Review of Electrodynamic Tethers for Space Plasma Science

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This paper presents a review and analysis of possible uses of orbiting electrodynamic tether systems. The concept involves the electrical and mechanical connection of orbiting bodies. One particularly interesting configuration has the two bodies radially oriented with respect to the Earth with an electrically insulated wire maintaining both a mechanical constraint upon the bodies and, at the same time, providing electrical connectivity. In application, electrodynamic tethers offer a new way of probing different natural and artificial processes in space plasmas. In particular, the combination of orbital emf and the fact that electrical currents can pass through the tether, a variety of novel charge and current injection experiments can be undertaken. The basic modes of interaction are reasonably well-understood from various rocket experiments and theory and, based upon this information, it is possible to project a variety of important scientific uses. A simple division of these is into applications supported by high-impedance tether systems and those relying upon the existence of low impedance. However, because the electrodynamic tether systems can operate at high voltages, there is considerable uncertainty about the precise way they will interact with the ambient plasma of low Earth orbit, and this also provides an area of new technical investigation.

Nomenclature

A_u = upper-body area
A_l = lower-body area
$\boldsymbol{B}(l)$ = magnetic-field intensity
D = linear dimension of body perpendicular to magnetic field
$\mathrm{d}\boldsymbol{l}$ = increment of vector distance measured along tether
e = electron charge
$\mathrm{emf} = \int_0^L \boldsymbol{V} \times \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{l}$ = tether electromotive force
I_S = electron source current
I_T = tether current
$j_{te} = \frac{1}{4} e n_e (8kT_e/\pi m_e)^{1/2}$ = electron thermal current density
j_e = electron current density
j_i = ion current density
$j_{it} = e n_i F$ = ion sweep-up current
k = Boltzmann's constant
L = total tether length
l = tether-length coordinate measured along deployed tether from lower to upper body
m_e = electron mass
n_e = electron density
n_i = ion density
R = resistance of tether and internal load
T_e = electron temperature
$V\perp$ = velocity of tether perpendicular to magnetic field
$\boldsymbol{V}(l)$ = tether velocity
Φ_u = potential of upper body relative to plasma
Φ_l = potential of lower body relative to plasma

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I. Introduction

IN-DEPTH studies of the use of tethers for space experiments were made by NASA's Atmospheres, Magnetospheres, and Plasmas in Space (AMPS) study group, convened from 1973–1976 in anticipation of new space-flight opportunities for the then-developing Space Shuttle. The idea of an electrodynamic tether evolved as a particular application of the general concept. In particular, it was noted that an orbiting wire, clad with an electrically insulating jacket, possesses three significant properties: 1) by virtue of its orbital motion, such a wire would have an intrinsic electromotive force (emf) of several tenths of a volt per meter of length perpendicular to the geomagnetic field; 2) as a consequence of the insulation, access of external electron and ion currents to the wire is confined to specific locations, such as the ends of the wire; and 3) the wire can provide a low-resistance path connecting different regions of the ionosphere having different electrical potentials.

Over the past 15 years, there have been a number of exploratory studies for applications of electrodynamic tethers in space plasma science and technology. During the AMPS studies, Grossi[1,2] proposed the use of a long, bare wire as an antenna for emitting low-frequency radio waves in the ionosphere. Williamson and Banks[3,4] conceived of the insulated-wire electrodynamic tether in the context of generating large currents which could be used to derive electrical power from orbital energy and to generate intense ELF and VLF waves. Many later studies have been made of various aspects of this system.[5-13] Topical discussions of important questions relating to the physics of tether-plasma interactions have been presented in several workshops.[14-16]

A seminal report on the uses of tethers was produced in 1980 by a NASA-sponsored Tethered Satellite Facilities Requirements Definition Team (FRDT).[17] The FRDT final report presented a significant list of important objectives for tethered satellites and, in particular, identified a set of fundamental space-plasma experiments, which could be undertaken with an electrodynamic tether system comprising the Space Shuttle Orbiter, an electrically insulated tether of ~20 km length, and an electrically connected satellite. The importance of the new scientific opportunities offered by this electrically active system was recognized by NASA, the Italian National Space Agency (ASI), and the space science community. By 1983, the U.S.-Italian tethered satellite system-1 mission was defined as one that would be devoted to exploring the complex plasma phenomena associated with flying electrically active

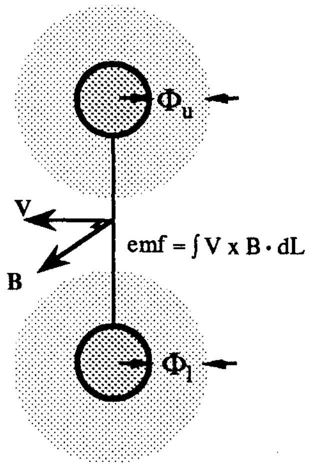

Fig. 1. EMF and potentials in an orbiting electrodynamic tether system as viewed in a co-moving coordinate frame.

wires in space. The details of this mission, expected to fly in space in 1991, are described by Stuart et al.[18]

In this paper, a review is given of the various scientific investigations associated with electrodynamic tethers. These include the need for exploring the way such systems interact with space plasmas as well as possible applications to other problems of interest to space science and technology. Although early thoughts about how electrodynamic tethers worked were largely conceptual in nature, there now exists a firmer understanding of the ways such systems interact with the ambient plasma of the ionosphere. And, although there have, as yet, been no orbital flights of electrodynamic tethers, there have been several rocket experiments that have simulated some aspects of the electrical processes thought to be important for orbiting systems.[20,21]

II. Basic Principles

Figure 1 shows a simple model of an orbiting electrodynamic tether system viewed from a co-moving coordinate frame. Two payloads are connected via an electrically conducting tether of total length L. Orbital motion of this system provides an electrical interaction between the wire and the geomagnetic field. The tether is electrically insulating so that current can enter or leave the system (via active or passive means) only at the connected bodies. Although other possibilities exist, we consider here only the situation where the tether system is deployed in the radial direction with respect to the Earth. With an eastward (normal) orbital velocity and the south-to-north direction of the geomagnetic field, the polarity of the emf is such as to drive electrons from the upper body toward the lower. The total tip-to-tip emf generated in this system is $\text{emf} = \int_0^L \boldsymbol{V}(l) \times \boldsymbol{B}(l) \cdot \mathrm{d}\boldsymbol{l}$, where l is a coordinate measured along the tether, $\mathrm{d}\boldsymbol{l}$ is a vector increment of length along l, and the integration is taken over the path defined by the deployed tether leading from the lower body to the upper. In addition, we have included the possibility that the magnetic field $\boldsymbol{B}(l)$ and the velocity $\boldsymbol{V}(l)$ of each increment $\mathrm{d}l$ of the tether may depend upon the tether-length coordinate l measured positive upwards from the lower body. Typical emf's generated in a low-inclination circular orbit with a static 20 km radially deployed tether range from 1500 to almost 5000 V. Electrical models of the electrodynamic tether system have been discussed previously.[6]

A. Passive Electrical Connection to the Plasma

A totally insulated wire tether has no electrical interaction with its surroundings: no current can pass to or from the wire and the internal emf is balanced by an internal polarization electric field such that, to zeroth order, there is no net force on the charge carriers of the conductor. Small, transient currents do exist in the tether, however, in response to temporal changes in the emf.

If one end of the tether system is exposed to plasma, and the other remains insulated (or unconnected), current passes in the tether until the exposed body potential is equal to the local plasma potential. The opposite tip of the tether then possesses a high voltage relative to its surroundings, but unless there is breakdown, no further current results.

Passive, direct electrical connection of both ends of the tether to plasma can be made in various ways and with different consequences. If the two terminating electrodes are simply bare conducting surfaces, then electrons will be attracted to the upper body and ions to the lower. In this situation, electron and ion currents will equilibrate with certain voltages (or potentials) existing between the two electrodes and their surrounding plasma. This current balance can be expressed as $j_e A_u = j_i A_l$. The electron thermal current in the ionosphere is much larger ($j_{te} \sim 1$–11 mA m^{-2} for typical ionospheric densities of $10^{11} \leq n_e \leq 10^{12}$ m^{-3}) than the ram current of the ions at orbital velocity ($j_{ti} \simeq 0.1$–1.0 mA m^{-2}). Thus, for equal collecting surface areas at the ends of the tether system, the electron current will charge the tether system to a point where the voltage of the upper body relative to its surrounding plasma is small and slightly positive. The voltage of the lower end will be large and negative. In this situation, the lower end of the tether is at voltage approximately that of the full emf of the system. This happens because even at voltages of several kilovolts, the ion current that can be extracted from the plasma is very small and the ram ion current j_i is not substantially increased above the thermal current j_{ti} by the presence of high voltage. For the Space Shuttle, $A_l \sim 40$ m^2 and with the same range of ion and electron densities mentioned above, $I_T \sim$ 4–40 mA when the metallic Orbiter engine bells are in the ram direction.

The tether current in the passive situation just described is small, being limited by the pick-up flux of ions (and photoemissive current, if the system is in sunlight) on the exposed conducting areas of the lower body. As a consequence, the interaction of the tether system with the ambient plasma is weak (currents are small, plasma wave amplitudes are low and the $\int I \mathrm{d}\boldsymbol{l} \times \boldsymbol{B}$ force on the overall tether system is negligible). The behavior of a passive, completely bare tether has been discussed previously[29] and, likewise, has only a weak interaction with the background plasma.

A different situation is obtained if $A_u \ll (j_i/j_e)A_l$. This could occur, for example, if the exposed conducting area of the upper body is small. If the inequality holds, the ion current will charge the tether system to the point where the lower body is at local plasma potential and the upper body is at a large, positive potential relative to its surroundings. However, unlike the situation for the ions, it is possible to appreciably increase j_e through the application of high voltage. The standard Langmuir relation expresses this increase for voltages on the order of a few volts, but for higher voltages complicated plasma processes intervene and there is no generally accepted result. For example, Linson[22] discusses this high-voltage sheath situation in the light of competing models for electron-current collection from magnetized plasma at high spacecraft potentials.

It should also be mentioned that if the upper (electron collecting) body possesses high surface resistivity, this will have an important effect upon the tether current. The presence of a nonconducting film or paint will result in a substantial voltage drop at the surface of the body, lowering the net voltage seen by the surrounding plasma. In this case, small ion currents entering the tether system from the lower body will be able to charge the overall tether system to produce a large voltage drop between the interior electrical ground circuit of the upper-body ground and its exterior surface. In this circumstance, Φ_u, the potential of the exterior surface of the film or paint relative to its surroundings remains small since the external thermal electron flux must pass through the high resistance of the surface covering. This unprofitable situation could be obtained, for example, if the upper body were anodized or covered with a nonconducting paint. For sufficiently large voltages, however, arcing and subsequent heating of the thin surface would occur, bringing at least portions of the surface back to its normal conducting state.

B. Active Electrical Connection to Plasma

The limits of the passive situation can be improved upon by finding ways to increase the transfer of current between the upper and lower bodies and their surrounding plasmas. In the normal flight configuration shown in Fig. 1, the first step is to increase the current to the lower body. In Williamson and Banks,[3,4] this was accomplished by active electron emission. With a simple electron source, it is possible to arrive at a situation where the overall tether current balance involves three separate voltages: that of the upper body relative to its plasma, the tether system and any internal load-resistance voltage drops, and the voltage of the lower body relative to its background. By providing electron emission at the lower body, it is possible to change the values of Φ_u or Φ_l as long as the active source current is small; i.e., $I_S < A_u j_{te}$. Larger values of I_S can bring Φ_l towards zero, leaving Φ_u as the difference between the emf and the internal $I_T R$ voltage drop. The actual values of the voltages depend, however, on the ability of the upper body to collect electrons. In the simplest model of electron-current collection, the current in the tether would be limited by the ability of the upper body to collect thermal electrons; i.e., $\sim A_u j_{te}$. For example, with a 1-m-radius sphere for the upper body, $I_T \sim 4.2$–42 mA with the range of ionospheric electron densities given previously. The actual current in the system and the voltages of the upper and lower bodies is determined by a nonlinear relationship between the impedance of the upper plasma sheath and the electrical characteristics of the lower-body electron emitter. As the lower-body electron current increases, the voltages of the upper and lower bodies will change, and this, in turn, will affect both the collection and emission currents.

Although it is relatively easy to construct high-current electron emitters, the basic limitation of the electron-emission method is the high impedance of the source and the collecting surface area of the upper body. To yield larger currents, Williamson and Banks[3] suggested using a large, metallically surfaced body similar to the radiowave-reflecting ECHO-1 balloon satellite of the 1960's (for a description of ECHO-1, see Ref. 23). With a 30-m-diam balloon, for example, tether currents between 3 and 30 A could be collected via the random thermal electron current of the ionospheric F-region. Although such large bodies have disadvantages in terms of orbital drag at F-region heights, i.e., 300 km or less, they also could be readily discarded, thereby avoiding the complexity of unstable retrieval that faces the practical use of all reusable tether payloads.

To achieve still larger tether currents, some way of increasing plasma-to-tether currents must be provided for both ends of the system. The use of so-called plasma contactors is one solution to the problem. These devices can emit large charge-neutral clouds of plasma and neutral gas at either end of the system. The clouds have electron and ion densities much greater than the background plasma and give substantial surface areas contacting the ambient plasma. Thus, it has been predicted that large currents can be drawn from and given to the ionosphere with low effective resistance.[9-11] In addition to raising the local plasma density, if significant potentials are present, internal electron impact ionization of the neutral gas in the vicinity of the plasma cloud can give an additional source of local ionization. In the best possible situation, the tether current is then limited by the combination of internal tether-system resistance plus the resistances of the plasma sheaths surrounding the upper and lower bodies.

It is clear, however, that the higher currents offered by plasma contactors must be obtained at the price of having to supply gas to the plasma devices. This is in contrast to the passive, large-conductor approach where current is obtained through a large surface area. Frequent use of contactors in applications such as auxiliary power for space stations could have negative environmental impacts measured in terms of plasma and neutral gas contamination.

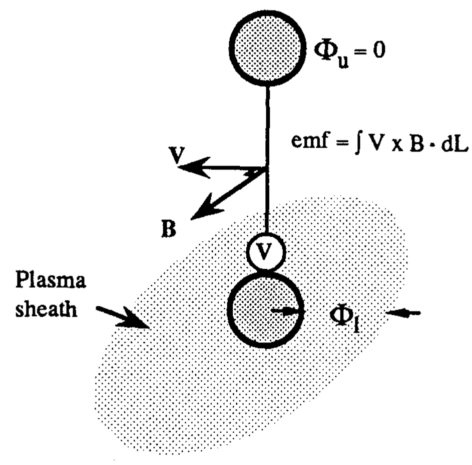

Fig. 2. Schematic of tether voltage measurement relative to the lower body.

Based on theoretical analyses,[9-11] it is thought that many tens of amperes of current can be driven through electrodynamic tethers using state-of-the-art plasma contactors. If so, then these become strongly coupled to the ambient plasma: strong magnetic-field currents will link the upper and lower bodies, a host of ELF and VLF waves will be generated from the tether and surrounding plasma, and various lingering echoes of the system will mark its passage around the Earth. These phenomena offer many new areas of investigation for space plasma physics and are important because they mimic, in many cases, natural plasma phenomena of the magnetosphere and other objects.

III. Applications

The last section emphasized the active coupling of tethers to the ionospheric (or other) plasma. However, it must be recognized that there are important scientific uses of electrodynamic tethers that do not require large coupling currents. Traditional radio wave antennas and the use of remote bodies as voltage references are two examples of systems that are not dependent upon extracting large currents from the surrounding medium. In addition, there are legitimate interests in the electrical model of the tether itself; i.e., its ability to act as a transmission line with distributed capacitance and inductance, the possibility of exciting resonances in the system, etc.

To discuss the full range of potential electrodynamic science questions, it is useful to divide the topic into two parts: one relating to low-impedance tether systems, which are strongly coupled to the plasma medium, and the other focusing on high-impedance tethers that require only weak coupling. We begin with high-impedance systems.

A. High-Impedance Electrodynamic Tether System

Using the description of the last section as a guide, consider a tether system that has a high-impedance voltmeter placed between the lower end of the tether and the lower conducting body (see Fig. 2). In this situation, there is no dc tether current and both conducting bodies will be at approximately local plasma potential and the full tether emf will be measured by the voltmeter. The lower body will be at a negative voltage (the full emf) relative to the tip of the tether. This particular arrangement permits us to make sensitive measurements of both the emf generated by the tether and any smaller voltages related to background radio and plasma waves or to electric fields present in the ionosphere. It is limited by the effects of ac currents and deviations of the two bodies from local plasma potential.

Since the emf due to tether interactions with the geomagnetic field is accurately known, measurement of the total emf has a certain practical usefulness. It has been suggested[19] that one can use this measurement to accurately deduce the tether vector length, $\boldsymbol{L}$. Since the location of the tether and its upper body will always be a concern to tether-system operators, this measurement may provide an inexpensive means of being sure that the system is still physically attached and in the correct location relative to its partner.

Many deviations from the full emf for orbital systems will also occur. The largest of these will relate to the presence of ionospheric electric fields. At low latitudes, these are ~0.1-1 mV m^{-1}; i.e, about 0.1-1 % of the $\boldsymbol{V}\times\boldsymbol{B}$ electric field. Measurements of these fields will be relatively easy to make and the results can be used to determine the nature of ionospheric electrodynamics. The length of the tether is an important factor since it provides a means of measuring weak fields which are difficult to obtain with various other types of satellite instruments. At the equator, the system will measure primarily the component of electric field perpendicular to $\boldsymbol{B}$.

At high magnetic latitudes, the passive measuring system encounters more dynamic situations. The electric fields perpendicular to $\boldsymbol{B}$ can be as large as 0.1 V m^{-1} or about 20% of the $\boldsymbol{V}\times\boldsymbol{B}$ electric field. However, the radial deployment of the tether will discriminate against these in favor of much small components of electric field parallel to $\boldsymbol{B}$. Such parallel components of the electric field are extremely difficult to measure directly in the ionosphere, and a polar-orbiting tether system could provide important, new information about the high-latitude electrodynamic environment.

Finally, at still lower levels, one can expect to measure ac voltages induced through the presence of various types of electromagnetic and electrostatic waves in the ionosphere. Based on results obtained from a 440-m electrodynamic tether flown on the CHARGE-II rocket of December 1985,[20] this broadband noise may give rise to voltages of several volts or more, depending upon tether length and location. Observation of such voltages is certain to provide interesting information about the electrical behavior of long wire antennas in plasma and on the occurrence of low-frequency waves in the ionosphere.

It is also possible to use a high-impedance tether system to make measurements of the electrical potential of the lower body. It is well-known from rocket and Space Shuttle experiments that measurement of the potential of beam-emitting platforms is difficult. When beam currents more than 100 mA or so are operated, both rockets and the Space Shuttle charge to high (~hundreds of volts) potentials, creating thick, turbulent plasma sheaths. Standard plasma probes are unable to provide accurate measurements of vehicle potential for these conditions. By using the remote upper body as a reference potential, and knowing the value of the tether emf via ephemeris data, the time-dependent potential and return current variations of the electrically active platform can be determined.

B. Low-Impedance Electrodynamic Tether Systems

There are a variety of fundamental science and technology investigations that are associatedwith low-impedance tether systems; i.e., configurations where the links to the plasma, are held to the smallest possible value. Both scientific and practical applications of low-impedance systems are discussed in the following paragraphs.

Plasma-Current Collection by High-Potential Conductors

Observations of the basic fundamental plasma processes affecting electron and ion current collection in a low-density plasma are very limited with only the results of a few space experiments available to guide the development of theoretical models. Early studies[22,24] attempted to give voltage-current relationships taking into account the anisotropy associated with magnetic field and plasma turbulence. These gave relationships that predicted order of magnitude differences at large voltages, depending upon the particular model.

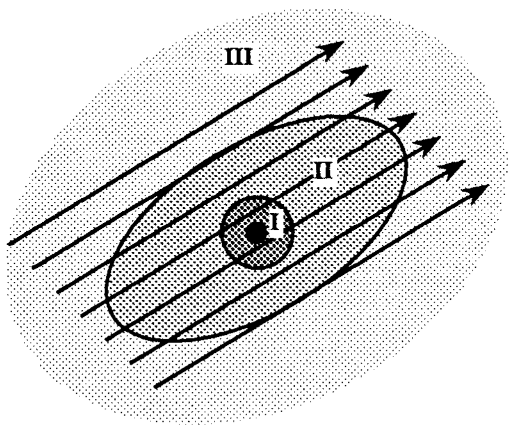

Fig. 3. Physical zones within a plasma contactor cloud.

Experiments with the recent CHARGE-II tethered rocket give some insight to what can happen in the ionosphere.[20] In this experiment, a 1-keV electron source was connected to a tether and various plasma parameters were measured during beam emissions. It was found that both payloads became highly positive (400-600 V) during beam emissions of a few tens of milliamperes. At these potentials, no substantial enhancement of electron current collection above that offered by the electron thermal current was measured. However, at times when small reaction control system thrusters fired, electrical discharges occurred. These provided sufficient electron current to bring the payloads to within a few tens of volts of plasma potential and allowed the full beam current to escape the rocket.

Similarly, measurements with the Maimik electron-beam rocket in 1985[25] showed that electron emissions created a large, disturbed sheath to distances of 20 m from the main electron-emitting payload. These were associated with strong charging of the payload and reflected an inability of the plasma to supply an adequate electron current to the solid surface of the payload.

In the context of electrically active tethers, these results indicate that physical current collection at metallic surfaces exposed to ambient plasma will never be substantially enhanced to levels much larger than j_{te}. Thus, even if strong plasma turbulence is created by high-voltage surfaces, this alone seems inadequate to establish a sufficiently large external (away from the surface) area to permit adequate, low-sheath-resistance current collection. Consequently, measurement of the plasma sheath surrounding the highly biased tethered satellite is a prime goal of space experiments and should be considered as an important part of the technology base surrounding the development of electrodynamic tether power and propulsion systems.

Plasma Contactors

Extensive studies have been made of the mechanisms operative in the use of plasma contactors.[7,9,10] This work shows that there are three distinct regions surrounding such a plasma emitter (see Fig. 3). In the inner zone I, a diamagnetic region forms within which ions and electrons move radially, unimpeded by magnetic effects. Outside of this, there is more extended zone II where the magnetic field is largely that of the background but where the plasma $\boldsymbol{V}\times\boldsymbol{B}$ electric field is substantially reduced owing to polarization within the plasma cloud and the overall electrical potential is that of the source. Within this zone, the electrons are magnetized while the ions expand radially. The outer boundary of this zone occurs where the ions begin to turn under the influence of the magnetic field. Zone III is that which extends to greater distances with gradual diminution of perturbations to the electric field.

In a practical sense, the operability of electron collection via plasma contactors has yet to be demonstrated in space. Although laboratory measurements of ion collection give reason-able agreement between theory and experiment, electron collection presents substantial difficulties from the demands placed upon the laboratory electron source. Attempts to draw large electron currents to mimic expected space applications lead to depletion of plasma electrons and large electric fields develop between the plasma contactor and the chamber walls. Thus, space experiments are essential to confirm theoretical predictions of plasma-contactor operations.

It has been suggested from theoretical studies that plasma turbulence will play an important role in setting the current-carrying capacity of the plasma cloud.[10] The modes of turbulence studied to date include the Buneman instability, the ion-acoustic instability, and the oblique ion-acoustic instability. Since the electron drift-velocity thresholds for these are about the same, determination of the actual processes responsible for assisting electrons in moving across magnetic field lines remains to be done with careful experiments in space. However, we note that the results of the CHARGE-II experiments indicate that this effect may not be as important as the theory suggests.

An additional source of uncertainty is the role that electron impact ionization plays in raising the local plasma density. If electrons are strongly energized, this may play an important part in the overall process.[26] From CHARGE-II results, it is clear that small amounts of neutral gas can be readily ionized to yield substantial collection currents.[27]

Plasma-Wave Generation

Much attention has been focused on the large-amplitude plasma waves which are generated by the tether and plasma currents associated with the low-impedance electrodynamic tether system. By coupling the long, insulated wire to physically separate regions of the magnetized plasma, it is possible to create low-frequency disturbances which propagate under the control of the geomagnetic field. These waves will travel to different regions of the ionosphere and magnetosphere and echo for substantial periods of time after their generation. During their lifetime, if they are sufficiently strong, it is possible that these waves may undergo resonant interaction with energetic electrons of the trapped electron radiation belts.

The waves generated by the tether system are unusual in that they result from the steady flow of current in the wire. These arise in the frame of reference of an observer from the injection of the current into the background ionosphere by the moving platform. The fundamental wave response of the system is determined by two things: the time the upper and lower conducting bodies (of linear dimension D) remain in contact with a given magnetic field line, i.e., $\tau = D/V$; and the propagation modes of the ionospheric plasma. When the dimension of the body is small, high-frequency waves are initiated but can propagate only to the extent that they satisfy the disperson relation of the magnetized plasma. When D is large, low-frequency hydromagnetic waves are created that propagate largely parallel to the magnetic field lines.

A number of analyses of these waves generated by tethers have been made in recent years[12,28,30] but no fully self-consistent model of the waves and the currents in the tether has yet been made. Initially, it was thought that the principal model of radiation was that of low-frequency Alfven waves, but more recently it has been shown[30] that it is possible that the major radiation will occur in the VLF whistler bands. The radiation resistance of a long tether is still a matter of theoretical debate.

VLF Wave Interactions

With sufficient current, large-amplitude waves are predicted to be generated by electrodynamic tether systems. These can be used in a variety of ways to probe the Earth's ionosphere and magnetosphere. For example, it is well-known that natural and man-made VLF waves interact through a gyroresonance with trapped radiation-belt electrons, causing the electrons to scatter into the atmosphere.[31]

It is also possible for large-amplitude VLF waves generated by a tether system to be detected far from their point of origin. Owing to the complex index of refraction governing the propagation of these waves with its dependence on plasma density and magnetic field direction, remote observations of these artificially generated waves can give a new means of probing the plasmasphere—a large toroidal, magnetic field-aligned structure of low-energy plasma surrounding the Earth up to about 60 deg-magnetic latitude.

Power and Propulsion

One of the immediate applications long foreseen for the electrodynamic tether is that of producing electric power. The basic principles of such a system were studied by Drell et al.[32] in 1965 and Moore[33] in 1967. A study of 100-kW tether power system has been made[13] and there is no reason to believe that projects of such magnitude are not possible, if the theoretical predictions of the plasma sheath resistance prove to be correct. In this context, there is a surprising lack of supported research into the fundamental plasma physics of enhanced current collection and emission required by such powerful systems. Laboratory and space experiments involving high-voltage, high-current collection are an essential part of future planning in this area, and the development of major plans without such supporting background work is certainly risky.

IV. Summary and Conclusions

There are many innovative uses for electrodynamic tethers in space science and technology. Unfortunately, at the present time we lack experimental evidence supporting the full range of ideas surrounding the use of electrodynamic tethers in space. Although various laboratory measurements provide information about ion-collection modes of plasma contactors, and several moderate voltage tether systems have been flown with rockets, there is, as yet, no confirmation of the fundamental system operation as it has been described in the literature. In a fundamental sense, theory has outrun measurement. Thus, over the next few years the principal aim of electrodynamic tether investigations must be to observe and understand the basic plasma interactions which give rise to, and limit the current in, the active tether system.

Acknowledgments

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