New High-Current Tethers:
A Viable Power Source for the Space Station?

A White Paper

by

R. D. Estes and E. C. Lorenzini
Smithsonian Astrophysical Observatory, Cambridge MA

J. R. Sanmartín
Polytechnic University Madrid

M. Martinez-Sanchez
Massachusetts Institute of Technology, Cambridge MA

N. A. Savich
Russian Academy of Sciences Moscow

December 1995

Abstract

The Space Station could be significantly enhanced by the addition of a supplementary power system. Recent space-flights (TSS-1 and PMG) have demonstrated that tethered systems can generate electrical power at the expense of orbital energy. Power levels have, of course, been far below Space Station requirements. We argue that the physics of electron collection in the ionosphere makes it unlikely that either the TSS or PMG approaches to tether power generation will ever achieve such levels. We present evidence that a new approach, using a tether that collects electrons along several kilometers of its length, where it has been left uninsulated, is worthy of serious study and possibly a demonstration flight. The innovative concept takes advantage of the particular geometry of tethers and well-established results from Langmuir probe theory. Such a 'bare' tether could attain currents orders of magnitude above values previously attained in flight and fairly insensitive to changes in ambient electron density. The White Paper outlines ways in which a proof-of-concept demonstration flight might be achieved at relatively low cost using existing technology (SEDS) and international participation. We propose that a Definition Study pointing to a possible demonstration flight (with a goal of achieving 10 Ampere currents) be undertaken.

Contents

New High-Current Tethers: A Viable Power Source for the Space Station?

R. D. Estes, E. C. Lorenzini, M. Martinez-Sanchez,
J. R. Sanmartín, and N. A. Savich

I. Introduction: High-Current Tethers for Space Station Power

The usefulness of the upcoming International Space Station could be substantially enhanced by the inclusion of a supplementary electrical power system for temporary over-capacity applications, either scheduled or arising from malfunctions of the base power system or from incomplete array deployment. This White Paper is intended to present a viable power system for the Space Station, based on a new type of high-current, high-power tethered system. While the possibility of such power generation applications has provided one of the strongest motivations for the development of tether technology, there remain major technical problems to be overcome before tether power generation for the Space Station can become a reality. We examine below these technical problems and present arguments, based on well-established physical results, for a new tether design—utilizing a tether with a long "bare" segment along which current would be collected from the ionosphere—to achieve useful Space Station power levels.

In August of 1992, TSS-1, the first tethered satellite system experiment using the Space Shuttle as a deployment platform, demonstrated that the principle of motion-induced electrical power generation by an orbiting tethered system in the Earth's ionosphere is sound, despite the incomplete tether deployment and consequent low voltages and tether currents. Then in 1994 the Plasma Motor-Generator (PMG) rocket-borne tether experiment, using hollow cathode devices to make electrical contact with the ionospheric plasma at each end of the system, achieved tether currents of 0.3 Amperes with only a 500 meter tether. The re-flight mission of TSS-1 (TSS-1R) hopes to attain currents twice that high and at much higher voltages. TSS-1R should provide valuable information on the limitations to passive current collection by a spherical conducting satellite at high voltages.

Utilization of TSS technology would seem a natural direction to explore in connection with Space Station power applications, but it soon becomes clear that the current-collection capability of TSS is insufficient by a couple of orders of magnitude for any significant contribution to Station power budgets. These first experiments, while validating the general principles of tether power generation, do little to demonstrate the possibility of achieving useful levels of electrical power by tethered systems. They were not designed to do so. However, there are strong physical reasons to believe that there are inherent limitations to the technologies used in TSS-1 and PMG that would preclude practical power generation for the Space Station, even with much improved versions.

We propose to investigate an alternative means of collecting electron current from the ionosphere using a tether which, contrary to those in previous experiments, has a long segment on which the electrically conducting portion (the central core in previous insulated tethers) is exposed to the ionosphere. Electrons would be collected from the ionosphere all along this long “bare” segment.

The analysis we present in detail below indicates that there are a number of potential advantages to such a system, including the possibility of much higher current values that are more stable under variations in the plasma density. In particular, power generation sufficient for a Space Station auxiliary source might be achievable. The simplicity of the design would make it especially attractive.

The large jump in current over and above existing technology, and the relative novelty of the anode design most likely to be adopted, makes it prudent to proceed in a step-by-step manner. A first step would consist of a short (nine months or less) Definition Study to confirm the physical basis and lay out the basic parameters of a technology demonstration mission. Assuming a successful definition phase, we would propose to commence work on the various design and execution phases of that mission, thus laying the groundwork for rapid implementation of the system on the Station, if desired.

II. Tethers for Space Station Power: Technical Challenges

A detailed general study of tether power generation [1] concluded a few years ago that the main difficulties were related to the efficient capture of electrons from the dilute and highly variable ionospheric plasma, and to the need for voltage leveling batteries to counter the e.m.f. (open-circuit voltage) fluctuations associated with geomagnetic irregularities. We address the voltage fluctuation problem for the specific Space Station application in this section; the more challenging problem of electron capture will then be taken up in the context of our proposed bare-tether anode design.

The planned 51 degree orbital inclination for the International Space Station results in both a reduction in the average tether e.m.f. (as compared with oribits with lower inclination angle, such as TSS-1) and large e.m.f. fluctuations, as D. Crouch has pointed out [2]. These are due to a combination of intra-orbital variations from overflights of magnetic anomaly regions, plus daily variations due to the rotation of Earth's dipole underneath the orbit. For a 51 degree orbit, there are several hours each day when the northern and southern segments of each orbit will be within 30-40 degrees of the magnetic poles; as a result, these periods will offer low tether induced voltages (300-800 V for a10 km tether [2]). The rest of the day is much more favorable, with voltages oscillating within each orbit between 700 and 1500 V, and averaging about 1200 V. For a constant internal impedance, power would scale as the square of tether voltage; the nonlinearities associated with contactor operation tend to reduce somewhat this sensitivity.

These variations impose limitations on the design of a supplementary tether power system. As an example, assume we wish to use a 20 km tether to generate an average of 20 kW. The daily average emf is then approximately 2000 V, requiring 10 A on average. If we imposed a constant system power output, the battery capacity needed to cover the several hours of low orbit-averaged e.m.f. would amount to approximately 45 kilowatt-hours, of the same order as the baseload battery bank. On the other hand, if we accept the slower (daily) variations, and provide leveling only within each orbit, this can be accomplished with a mere 3 kW-h battery bank; but the consequence is then a period of some 8 hours with e.m.f. below 2000V, reaching a smooth minimum of some 1200 V, while the remaining 16 hours are at a nearly constant 2400 V e.m.f.. These supply variations may be acceptable, since they are smooth and occur on a daily schedule, which may be synchronizable with the station's power needs. Alternatively, the tether might be designed for a condition below average voltage, and the upper sections could then be disabled (open-circuited) during the higher voltage periods.

Reaching currents of order 10A in flight would mark a technical breakthrough for electrodynamic tethers. Such currents have been deemed necessary for applications that range from propulsion and braking to power generation. The tether, however, needs an anodic device to draw electrons from the ionosphere at that rate, a task made difficult by the low ambient (thermal) current density, which never exceeds 0.01 A/m^2. Furthermore, regular drops in that value, if affecting collection, would be a feature particularly undesirable for generator tethers. There is clearly no symmetrical difficulty in ejecting electrons into the ionosphere through a cathodic device (ejecting ions at the anode would not do because of the disparate ion and electron masses). The standard tether carries insulation along its entire length, exchanging current with the ionosphere only at the ends. TSS-1 carries a metallic sphere as anode and an electron gun as cathode. PMG carries active (plasma) contactors at both ends, an active-contactor technology being intensely pursued at present. In any case, current values attained in flight in the past, under the best ionospheric conditions, did not exceed 0.3 A. Here, we propose using a tether stripped of insulation and with no collecting device at its anodic end to act as its own anode.

In the remaining sections, we concentrate on the problem of electron capture, which can in principle be addressed using a bare tether design. To ascertain the feasibility of that design, and its relative advantages compared to alternative contactors, we propose a Design Study for a relatively inexpensive demonstration mission.

III. Current Collection: Need For Effective Anodes

As a collector, a typical passive anode such as carried by TSS-1 is poor, inefficient, and heavily dependent on the ambient current density. Clearly, its surface should be (realistically) large and its bias capable of enhancing collection well above thermal. Unfortunately, the bias required for the currents of interest is extremely high. This is because ionospheric Debye length (~ 5 mm) and electron gyroradius (~ 25 mm), being small compared with the anode, lead to both space-charge shielding and geomagnetic guiding of the electrons. Ignoring magnetic effects, standard probe theory shows that, say, a 4 A current into the $8m^2$ anodic area of TSS-1 requires no less than a 15,700 V bias (corresponding to a tether length of around 100 km!), the contact impedance (here 3.9 kΩ) increasing with current. Magnetic effects make the case worse [3].

An active anode would solve these difficulties by a) creating a self-regulating plasma cloud to provide quasineutrality and b) emitting ions to counterstream attracted electrons and produce fluctuations that scatter those electrons off magnetic field lines. Ideally, collection by an active anode should be insensitive to ambient conditions. Unfortunately, there is no broad (non *ad hoc*) theory for such a contactor. Furthermore, data from laboratory experiments cannot be scaled for flight because there is no way to reproduce on the ground the appropriate dimensionless numbers (length ratios) characterizing contactor physics. To be definite, for hemispherical collection of 10 A the effective collecting radius (distance to undisturbed plasma) would be no less than 13 meters, whereas, to avoid wall effects, that radius should be less than 1 meter in the laboratory. Clearly, to keep all length ratios, the Debye length, electron gyroradius and mean free path for ionization, as well as the contactor itself, should be impractically scaled down in the laboratory by a factor 1/13 [4,5].

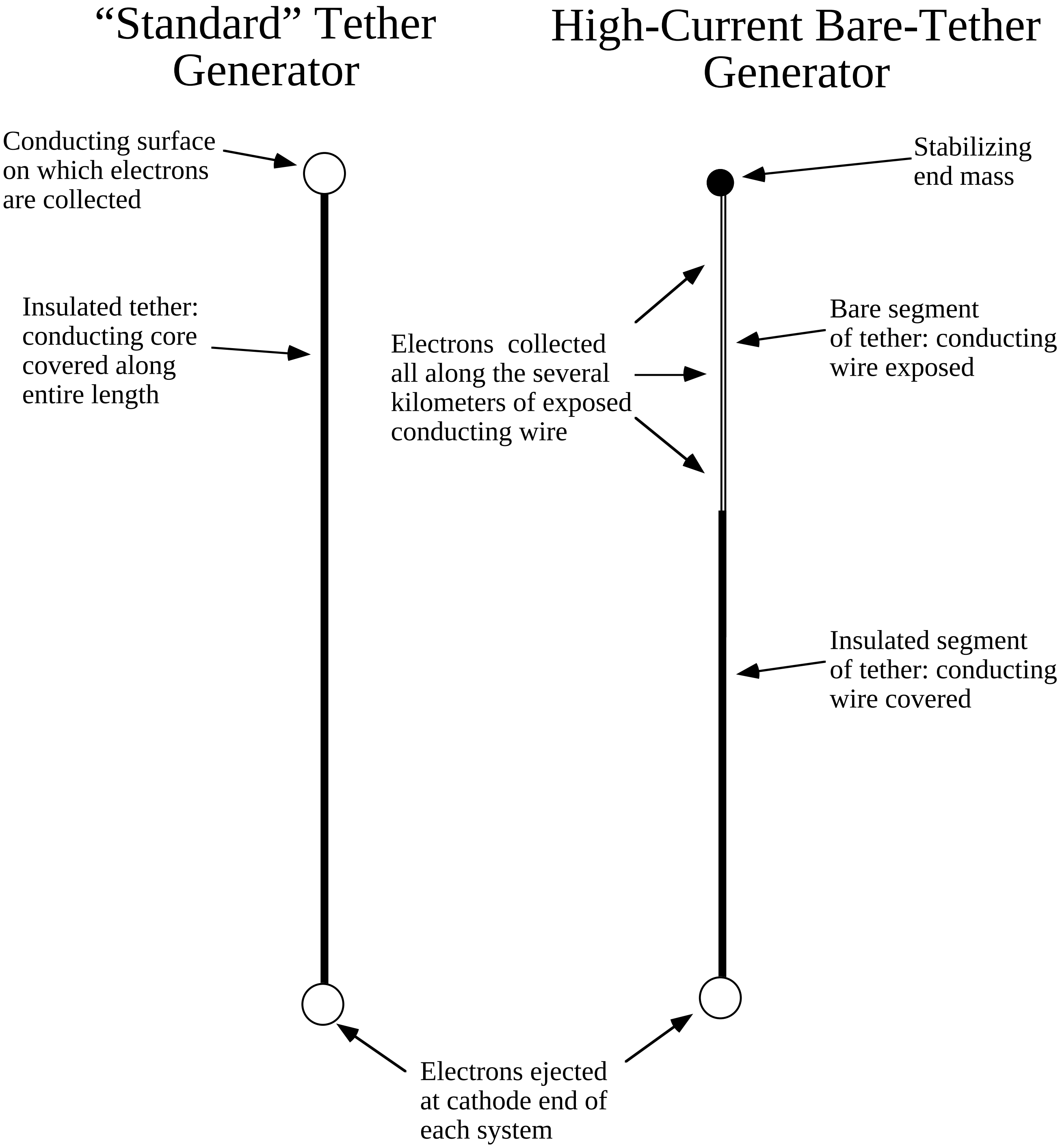
The PMG tether used active contactors at both ends to reach 0.3 A in flight under a 130 V bias and the best ionospheric conditions. These results are encouraging but limited. The resulting contact impedance 0.43 kΩ is still high for such a low current. Also, there is no way to scale the results to high currents. Finally, the current collected decreased sharply with the ambient electron density, as expected from a passive contactor. In fact, active-contactor effects were weak. Considered as a passive device the metallic box holding the PMG anode could be crudely characterized by a 0.26 m equivalent radius, for which standard probe theory would yield 0.043 A at 130 V. The effective collecting radius was thus increased by just a factor of $(0.3/0.043)^{1/2} = 2.6$. [6,7]

IV. The Bare-Tether Solution: Theoretical Basis

We claim that a passive anode can work efficiently under the conditions of interest if it has two disparate characteristic lengths (instead of just one as in the case of a sphere). The simplest example is a cylinder of length much larger than its radius. Clearly, particle collection would be governed by the stronger gradients and would thus be a two-dimensional process. For a radius smaller than both Debye length and gyroradius, say 1mm, there might be neither space-charge nor magnetic-guiding effects, the current taking the largest possible value for the given geometry and bias (the orbital motion limited—called OML in what follows—regime of standard Langmuir theory). In the OML regime, and under the best ionospheric conditions, a cylinder with the same area as the TSS-1 anode ($8\text{m}^{2)}$ would collect 4 A if its bias was about 300 V, down by a factor 1/50 from the corresponding TSS-1 value! [8]

A cylinder of 1mm radius and 8m^2 area would be over 1 km long, however. Fortunately, tether lengths lie in the required range and their shape is optimal for collection. Hence, if left uninsulated, a tether could act as its own anode, capturing electrons efficiently over some positively biased segment. Collection would depend on a certain average of the voltage bias, which varies along the tether because of the motional electric field even if the ohmic voltage drop is negligible (in this case the average is 2/3 of maximum).

The current to a bare tether increases with both radius and (collecting) length. Certainly, for too large a radius, space-charge and magnetic effects would clearly come back into play, but this comes out to be hardly a limitation; a conservative value for maximum working radius would be 5 mm, a rather thick tether. This is a convenient result stemming from particulars of cylindrical collection well established in probe theory: In 3D geometry and ignoring magnetic effects, the OML regime holds only for a small radius-to-Debye length ratio, whereas, in cylindrical geometry it also holds for ratios of order unity [9]. Again, a 2D geometry has favorable consequences concerning



“Standard” Tether Generator

High-Current Bare-Tether Generator

Figure 1. Schematic comparison of standard insulated-tether and proposed bare-tether generators (not to scale). The bare-tether system should achieve higher current levels by collecting electrons more efficiently and over a large surface area.

magnetic effects. Although exact results on such effects are scarce, there is a known ("canonical") upper bound to current into a probe. For a sphere, the OML regime fails to hold, its current exceeding the canonical bound, when the bias is large enough (the condition of interest here) even if the radius is small compared to both the gyroradius and Debye length. The opposite holds in the case of a cylinder [10]. Hence, a cylinder of 5 mm radius (about one Debye length and small compared with the gyroradius) would work in the OML regime.

There is a final fortunate fact for 2D collection. It is known that current collected in the OML regime is identical for all cylinders with convex cross sections of equal perimeter; there is no similar result for 3D bodies [11]. To choose among cross section shapes note that, with maximum crosswise length fixed by OML considerations, a circle of that diameter (here 10 mm) would have the largest perimeter and would thus collect the largest possible current. On the other hand, for given perimeter the circle is the cross section with biggest area. This reflects on the weight of the tether and on certain dynamical considerations. There may be some virtue in trading some current for weight reduction. We might accomplish this by using a conductive tape, instead of a wire, as tether (getting an anode with 3 disparate characteristic lengths!). Reduction of weight might also be accomplished by making a tether of circular cross section to be conductive on a thin outer layer only. This is the type of question that we would address in the proposed Definition Study.

V. Bare-Tether Experiment in Space to Demonstrate High Currents

The availability of inexpensive deployers, like the Small Expendable Deployment System (SEDS), makes a low-cost demonstration flight particularly attractive. The SEDS deployer has already flown twice, in 1993 and 1994, when it deployed successfully a payload of about 25 kg to a distance of 20 km from a Delta II second stage (the mother station) orbiting in LEO. Specifically, the second mission (SEDS-II flown in 1994) demonstrated that a simple and passive (i.e. without any motor for reeling in the tether) deployer can deploy and stabilize a tethered payload along the local vertical if robust control techniques are adopted. The payload of SEDS-II achieved a stabilization of ± 4 deg about the local vertical at the end of deployment. Even more accurate values could be achieved if the safety constraint of zero control authority within close range of the mother station adopted in the SEDS-II is removed. A libration amplitude of ± 4 deg, however, would safely meet the stabilization requirements for a tether power generator. The SEDS deployer in its original configuration is suitable for deploying thin and flexible tethers. Modifications are necessary for adapting the deployer to the thicker and stiffer tethers required for a high-power power generator. The design simplicity of the deployer can, however, be retained while modifications to the spool and the actuator (braking system) would be required to handle the electrodynamic tether. One modification of the SEDS deployer concept to handle stiffer and thicker tethers was PMG that also flew in 1994. This modified deployer deployed a 500-m-long conductive tether for a low-power generator experiment with a tethered system. The PMG deployer had a larger-diameter spool than the SEDS deployer and, because of the relaxed requirements of that specific mission, did not have any actuator for controlling the tether exit velocity. It is conceivable that a suitable deployer for the proposed high-power power-generation mission could be made by simply adding a braking system to a PMG-type deployer.

The composition of our author group expresses the international character of our effort up to now. In keeping with the international character of the Space Station, we would seek to utilize the talents and resources of European and Russian contributors, whenever this appears desirable and feasible. The final makeup of the team is of course impossible to foresee at this early stage. It would be one of the primary goals of the Definition Study to come up with a specific recommendation on such matters.

We envision an experiment using a bare tether, with no power supply required. The tether would be uninsulated along its entire length. For usual eastward orbits, current flows upwards (electrons flow downwards), the anodic end, where there is no collecting device, lying at the top (marked A). Both a "useful" load of impedance Z and an electron-ejecting contactor, such as a hollow cathode, would lie at the bottom C (see Fig. 2). Neglecting the ohmic impedance, the tether bias relative to the ambient plasma would vary linearly along the tether, being positive at A, negative at C, and vanishing at some intermediate point B. Then, neglecting the cathode and ionospheric-closure impedances as well, the circuit equation becomes just

$$ZI_C = E_m L(1-l), \qquad (l \equiv L_B/L) \tag{1}$$

where L is the tether length, L_B the electron-collecting length from A to B, and E_m the motional electric field. We later discuss the impedances that have been neglected.

Between B and C the tether will collect ions (at a rate slow compared with the electron rate). The current $I(y)$ flowing along the tether clearly vanishes at A and reaches a maximum at B (the total electron current). Simple OML formulae lead to $I_B = I_M l^{3/2}$ and

$$I_C = I_M\left[l^{3/2} - \mu^{1/2}(1-l)^{3/2}\right] \tag{2}$$

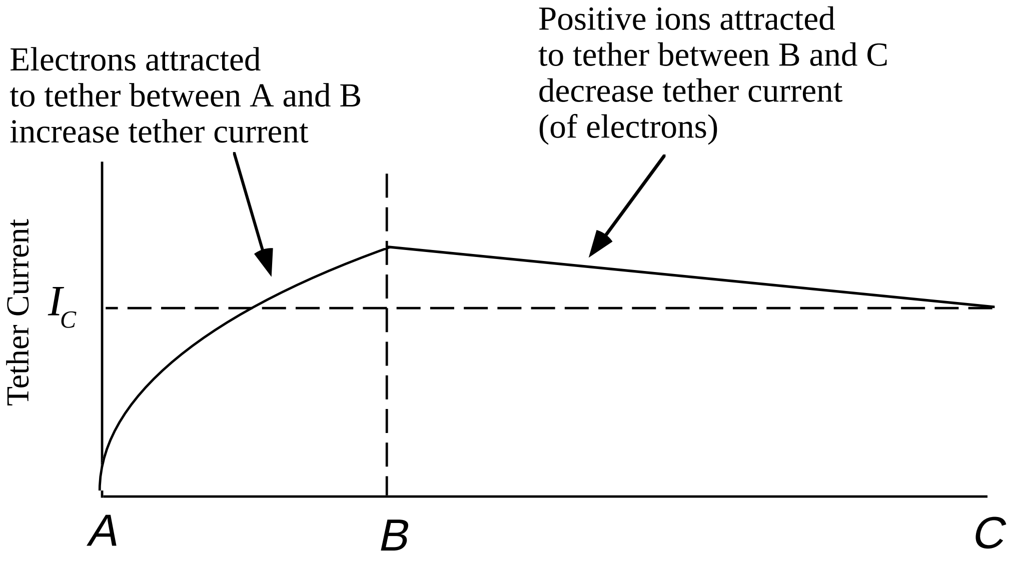


Figure 2a: Tether current versus distance from top of bare tether (*A*).

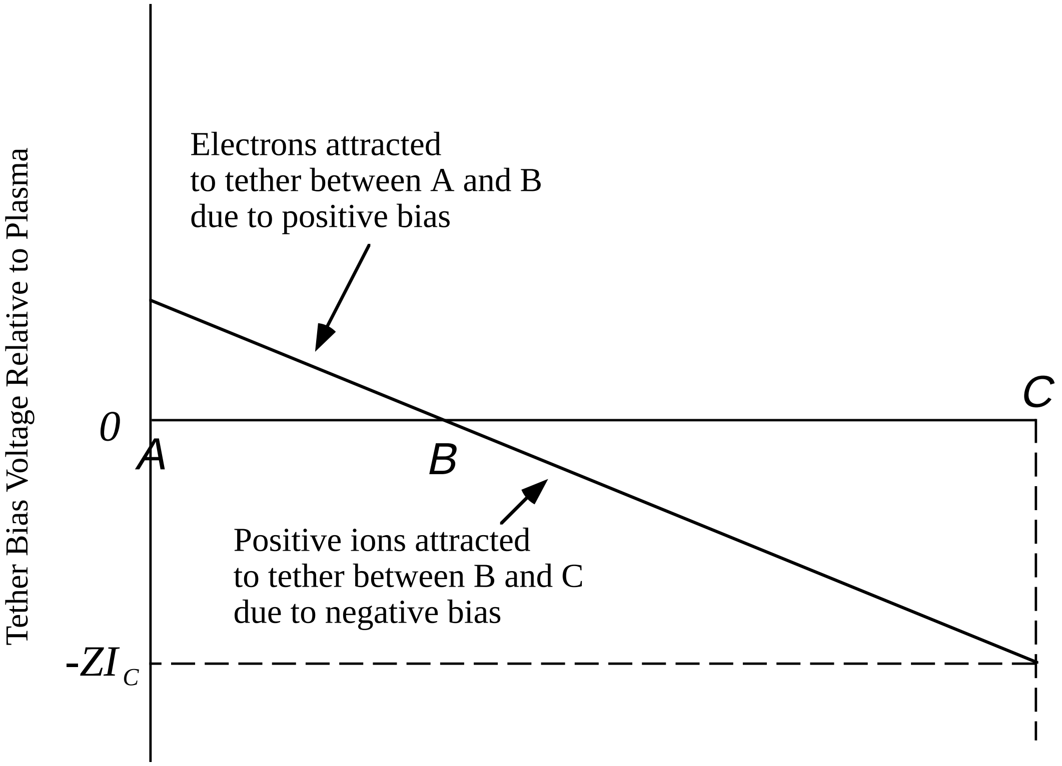


Figure 2b: Tether bias voltage versus distance from top of bare tether (*A*). Distance across load (*Z*) at lower end of tether is taken to be negligible. *C* is at plasma potential when active cathode is operating.

A is at top of tether. *C* is at lower end, where active cathode may operate. The point *B* designates the position along the tether where the tether is at the plasma potential. It is a distance L_B from top.

with $\mu \equiv \frac{m_e}{M_i}$ and $I_M = en_\infty \frac{2}{3} L \frac{p}{\pi} \sqrt{\frac{2eE_mL}{m_e}}$; n_∞ being the undisturbed electron density and *p* the perimeter of the tether cross section. There could be three parts to the experiment, corresponding to three different configurations, which we describe below.

First, we would test whether passive electron collection by bare-tether generators in space is fairly insensitive to ionospheric plasma density (n_∞) variations. There had been hope that *active* contactors would have this desirable property, but the results of the PMG experiment were discouraging. For a bare-tether generator, if n_∞ decreases, point *B* drops in Figure 2, increasing the anodic (electron-collecting) surface, and this in such a way that I_C keeps fairly constant, as we now show. For given ambient conditions and tether geometry, the impedance *Z* determines I_C *and* l (i.e. the position of *B*) in Eqs. (1)-(2). For our experiment, as well as for a future application in the Space Station, one takes Z such that the efficiency of generation, W_g / W_m, is maximum; W_g is the power at the load and W_m the mechanical power loss due to magnetic drag. The efficiency has a maximum when both l and $\mu^{1/2} / l^{3/2}$ are small, then taking the approximate form

$$W_g / W_m \equiv \frac{Z I_C^2}{\int_0^L E_m I(y) dy} \cong 1 - \frac{3}{5}\left(l + \frac{\mu^{1/2}}{l^{3/2}} \right),$$

leading to $\left(W_g / W_m \right)_{\max} \cong 1 - l_{opt} \cong 0.85$ at $l = l_{opt} \cong \left(\frac{3}{2}\right)^{\frac{2}{5}} \mu^{1/5} \cong \frac{1}{6.7}$.

The exact result is $l_{opt} \cong 0.140$. Using l_{opt} in (1)-(2), one finds the current I_C and Z_{opt}, which depends on n_∞ through the factor I_M. Z_{opt} is selected for maximum (day) conditions, $n_\infty = 10^{12} m^{-3}$. When n_∞ drops by half an order of magnitude to night values, l increases to a value $l \cong 1.8 l_{opt}$ as given by Eqs.(1)-(2), with the current I_C dropping by about 13%.

Next, there would be flight testing of the electron-collecting capability of a bare tether. This would be the critical demonstration that bare-tether systems are indeed capable of generating power at levels that could be useful for the Space Station. Our tether will be designed to reach a 10 A electron current under the best ionospheric conditions, while keeping the tether size as small as possible. This is accomplished by short-circuiting the load impedance (effectively setting $Z = 0$ in Eq.(1)) to move point *B* to

C, making the entire tether electron-attracting, $l = 1 \Rightarrow I_B = I_C = I_M$.

There is no useful power W_g during this part of the experiment; naturally, for power generation on the Space Station one would use a tether longer (and thicker) than the one here considered, so that a fraction l_{opt} of its total length could collect the high currents desired.

The 10A current attained in the experiment could serve two additional purposes. First, it would allow testing an active cathode at high currents and under (flight) conditions impossible to simulate in the laboratory. Secondly, it would resolve issues on tether radiation (current closure, whistler emission, signal on the ground) upon which there is as yet no agreement in the literature [12,13]. This would be made possible by two facts: a) power radiated by our tether would reach three orders of magnitude above values attained in previous flights; b) bare-tether collection being described by the simplest (passive) probe theory, reliable signal predictions would be available.

A final stage of the experiment, which may be considered a science bonus available with the system, could generate and study artificial auroral effects in the sub-keV energy range. The high-energy ions bombarding the segment *BC* of the tether liberate secondary electrons that are then outwardly accelerated to form a magnetically guided two-sided electron beam [14]. To get maximum ion current we would switch off the cathode at *C*. This makes I_C vanishing (equivalent to letting $Z \to \infty$ in Eq.(1)) and moves point *B* near *A*, with l obtained from Eq.(2)

$$l \cong \mu^{1/3} \cong 1/30 \Rightarrow I_B \cong I_M \mu^{1/2}.$$

The tether is now electrically floating ($I_A = I_C = 0$), collecting as many ions over 97% of its length as electrons reaching its upper 3% and again generating no power.

VI. Tether Design for High Power

For efficient power generation by tethers, the ohmic voltage drop, neglected up to here, should indeed be small compared with the induced e.m.f., $E_m L$. This leads to the condition

$$\frac{\int_0^L I(y)dy \Big/ \sigma_C A_C}{E_m L} \equiv \frac{W_M}{\sigma_C A_C E_m^2 L} << 1 \tag{3}$$

where A_C is the cross-section conductive area and σ_C is the conductivity.

On the other hand, the power per unit mass of conductive material,

$$\frac{W_g}{\rho_C A_C L} \equiv \frac{\sigma_C E_m^2}{\rho_C}\frac{W_g}{W_m}\frac{W_M}{\sigma_C A_C E_m^2 L} \qquad (\rho_C \equiv \text{density}),$$

should be kept high. Since the first factor on the right-hand-side above is bounded (about 0.52 kW/kg for aluminum with $E_M = 200\,V/km$) and the ratio W_g/W_m will not be far from unity, there is a trade-off between efficiency and weight. There is, clearly, no gain in reducing the ohmic drop beyond some point because the efficiency growth would taper off whereas the power per unit mass would keep decreasing. This poses mass requirements on power generation for both bare and standard tethers. Condition (3) itself makes less attractive the idea of using tapes (or tethers conductive on a thin outer layer) to reduce weight while keeping bare-tether collection high; tapes would be useful as floating tethers, which will always support low currents.

The best trade-off choice for bare-tether generators would make the relative ohmic drop comparable to the intrinsic efficiency loss l_{opt}, found in the previous section. In our experiment, condition (3) is most critical for stage 2, when the efficiency vanishes; the current I_M, however, may replace efficiency in the argument, the ohmic drop condition then reading

$$\frac{\int_0^L I(y)dy \Big/ \sigma_C A_C}{E_m L} \equiv \frac{3}{5}\frac{I_M}{\sigma_C A_C E_m} \cong \frac{1}{7}.$$

For a TSS-type orbit with $I_M = 10A$ and $\sigma_C E_m \cong 7A/mm^2$ (Al, $E_M = 200\,V/km$), this condition determines the radius of our tether to be 1.4 mm ($A_C \cong 6mm^2$).

The length L is determined from the equation

$$I_M \cong \tfrac{10}{12.5} e n_\infty \tfrac{2}{3} L \tfrac{p}{\pi}\sqrt{\frac{2eE_m L}{m_e}} = 10A$$

with $n_\infty = 10^{12}\,m^{-3}$ and p = 2.8π mm. We introduced the factor $\frac{10}{12.5}$ to account for the ohmic and cathodic voltage drops; the cathode must eject 10A under a bias not exceeding 70V. (The ionospheric closure impedance is too low to merit consideration.) We then find $L \cong 3km$. Finally, we determine the useful impedance from Eqs.(1)-(2),

$$Z_{opt} \cong \frac{E_m L}{I_M}\frac{1 - l_{opt}}{l_{opt}^{3/2}} \cong 0.99k\Omega.$$

We summarize below preliminary basic design characteristics:
Tether length and diameter: 3 km, 2.8 mm.
Tether material: Multistrand Al wire coated with an oxidation-resistant conductive paint (to maximize σ_C/ρ_C, reduce beam rigidity and prevent formation of an oxide layer).
Tether mass: 49.9 kg.
Useful impedance: 0.99 kOhms

VII. Summary and Conclusions

We have established in principle the potential for a bare-tether high-power generator for the Space Station. Powers in the range of 10-25 kilowatts appear feasible with simple hardware. While the detailed timeline needs to be established through further studies, we envision a development program leading to implementation of this concept through a series of program elements as shown in Table 1:

TABLE 1: A PROPOSED ROADMAP

PROGRAM ELEMENT	APPROXIMATE DATE
1. White paper	This document
2. Definition Study Feasibility analysis Conceptual Design of Demonstration Flight Mass, Cost and Schedule estimates	By Dec. 1996
3. Demonstration Flight Detailed Design Procurement and Construction Flight Operations	By July 1999
4. Space Station Implementation	Early 2000's

Specifically, at this point we propose to initiate the Definition Study phase of this program. This phase could take about eight months. The Smithsonian Astrophysical Observatory could serve as prime contractor for the study. We recommend that NASA provide funding for this study in the near future, in order to keep open the option of using high current tethers for a supplementary power system in the early stages of the Space Station operations.

VIII. References

1. Martinez-Sanchez, M. and Hastings, D.E., “A Systems Study of a 100 KW Electrodynamic Tether,” *J. Astro. Sci.* **35**, 75 (1987)

2. Crouch, D. in *Proc. 4th Int. Conf. on Tethers in Space* (1995).

3. Lam, S., “Unified Theory for the Langmuir Probe in a Collisionless Plasma,”*Phys. Fluids* **8**, 73 (1965)

4. Katz, I. and Davis, V.A., “On the Need for Space Tests of Plasma Contactors as Electron Collectors” in *Proc. 2nd Int. Conf. on Tethers in Space*, 241 (1987)

5. Savich, N.A. and Sanmartín, J.R., “Short, High Current Electrodynamic Tether” in *Proc. Int. Round Table on Tethers in Space*, 417 (1994)

6. Lilley, J.R.; Greb, A.; Katz, I.; Davis, V.A.; McCoy, J.E.; Galofaro, J.; Ferguson, D.C., “Comparison of Theoretical Calculations with Plasma Motor Generator (PMG) Experimental Data,” AIAA paper No. 94-0328 (1994).

7. Sanmartín, J.R., Hayard, M. and Soudet, M., “Science with an Electrodynamic Tether” in *Proc. Int. Round Table on Tethers in Space*, 171 (1994)

8. Sanmartín, J.R., Martinez-Sanchez, M. and Ahedo, E., “Bare Wire Anodes for Electrodynamic Tethers,” *J. Prop. Power* **9**, 353 (1993); Sanmartín, J.R., Ahedo, E. and Martinez-Sanchez, M., “An anodeless tether generator” in *Physics of Charged Bodies in Space Plasmas,* 201 (1991).

9. Laframboise, J.G., “Theory of Spherical and Cylindrical Langmuir Probes in a Collisionless, Maxwellian Plasma at Rest,” *Univ. of Toronto - Institute for Space Research Report* No. 100 (1966)

10. Rubinstein, J. and Laframboise, J.G., “Upper-bound current to a cylindrical probe in a collisionless magnetoplasma,” *Phys. Fluids* **21**, 1655 (1978); “Theory of a spherical probe in a collisionless magnetoplasma,” *Phys. Fluids* **25**, 1174 (1982)

11. Laframboise, J.G., and Parker, L.W., “Probe design for orbit-limited current collection,” *Phys. Fluids* **16**, 629 (1973)

12. Sanmartín, J.R. and Martinez-Sanchez, M., “The radiation impedance of orbiting conductors,” *J.Geophys. Res.* **100**, 1677 (1995)

13. Estes, R.D. and Sanmartín,, J.R., “Alfven Wave Signature from Constant-Current Tethers” in *Proc. 4th Int. Conf. on Tethers in Space*, (1995).

14. Martinez-Sanchez, M. and Sanmartín, J.R., “An Extended Electron Beam for Auroral Studies,” in *Proc. 4th Int. Conf. on Tethers in Space* (1995).

Appendix: Proposed Team for Definition Study

The authors of this paper would bring to the study the following strengths and experience in the fields of tether science and technology. R. D. Estes of the Smithsonian Astrophysical Observatory (SAO) is PI on the TSS-1R investigation to measure electromagnetic waves excited by the tether. He has also carried out several NASA-funded studies on tether power generation and wave excitation in the past dozen years. E. C. Lorenzini, another SAO scientist with over a decade of tether work, specializes in tethered system dynamics and was PI on the project that developed the SEDS control laws. M. Martinez-Sanchez of MIT's Aeronautical and Astronautical Engineering Faculty has also been active in tether research for many years, focusing particularly on feasibility and systems studies for tether applications. J. R. Sanmartín of the Madrid Polytechnic University is a leading theoretician on the subject of bare tether current collection. In recent years Prof. Sanmartín has also made numerous contributions to the physics of tether wave generation and propagation. His proposal for an early and simple check on bare tethers was recommended for a Columbus Precursor Flight by a Science Panel convened by the European Space Agency in Heidelberg, March 1992, but the flights were canceled due to funding shortages. N. A. Savich, a member of the Institute of Radio Engineering and Electronics of the Academy of Sciences, is a veteran of numerous Russian space experiments. His presence in our group signals his strong interest in participating in the evolution of the project on through the demonstration experiment, which he hopes to see carried into space on a Russian launch vehicle as part of his recently approved *Volcano* project.