SHORT, HIGH CURRENT ELECTRODYNAMIC TETHER

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ABSTRACT

An electrodynamic tether experiment, to be carried out in the Russian spacecraft Almaz, is proposed. A 10 km tether would be deployed downwards; the lower 8 km would be nonconductive, the upper 2 km would be conductive, bare, and 2.2 mm in diameter, and would act as a thruster, with power supply at the top. This hybrid arrangement allows for other, nonelectrodynamic experiments, reducing costs; it also limits the induced electromotive force, reducing the power to be handled. The current-voltage characteristic of contactors would be measured. With the anode switched off, the wire itself should collect a current over 5 A at day conditions, providing a thrust of 0.11 N at a 0.77 kW power.

Keywords: Electrodynamic Tethers, Plasma Contactors

1. INTRODUCTION

Reaching currents of order 10A will entail a coming of age for electrodynamic tethers. Such currents have been deemed necessary for applications that range from power generation to thrusting or braking (Ref.1). Further they are also essential in providing tests of contactors (the weakest link in the electrodynamics), and experimental data on their complex plasma physics, for ranges of appropriate dimensionless numbers that appear impossible to reproduce in the laboratory. Those data should prove quite helpful as a complement to numerical simulations of the highly nonlinear region of electrical contact with the ionosphere (Ref.2).
An understanding of that region is a requirement for self-consistent predictions on wave emission, in particular on the signature left by the tether in the ground, and in the far ionospheric wake; up to now, for instance, every computation of radiation impedance, except for some recent simple analysis (Ref.3), has been based on a linear approximation. Independently, a high current will be, naturally, of help in detecting any such signature. This might provide a solution to a number of issues upon which there is as yet no agreement in the literature (whistler emission, current closure, propagation to the ground).

2. HIGH-CURRENT TETHERS

2.1 Laboratory experiments on contactors

There is at present no broad (non ad-hoc) theory of contactors (Ref.4). This is a field teeming with difficulties, arising on the one hand, from the usual atomic and ionization physics involved in electrical discharges, and on the other hand, from the richness of instability mechanisms causing the fluctuations that must scatter attracted electrons off magnetic lines. One need only remember here the long, tortuous path to electric propulsion.

Lacking a reliable theory, results from ground experiments on contactors might be used for predictions if given in dimensionless form, for appropriate values of certain dimensionless numbers characterizing contactor physics. To a current I=10 A collected in the ionosphere, would correspond laboratory conditions conveniently scaled, because there is no basis, in principle, to expect that dimensionless results would be independent of the actual values of the dimensionless numbers (as the aerodynamic drag coefficient, say, is independent of Reynolds number R_e, for the limited range $10^3 < R_e < 2\times10^5$). Unfortunately, there is no way, in practice, to reproduce all such numbers in the laboratory, as can be easily argued.

Define $S_{eff} \equiv I/J_{th}$ as an effective surface area of a contactor; here J_{th} is the electron thermal current density, which ranges from 0.0003 A to 0.01 A, for a 0.15 eV ionospheric temperature and a $3\times10^4-10^6$ cm^{-3} ionospheric density. For I=10A, and assuming roughly hemispherical collection, the effective collecting radius would be

$$R_{eff} \equiv \sqrt{S_{eff}/4\pi} \sim 15\text{-}75 \text{ m}.$$

Clearly, to avoid wall effects, R_{eff} should be scaled in the laboratory to values $\lesssim$ 1m, say, by a factor 1/15 - 1/75.

The contactor itself would then have to be scaled down in size, accordingly. Both Debye length (~ 3-15 mm) and electron thermal gyroradius (~3 cm), which represent electrical screening and magnetic guiding effects respectively, would also have to be scaled, and so it would some appropriate mean free path for ionization, which plays an essential role in active contactors. Such fully scaled simulation appears quite impossible, actual experiments, in fact, being very far from achieving it. Flight tests of both anodic and cathodic contactors at high-current (high R_{eff}) values are thus necessary, present tests covering values below 0.3 A (Ref.5).

2.2 Short electrodynamic test tether

Tests with long tethers (L_t~20 km) carrying high currents would require unconvenient handling of high powers (~4kV×10 A ≃ 40kW) by the electronics involved in the repeated, full measurement of current-voltage (CV) characteristics of contactors. On the other hand, the length L_t should not be too short either, to avoid interaction between the plasma clouds ejected by active contactors at the ends of the tether,

$$L_t \gg 2\times75 \text{ m} = 150 \text{ m}.$$

The optimal length would thus lie in the range $L_t \sim 500$ m - 2 km.

Such short lengths might provide, however, too low a tension for a proper, stable mechanical configuration of thick tethers carrying a high current; residual stresses, for instance, might result in a pig-tail shape. A solution to this difficulty would be the use of a downward deployed, hybrid tether, most of its length (10-20 km) being of dielectric material. The long, nonconductive segment could be used to carry out atmospheric or Earth measurements and would help insuring a straight configuration for different deployed lengths of conductive tether.

3. THE ALMAZ EXPERIMENT

An experiment to fully test contactors at high currents, using a hybrid tether on board the space station Almaz (1B or 2), is now being considered. Almaz would orbit in the F-layer (300-400 km altitude, possibly reduced to 200 km); at a high inclination (73° for Almaz 1B); and over a long period of time (~180 days). In a first stage, only the lower nonconductive 8 kilometers would be deployed in order to carry out extensive Earth (geomagnetic, gravitational) measurements, accompanied by determinations of local electric and magnetic fields along the orbit. In a second stage, a 2 km long, 2 mm thick, conductive part, with a second subsatellite at its end, would be deployed (Fig. 1).

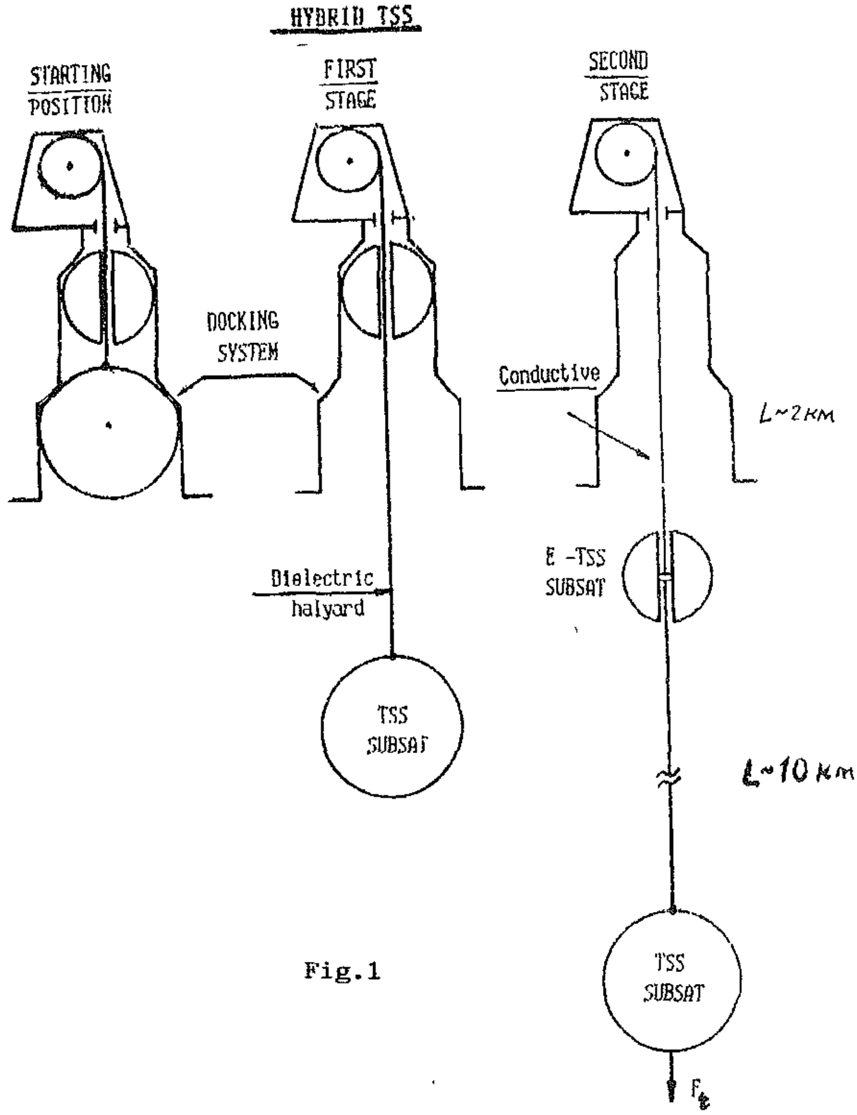


Fig.1

The electric supply of the CV-meter would provide output voltages in the range -360V to +360V, at a maximum current of 5A. Thirteen modules would allow voltage steps of 10V, and would be switched in accordance with a program by means of controllable power switches. The reference frequency of a synchronizer (and address decoder) would activate voltage transformers for each individual module.

Measuring units for both voltage and current would include an analog to digital board to convert analog signals into 10 bits digital data. The current meter would be connected across the terminals of a special series resistor in the tether current circuit. The duration of each voltage step is 0.1 s, the time interval for a full CV determination being 3 s. A measurements session involving 100 CV characteristic, repeated at different ionospheric conditions and different lengths of conductive tether deployment, would provide an information volume of about 100 kbytes (Ref.6).

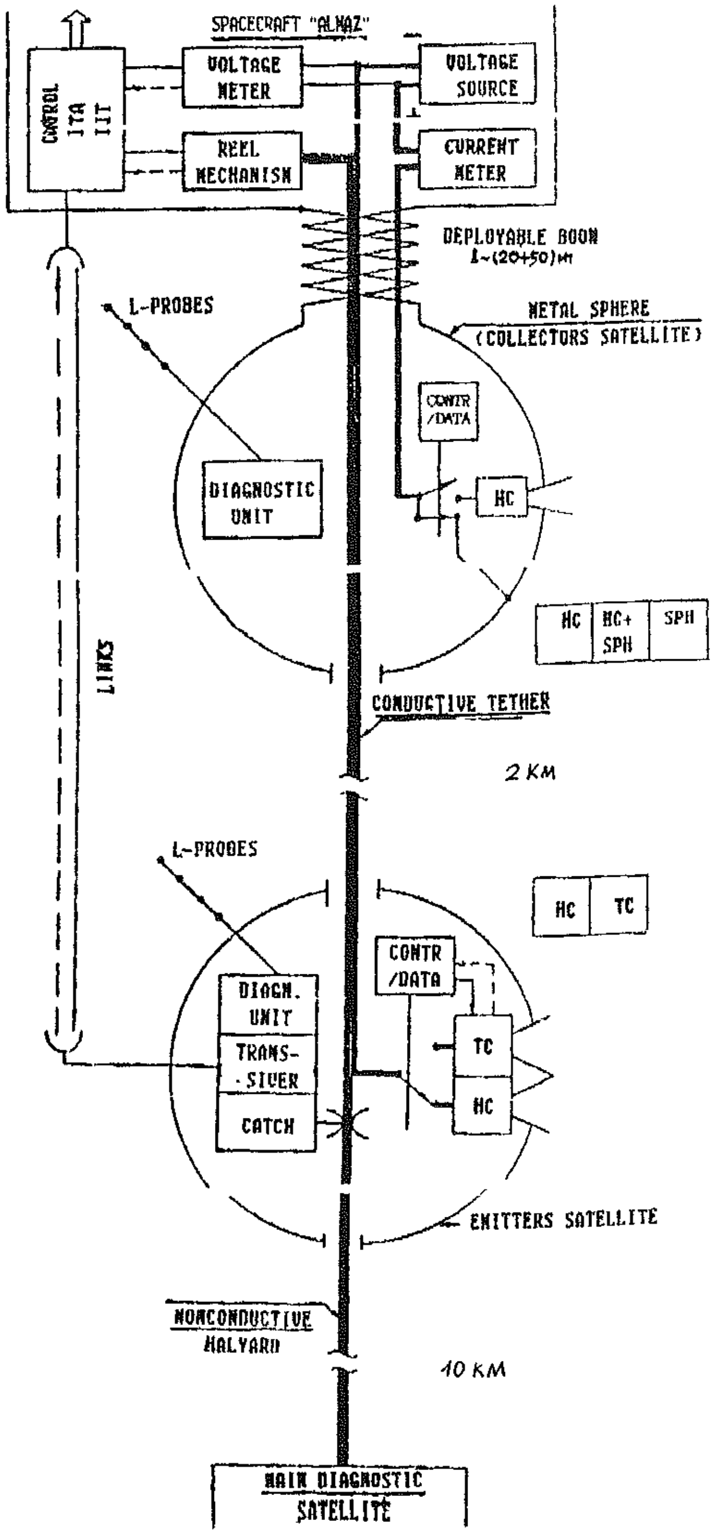
4. TESTING A BARE-TETHER ANODE

The conductive segment of the hybrid Almaz tether would carry various contactors at both ends: hollow cathodes acting as anode and cathode; a passive sphere as anode; an electron gun as cathode (Fig.2). Further, if that segment carries no insulation, no anodic contactor might be required, the wire itself acting as anode over part of its length, which would be electron-attracting (Ref.7). The Almaz experiment will test the electron collection capability of a bare tether at high currents.

For usual eastward orbits, the current in a generator flows upward, with the anode A at the top and the cathode C at the bottom (Fig.3a, where R is a load impedance); in the case of a bare tether, upward deployment would be most *convenient, with the single (cathodic) contactor lodged in the main* spacecraft. In a tether acting as thruster, a voltage source supplying power makes the current flow downwards, with cathode C at top and anode A at bottom (Fig.3b, where ε is the source emf); bare-tether deployment should be also downwards. For a generator, the local bias between tether and undisturbed plasma, (V_t-V_p, where profiles V_t and V_p are due to the ohmic drop and the induced motional electric field, Fig.3a) gets negative at some point B, as one travels away from the anode A. In a thruster, on the other hand, the bias gets <u>more positive</u> away from A.

A thrusting tether, if fully bare, will thus be clearly electron-collecting over its entire length and it will have higher current-collection capability than a similarly sized generator tether. It will also have, however, a lower efficiency, as electrons collected near the emitting cathode at the top will do little push work but will still cross the voltage source. For thrusting applications, therefore, it would be advantageous to insulate most of the wire, leaving some anodic segment intentionally bare. On the other hand, if one just wishes to attain large electron currents, ignoring efficiency questions, the tether should work as thruster and be left fully bare. This is the case with the Almaz tether; naturally, when testing bare-tether collection, the anodic contactor in the subsatellite at the lower end would be switched off.

A bare tether, unless centimeters thick, will collect electrons in the so called orbital-motion-limited (OML) regime of Langmuir probe theory, collection being affected by neither Debye length or thermal gyroradius effects (Ref.7). The OML description is quite simple, the current per unit length of tether being proportional to the square root of the local voltage bias. For given ionospheric conditions (motional electric field E_m, electron



SPACECRAFT "ALMAZ"
CONTROL ITA IIT
VOLTAGE METER
VOLTAGE SOURCE
REEL MECHANISM
CURRENT METER
DEPLOYABLE BOOM
L~(20÷50)m
L-PROBES
METAL SPHERE (COLLECTORS SATELLITE)
CONTR /DATA
DIAGNOSTIC UNIT
HC
HC
HC+ SPH
SPH
LINKS
CONDUCTIVE TETHER
2 KM
L-PROBES
HC
TC
CONTR /DATA
DIAGN. UNIT
TRANS- -SIVER
CATCH
TC
HC
EMITTERS SATELLITE
NONCONDUCTIVE HALYARD
10 KM
MAIN DIAGNOSTIC SATELLITE

Fig.2

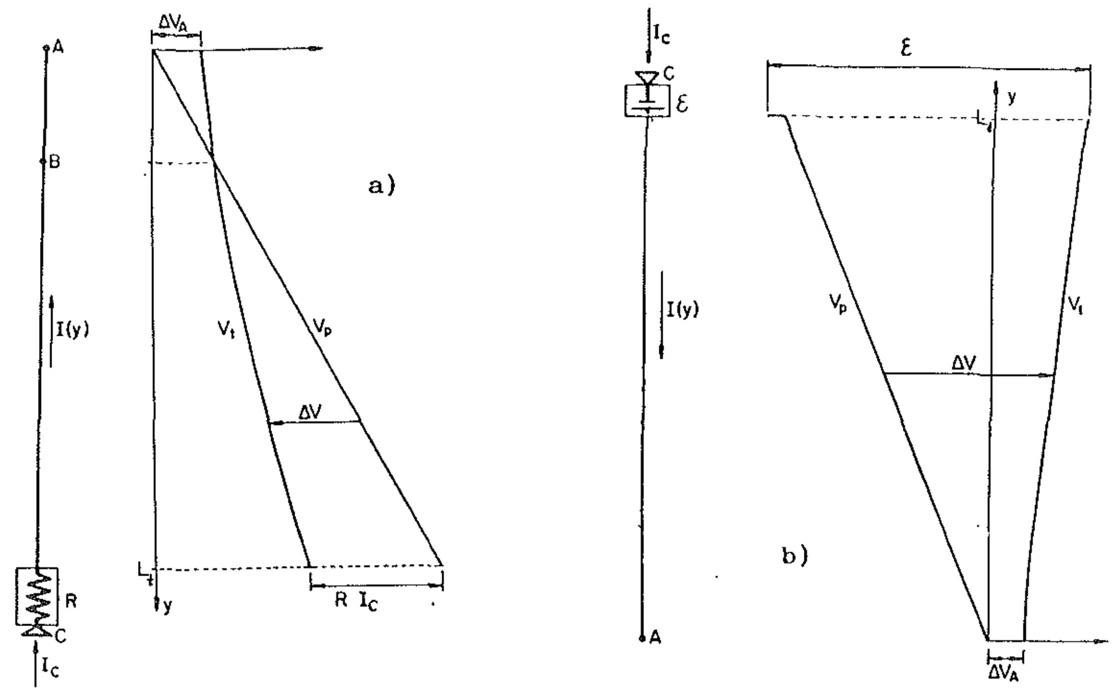


Fig.3

density n) and tether characteristics (length L_t, cross section S_t, conductivity σ_t), one can choose the emf ε so as to have zero bias at point A of Fig.3b (corresponding to maximum conditions in efficiency, or thrust per unit mass of tether). A straight-forward calculation yields ε implicitly

$$\frac{L_t}{L_*} = \int_0^{\varepsilon/E_m L_*} \frac{d\phi}{\sqrt{1+\phi^{3/2}}}$$

with

$$L_* \equiv \left(\frac{9\pi m_e \sigma_t^2 S_t E_m}{128 e^3 n^2}\right)^{1/3} \simeq \frac{[S_t(\mathrm{mm}^2)]^{1/3}}{[n(\mathrm{m}^{-3})/10^{11}]^{2/3}} \times 9.6 \text{ km},$$

where we took E_m=150 V/km and an aluminum tether. The current I_c reaching the top of the teher is then

$$I_c = \sigma_t E_m S_t \left[\sqrt{1+(\varepsilon/E_m L_*)^{3/2}} - 1\right]$$

with $\sigma_t E_m \simeq 5.25$ A/mm^2.

At a density $n=10^{12}\,\mathrm{m}^{-3}$, a cross section $S_t=3.5$ mm^2 (diameter ≃ 2.11 mm) gives $L_* \simeq 3.14$ km; a length $L_t=2$ km then yields $I_c \simeq 5$ A, $\varepsilon \simeq 342$ V. The magnetic thrust is about 0.11 N with a magnetic power 0.77 kW, and an efficiency, (magnetic power)/$\varepsilon I_c \simeq 0.45$. We note that *i)* a fully bare thruster cannot adjust to changing ambient conditions (as a fully bare generator does, Ref.8): if n drops, say, from 10^{12} m^{-3} to 10^{11} m^{-3}, I_c will drop similarly; *ii)* the equilibrium angle off the vertical due to the magnetic force is here small ($\sim 0.5^{o}$), even if the current is large, because of both a large end mass (~300 kg) and the small conductive to total length ratio.

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