the above difficulties was to use *active* plasma contactors, like the hollow-cathode devices, which, besides sustaining some potential drop, emit plasma. This artificial plasma might avoid i) the Debye shielding by creating a quasineutral cloud around the anode, and ii) the magnetic guiding by scattering electrons via plasma turbulence. At present, however, both theory and technology on these contactors still show gross uncertainties. In the interim, and also in any case as a long-term option, our bare-wire anode concept is a simple and attractive alternative.

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The bare tether system is based on a two-fold concept (Ref.4). First, we claim that a good passive anode should have two disparate characteristics lengths, just the opposite of anything like an sphere. The simplest example is a cylinder with a diameter d much smaller than its length l. Electron collection is then a two-dimensional problem, where the total collected current is proportional to l but the collection process is governed by d. If $d \ll \lambda_D$ and $d \ll l_e$, electrostatic-shielding and magnetic-guiding effects are negligible and the current attains its largest possible value for given geometry and potential (Ref.3). For instance, applying 500 volts to a cylinder with $d = 1.3$ mm and $l = 2$ km (anode area=8 m^2) gives an area gain of about 80.

Secondly, we can actually do away with the cylinder because a part of the tether itself, *if uninsulated*, may serve as anode. In Fig.2 we show the scheme of a bare tether system operating as an electric generator; for a normal west-east orbit the anodic end of the tether is upwards. V_t is the tether potential and V_p is the plasma potential in the tether frame; the slopes in the potential lines are due to the ohmic losses and the motional field, respectively. Point B, where both potentials are equal, self-adjusts with the ambient conditions. Electrons are collected in the bare segment AB, where $\Delta V = V_t - V_p > 0$. The current increases along the tether from point A to point B at a rate $en_e d(2e\Delta V/m_e)^{1/2}$ per unit of length. Part of this current is lost in the segment BC, *if bare*, due to ion collection, at a rate $-en_e d(2e|\Delta V|/m_i)^{1/2}$. Electrons are finally ejected at the cathodic end C by some device such as a thermionic emitter or a hollow cathode, at a cost of a negative potential drop ΔV_C (that should be small compared to IR_L).

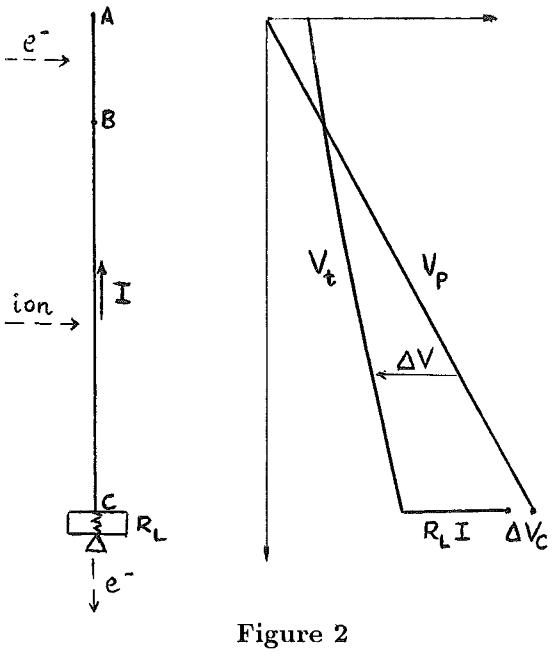

Figure 2

If L_B and L are the lengths of the segment AB and the whole tether, respectively, the relative loss of current scales as

$$\frac{\text{ion current}}{\text{electron current}} \sim \left(\frac{m_e}{m_i}\right)^{1/2} \left(\frac{L - L_B}{L_B}\right)^{3/2}$$

with $(m_e/m_i)^{1/2} \simeq 1/172$. Of course, these losses can be avoided by insulating all or most of the segment BC.

It is clear now that a good bare tether generator requires the ratio L_B/L to be moderately small: were it very small the useful power would be small (due to the small electron collected current and, occasionally, the important ion losses), were it not small the efficiency would be small (because the anodic potential drop would be comparable to the potential available at the load). For a fully bare tether the optimum value of L_B/L is determined from maximizing the power per unit of mass for given efficiency $\eta \equiv W_g/W_m$. We found that for η in the range of interest, let's say 60-80%, the optimum L_B/L is fairly constant, around 13-14%; the corresponding loss of current is 9-10%. Moreover, this optimum design also determines the tether geometry, d and L, once the tether material, the nominal ambient conditions, the efficiency and the useful power are fixed. For aluminum (conductivity $\sigma = 3.5 \times 10^7 \Omega^{-1}\text{m}^{-1}$) and $E_m = 200$ V/km, we have (Ref.3)

$$d \simeq 0.7 - 1.7\text{mm} \times \left(\frac{W_g}{1\text{kW}}\right)^{3/8} \left(\frac{n_e}{10^{12}\text{m}^{-3}}\right)^{1/4}$$

$$L \simeq 10.5 - 6.0\text{km} \times \left(\frac{W_g}{1\text{kW}}\right)^{1/4} \left(\frac{10^{12}\text{m}^{-3}}{n_e}\right)^{1/2}$$

for the efficiency in the range 0.6-0.8. Diameter and length scale with inducting field and material conductivity as $E_m^{-7/8}\sigma^{-5/8}$ and $(\sigma/E_m)^{1/4}$. The corresponding tether mass is (aluminum density $\rho = 2.7$ gr/cm^3)

$$M \simeq 10.9 - 36.8\text{kg} \times \frac{W_g}{1\text{kW}}$$

Length limitations arising from material strength or collisions with orbital debris would appear to allow values $L \sim 100$km. In fact the most stringent limitation on L arise from high-voltage insulation if the tether were partially insulated; a maximum voltage around 5 kV has been suggested (Ref.2). There is no thermal obstacle to choosing cables with such small diameters (Ref.4).

We may therefore conclude that a bare conducting tether can operate as a multikilowatt generator relying solely on passive electron collection by the cable itself. The system does not require to operate and control a complex contactor at the end of a wire kilometers long. Altogether the fact that its theory of operation does not present major uncertainties and the simplicity of the device, make the bare tether concept ideal for early implementation. The New Electrodynamic Tether Technology (NETT) experiment was just envisaged to demonstrate such capabilities.

2. DEPLOYMENT STRATEGIES

One of the most critical issues in any tether application is the deployment, stabilization, and retrieval of the cable. During last years tether dynamics have been studied in depth and several deployment and retrieval schemes have been considered. The deployment starts by the ejection of an endmass that, being moved away by the initial momentum and gravity-gradient forces, drags along the tether. Deployment is basically a stable operation but it usually leaves out the tether and the endmass swinging around the vertical. Thrusters placed at the endmass or tether pumping have been proposed to eliminate this libration. In contrast to deployment, retrieval of a tether is an unstable manoeuvring making necessary to use a control system to avoid the growth of vibrational and rotational motions. For instance, in the TSS-1 mission there were eight thrusters mounted on the endmass satellite (two in line thrusters to keep the tether taut, two for yaw control and four for pitch and roll oscillation rate damping).

According to our idea of designing both a simple and innovative experiment, the main objective of the dynamical analysis for NETT is to obtain an open loop strategy for the deployment, that leaves out the tether aligned with the vertical, at rest, without requiring further dynamics control, like auxiliary thrusting or pumping. Besides, to escape the mechanical and control difficulties associated with retrieval schemes, in NETT there will not be retrieval of the tether, that will be cut and discarded when the experiment ends.

In the following we briefly expose the deployment model we try to implement in NETT. For the theoretical analysis (Ref.5) several simplifying assumptions are taken into account in order to pinpoint the essential aspects of the dynamics. These assumptions are: the Earth has a spherical gravitational potential; aerodynamic forces, solar radiation pressure, and Sun and Moon attraction have been considered negligible. The orbiter follows a circular orbit, and only stable in-plane motion is taken into account. The tether is flexible, nonextensible, and its mass, together with the end mass, is negligible compared with the mass of the orbiter. The vibratory motion of the tether due to its elastic behavior has not been considered. However, the procedure can be extended to take into account all these effects in the tether dynamics.

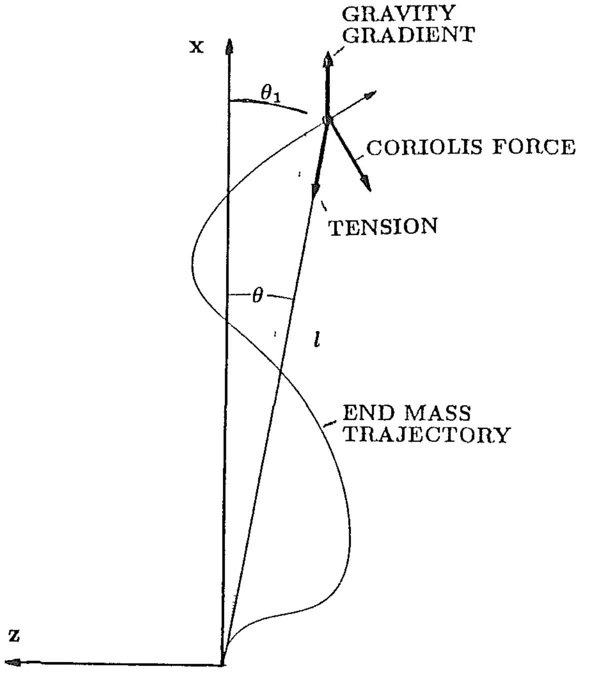

Figure 3

A light tether holds a rectilinear shape during the deployment and the tension does not vary along the tether. In such a case, the governing equations for the tether's deployment are the linear momentum equations for the endmass when acted upon by: the gravity gradient force, the inertial Coriolis force, and the tension $T(t)$ imposed at the base of the cable and transmitted to the endmass through the straight tether (Fig.3). Therefore, the in-plane motion of the endmass depends on the following control parameters: i) the ejection velocity V_0, ii) the ejection angle φ_0, and iii) the tension law $T(t)$. In this approximation, it is only necessary to know the position of the endmass that can be given by its polar coordinates (l, θ).

The deployment begins when the endmass is ejected from the orbiter. There are two different phases in our deployment process: i) Uniform deployment (the deployment rate $\dot{l}$ is constant), and ii) Exponential deployment (the deployed length grows exponentially). During the first phase the tension is low, the gravity gradient is small and the Coriolis force is dominant; the end mass goes away (and backwards) from the orbiter and the gravity gradient grows. However, at certain moment it is necessary to put the tether in tension, because the Coriolis force must be reduced to avoid the tether revolves around the orbiter; the exponential phase begins then. During this exponential phase, the tether tension brakes the deployment and reduces the Coriolis force, but does not stop the end mass because the gravity gradient is sufficiently large already.

In the exponential deployment there is an upward, stable, steady solution in which the tether deploys following a radial straight line; this steady solution corresponds to particular initial conditions and can not be reached using the first phase only. For other initial conditions, the tether swings around this radial line while deploying; if the exponential phase is suitably designed, in the first oscillation the tether is brought to the vertical when it reaches the maximum deviation from the radial line; if the deployment is then stopped (i.e. the distance of the endmass to the orbiter coincides then with the cable length) the tether stays aligned with the vertical.

During the exponential phase, the deployed length grows as

$$l(t) \propto \exp(2\pi C_0 t/T_o),$$

where T_o is the orbital period. If one wants the deployed length of the tether to follow this exponential law, it is necessary to impose a tension at the cable that also grows exponentially. The main parameter of this stage is C_0. For $C_0 < 3/4$ there are four steady solutions, in which the tether deploys following a radial straight line; two are stable and, one of these, is upward. Such a solution appears, in the phase plane $(\theta, \dot{\theta})$ as an stable focus. To approach that solution, initial conditions must lie inside its attraction domain. Due to the very hard contraction of the "volume" in the phase plane, all trajectories of the attraction domain cross the segment $\bar{PQ}$ of Fig.4. When C_0 ranges in the interval $I = [0.2454, 0.3662]$, the origin $(\theta = 0, \dot{\theta} = 0)$ lies in the segment $\bar{PQ}$. Therefore, there is a trajectory (curve A in Fig.4) that goes into the origin of the phase plane. If the final conditions of the first stage lie in this particular trajectory, the conditions: $\theta = \dot{\theta} = 0$ will be reached eventually. At this point the deployment must stop to leave out the tether aligned with the vertical, at rest.

The first stage ($\dot{l}$ constant) must end when the ratio $\dot{l}/l$ reaches the value C_0 previously fixed for the second stage ($\dot{l}/l = C_0$). Besides, initial conditions for the first stage must be such that final conditions for this stage lie in curve A of Fig.4. For each value of C_0 in the interval I there is a critical value of the ejection angle: $\varphi_0^* = \varphi_0^*(C_0)$ for which, at the end of the second stage the following conditions: $\theta_f = \dot{\theta}_f = 0$ are reached. Let l_f be this final value of the non-dimensional tether length corresponding to the critical ejection angle $\varphi_0^*(C_0)$; it is possible then to obtain the ejection velocity needed for such a deployment from the relation:

$$V_0 = 2\pi L / l_f T_o.$$

Notice that any tether's length can be deployed adjusting the ejection velocity. Also, C_0 should be chosen close to 0.36 to minimize the deployment time.

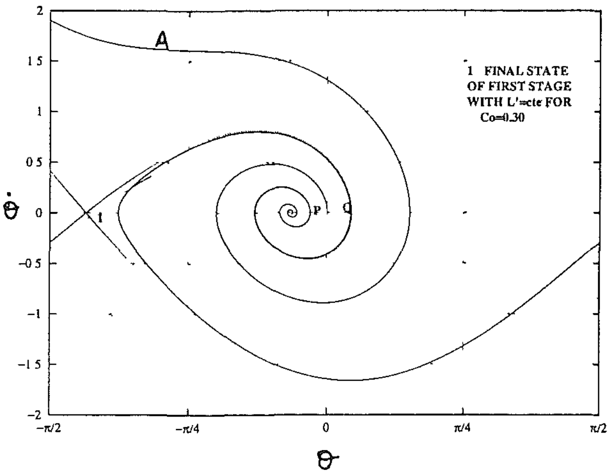

Figure 4

3. THE N.E.T.T. EXPERIMENT

For this technology-demonstration experiment and in order to facilitate the accommodation to the Spacelab, we designed a light-weight, moderate power generator. Besides, a fully uninsulated cable was chosen to broaden the scientific posibilities of the experiment (indirectly, we were saving the insulator mass and simplifying the tether manufacture). The Spacelab was selected as carrier since Eureca would be permanently pointing the Sun. This is clearly incompatible with the celestial (away from the Earth) pointing of our tether during both deployment and its active life. The experiment would be mounted as an exposed payload on the Unique Support Structure(USS) attached to the Spacelab. Besides the design studies made by our group, a phase B study has just been carried out by Alcatel Space (Toulouse, France) to (i) identify critical issues, (ii) develop a deployment mechanism, and (iii) get an overall baseline design, chiefly.

The NETT bare tether was designed for a nominal useful power of $W_g = 1$kW and an efficiency of $\eta = 75\%$. Nominal ambient conditions were $E_m = 200$V/km and $n_e = 10^{12}$m^{-3}, corresponding to a low latitude (28.5°), 250-300 km altitude orbit, and a daylight ionospheric density. For an aluminum cable the resulting optimal size was

$$d = 1.15\text{mm}, \qquad L = 7.5\text{km},$$

yielding a tether mass of 21 kg. The total induced voltage, current at the load, and load impedance were

$$E_m L = 1500\text{V}, \quad I_L = 0.87\text{A}, \quad R_L = 1.31\text{k}\Omega.$$

The electric circuit is closed at the bottom end of the tether by an electron-ejecting hollow cathode. Its estimated impedance would be about 10-20 Ω and the voltage drop amounts roughly to 10-20 volts; this would reduce the efficiency to $\sim$ 74%. (The TSS-1 uses an electron-gun, instead, as cathode. This better known technology is very inconvenient because of its high impedance. In fact, the TSS-1 uses all the generated power in the gun operation).

As the tether will fly in a variable ionosphere, calculations were made to estimate the tether performance out of the design point. We found that (i) for the motional field in the range 150-250 volts, the useful power would be in the range 550-1500 W, (ii) a density drop by a factor of 3 would reduce the useful power about a 20%, and (iii) in both cases the efficiency would be little affected. (See also Ref.6).

Although the generated power could be available for on-board use, we decided to just dissipate the power at an off-board dummy load. This requires to use the active thermal control equipment from the Spacelab; in exchange, the experiment does not interfere with the electrical power system of the carrier. The dummy load of 1.31 kΩ would consist on a series array of power-transistors, each working at about 1 amp, 100 volts. An aluminum plate connected to the dissipators of all individual transistors would make easy the thermal control of this electronic load. The Al plate is bolted to a standard coldplate cooled by the Spacelab freon loop. We estimate that a maximum conductance of 600 W/K/m^2 can be attained; this would keep the Al temperature only 7 K above the freon loop.

To keep with the proposed conception of a light-weight, simple system, we designed the low-tension deployment strategy explained before, initiated by upwards spring-ejection of an end-mass of about 20 kg. The tether unwinds from a stationary, spinning Al reel and feed through a friction brake operated by a stepper motor. The estimated deployment time is about 55 minutes and when it ends the tether is, at rest, aligned with the vertical. When the electric circuit is closed the cable keeps fairly straight; maximum deflection due to Lorentz force is estimated in less than 10°. After the different experiments are carried out, the cable is cut and discarded. The short operative life makes unnecessary to control out-of-plane libration at twice the orbital frequency. Also, the probability of a micrometeorite cut during operation is less than 0.2%. Since deployment is accompanied by a backwards pendulum swing, the Orbiter attitude should be bay up, tail forward, so as to provide in-plane, backward field-of view well in excess of the expected $\sim$ 50° swing. (Clearance angle for Orbiter cabin from middle of cargo bay is 70°).

Figure 5 shows a pespective of the whole experiment mounted on one panel of the Unique Support Structure. Element (1) is the end-mass. In order not to be just a deadweight, we considered the possibility of installing there scientific instrumentation to monitor the plasma properties at the top end of the tether; the information would be sent to the Orbiter by a UHF transmitter. A more ambitious idea, its viability is presently being studied, is to place part of the tether and deployment system there. Element (2) includes the ejection, unwinding and cutter mechanisms. Element (3) is the reel. Element (4) is the dummy load, electrically connected to the tether in the reel and to element (5), the hollow cathode. Element (6) is the argon capacity ($\sim$ 1 liter) that feeds the hollow cathode. Element (7) is the electronics box that mainly controls the tether deployment and the hollow cathode operation. Elements (8) and (9) are the cold plate and the freon loop, which are provided by the Orbiter. The overall volume of the experiment would be $0.70 \times 0.78 \times 0.73(\text{height})\ m^3$. The total mass would be around 100-110 kg. This gives a good (useful power)/(total mass) ratio, one or two orders of magnitude above that of the TSS-1.

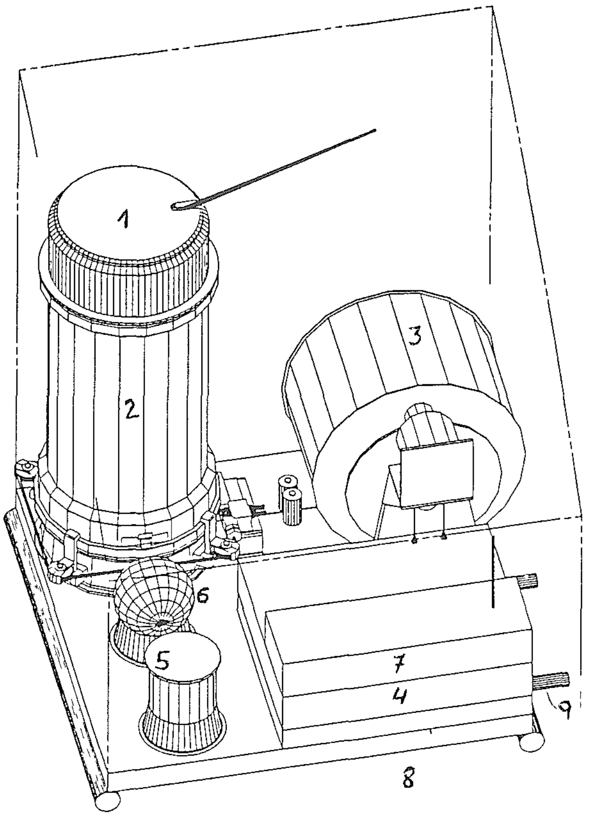

Figure 5

Besides the technology demonstration, NETT includes two scientific experiments specific for a bare tether. They only require limited on-board instrumentation and ground detection. The first one is related to electron secondary emission. Our cable presents 6.5 km of bare metallic surface (segment BC), with negative bias ranging from zero to about 1.5 kV. Therefore, highly accelerated ions impact the cable producing the emission of a secondary electron current of the order of 0.01 amp. Emitted electrons are accelerated outwards by the electrostatic field and chanelled, at both sides of the tether, by the magnetic field. Most particles would precipitate to the feet of the magnetic tube, in the D-layer. Optical and UV emission caused by excited atoms should produce auroral displays, that would move parallel to the tether orbital trace. It is worth noticing that the flux from our small tether, about 2×10^8 electrons/$(cm^2 s)$, is just one order of magnitude below values found in auroral arcs by low altitude polar orbiting spacecraft.

The second space science experiment is the detection of waves in existing ELF ground-based stations. Radiation could be emitted for both current modulated (by varying the load impedance) and continuous (steady flow of current through an orbiting tether appears unsteady in the ionospheric frame). Even for this simpler case, however, there is no definite agreement on whether the radiation is dominated by shear Alfven waves or whistlers. It is worth to notice that a tether is always a hybrid between an antenna and a powerful Langmuir probe (current flowing toward and away from it). Besides, for a bare tether system the geometry of the radiation surface is radically different from a standard tether. Although preliminary estimations indicated that the wave impedance for continuous current would be small (we actually neglected it in the tether design), it is important to confirm this point. In work to be published, we show that for continuous current thermal effects are essential, resonant damping strongly attenuating all radiation.

As it has been previously mentioned NETT uses an electron emitting hollow cathode to return the electrons collected along the wire to the ionospheric plasma that surrounds the spacecraft. The electron collection performances of the complete tethered system are limited by the maximum amount of charge that could be effectively transferred to the ionosphere. Ground tests have demonstrated that these devices have the adequate long lifetime and capability for supporting large currents (Ref.7) but the electron emision process depend on several mechanisms still not well understood. Thus, the design and development of an efficient electron emitting hollow cathode were adopted as part of the NETT project. Experimentation is carried out in a small plasma facility we installed last year in our laboratory. The first experimental device and results have been described elsewhere (Ref.8). We found, first, that a stable potential structure formed by multiple double layers develop in the region around the contactor; and second, close to the region of the maximum voltage drop a zone of relative high ionization rate also develops. Complementing these experiments, theoretical models for hollow cathodes are being worked out to understand the main processes and parameters that control both the emission and collection of current from a plasma (Ref.9).

We may therefore conclude that the NETT experiment, besides its primary goal: to demonstrate its efficient electric-generator capabilities, includes a rich diversity of technological and scientific objectives. This was acknowledged by a Scientific Panel of ESA in 1992 which recommended the experiment for flight.

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