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High Voltage Characteristics of the Electrodynamic Tether and the Generation of Power and Propulsion

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BY

P. Roger Williamson

STAR Laboratory
Department of Electrical Engineering
Stanford University
Stanford, CA 94305
(415) 497-9774

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1. Introduction

The Tethered Satellite System (TSS) will deploy and retrieve a satellite from the Space Shuttle orbiter with a tether of up to 100 km in length attached between the satellite and the orbiter. Instruments on the satellite and in the payload bay of the orbiter will be used to perform measurments of the environment and conduct active experiments. On the first and third missions of the TSS, called Electrodynamic Tether missions, with a deployed length limited to 20 km, the tether will include a conducting core covered with insulation. On the second mission, in which the full 100 km length of the tether will be deployed, the tether will be composed of only nonconducting materials. Electrodynamic Tether missions will include equipment on the orbiter for emitting electrical charge and controlling the current in the tether. In general, the satellite will collect electrons, the tether will conduct current between the satellite and the orbiter, and the orbiter will emit electrons. Variations in the tether current will be used to perform unique active experiments in the space environment and study the interaction of the orbiter (a large spacecraft) with the Low Earth Orbit (LEO) environment.

The TSS tether will be the largest object to ever fly. Although the tether is essentially one-dimensional, this one dimension is several orders of magnitude larger than any object previously put into orbit. The interaction of this large object with the space environment includes several phenomena already known. The most prominent of these effects arises from the motion of the tether combined with long length; an emf, produced by VxB, of 0.1 to 0.25 volts per meter, translates into a potential difference of up to 5000 volts between the locations of the two ends of the tether. The satellite is positive with respect to the surrounding plasma and in general is attached to the conducting tether. The end of the tether in the payload bay of the orbiter appears as simply a wire, connected to a negative, high voltage power supply. Experiments are carried out by emitting electrons from this "negative power supply" into the space surrounding the orbiter. Numerous variations on this configuration are possible, including the use of a negative, high voltage power supply on the orbiter to reverse the flow of current in the tether such that the satellite collects positive ions and the orbiter either emits positive ions or collects electrons. The tether may also be disconnected from the satellite and connected to the orbiter, in which case the end of the tether in the orbiter payload bay is at the same potential as the orbiter and the end of the tether at the location of the satellite appears to be a wire connected to a positive, high voltage power supply of up to 5600 volts.

The TSS differs substantially from any spacecraft ever flown. The large size will present new characteristics to be taken into consideration; characteristics important not only for the operation of the TSS, but also for the future as larger and larger spacecraft are built, including the Space Station, large antenna arrays, and spacecraft contemplated for the future. Many of the new characteristics of large spacecraft are virtually unknown. Little engineering knowledge of such structures exists, and no design procedures or standards are available to guide in the development of such spacecraft. Scientific studies over the past two decades or more provide some insight into the problems which can be expected, and many of the limits and characteristics of the system can be described with present knowledge. Since one of the objectives of the First Electrodynamic Tether mission is to study these effects, there have been some studies related to these effects including preliminary investigations carried out on STS-3, Spacelab 1, several sounding rocket experiments (TPE I,II; CHARGE I,II) and chamber experiments.

This report describes the characteristics of the TSS which are related to high voltages, electrical currents, energy storage, power, and the generation of plasma waves because these properties must be taken into consideration during the safety review. The safety review is conducted by NASA in the course of each mission. Since the TSS is a new and different type of spacecraft, it is encumbent on the scientific investigators to provide the known characteristics of the system which must be taken into consideration during the safety review. In many cases, the scientific requirements on the TSS are much more stringent than existing safety requirements. For example, the level of EMI permitted inside the satellite or in the payload bay of the orbiter is far higher than the level set by sensitive measurements of electric and magnetic fields performed in conjuction with the TSS science mission. This report includes science related issues which may or may not be determined to be safety issues. Since NASA determines safety issues, this report makes no conclusion about the safety of the TSS.

The objective of this report is to identify a number of specific features of the tether system of importance in assessing the operational characteristics of the electrodynamic TSS. The report is not comprehensive and should not be taken as identifying every area or aspect of concern for safe operation of the TSS. The TSS is a complex system in which many of the characteristics are vastly different from those of previous spacecraft. A thorough exposition of all system characteristics must await the combined efforts of the TSS Project Office, the system builders and integrators, the scientific expertise of the Investigator Working Group, and the scientific and engineering communities interested in the TSS.

2. TSS Description

The TSS is composed of three components:

- the TSS Satellite (TSS-S),
- the tether, and
- the TSS Deployer (TSS-D) mechanism.

The TSS is mounted on a pallet in the payload bay of the Space Shuttle orbiter with the satellite stowed during the launch and landing phases of a mission. Once on orbit, with the payload bay doors open, the satellite is extended on a boom mechanism a short distance above the pallet and then released. Thrusters on the satellite assist in deployment and, later, in retrieval operations. Deployment and retrieval each take several hours to perform. When the tether is fully deployed, the satellite and tether will take a position which is generally along a radial direction between the orbiter and the center of the earth. The variation in the gravitational force with distance away from the earth combined with the orbital differences between the satellite and the orbiter result in a tension in the tether between the two which is sometimes referred to as the gravity gradient force, and the TSS is said to be gravity gradient stabilized.

2.1. TSS Deployer

In the payload bay of the orbiter, the TSS-D contains the satellite cradled at the end of a boom mechanism until deployment begins. The tether is carried through the boom, controlled by a sensitive tension measuring instrument, and wound onto an insulated reel. The end of the tether connects through a slip ring mechanism to a switching system on the Deployer which connects to the scientific instruments and current controlling equipment including an electron gun.

The tether is wound onto a reel which is 0.116 meters in diameter and 1.222 m in length. The reel is aluminum covered with fiberglass epoxy to provide additional insulation between the tether and the chassis of the Deployer. Assuming a tether diameter of 2.87 mm and a close packing on the reel, there will be 58 layers and 25,000 turns on the reel when 22 km of tether is fully wound. The inductance of this reel is 40 henrys. The relatively large size of the reel results in a large magnetic solenoidal field, depending on the current in the tether, and large instantaneous voltages, because of the large inductance of the solenoid, depending on the rate of change of the tether current. The magnetic field produced by the reel mechanism depends on the length of tether remaining on the reel and the current in the tether.

The reel inductance as a function of remaining tether length is shown in Table 2-1.

In the initial stages of deployment, when more than 10 km of tether still remain on the reel mechanism, the reel inductance is greater than ll henries. When the tether is nearly fully deployed, the induced voltages become small compared to the VxB potential. At other times, the effects of interwinding capacitance and the shunting effect of the aluminum spindle which acts as a shorted secondary winding, must be taken into account to determine the voltages to actually be expected.

The Deployer end of the tether is snaked into the axis of the reel and carried to a slip ring mechanism at one end of the reel core. The slip ring mechanism design includes a cover designed to permit a discharge between the slip ring and the deployer chassis. It is essential that leakage current from the tether and slip ring to the orbiter structure be controlled. Design of the slip ring mechanism should control the location and technique for the voltage drop between the tether and chassis. No electric fields should be present at the location of the slip ring, tether attachment or slip ring pickoff.

Table 2-1

Layer	Turns	Winding Length	Tether Deployed	Inductance (H)
1	440	163.8	21836.2	0.0022
2	879	335.3	21664.8	0.0092
3	1319	514.4	21485.6	0.0216
4	1758	701.2	21298.8	0.0402
5	2198	895.7	21104.3	0.0657
6	2638	1097.9	20902.1	0.0987
7	3078	1307.8	20692.2	0.1400
8	3519	1525.2	20474.8	0.1905
9	3959	1750.6	20249.4	0.2510
10	4399	1983.6	20016.4	0.3223
11	4839	2224.0	19776.0	0.4052
12	5279	2472.0	19528.0	0.5008
13	5719	2727.5	19272.5	0.6099
14	6159	2991.6	19008.4	0.7335
15	6599	3263.2	18736.9	0.8726
16	7040	3542.3	18457.7	1.0282
17	7480	3828.9	18171.1	1.2014
18	7920	4123.0	17877.0	1.3933
19	8359	4425.7	17574.3	1.6046
20	8797	4734.9	17265.1	1.8363
21	9235	5052.7	16947.3	2.0898
22	9673	5376.8	16623.2	2.3665
23	10111	5709.6	16290.4	2.6676
24	10549	6051.0	15949.0	2.9942
25	10987	6398.8	15601.2	3.3477
26	11425	6755.2	15244.8	3.7293
27	11863	7118.0	14882.0	4.1405
28	12301	7489.5	14510.5	4.5825
29	12739	7867.3	14132.7	5.0568
30	13177	8253.8	13746.2	5.5647
31	13615	8648.8	13351.2	6.1077
32	14053	9052.5	12947.5	6.6874
33	14491	9460.4	12539.6	7.3051
34	14929	9876.9	12123.1	7.9625
35	15367	10302.0	11698.0	8.6610
36	15805	10735.7	11264.3	9.4024
37	16243	11178.0	10822.0	10.1881
38	16681	11624.5	10375.5	11.0199
39	17119	12079.7	9920.3	11.8994
40	17557	12543.4	9456.6	12.8284
41	17995	13015.8	8984.2	13.8086
42	18433	13492.4	8507.6	14.8416
43	18871	13977.6	8022.4	15.9294
44	19309	14471.4	7528.6	17.0738
45	19747	14973.8	7026.2	18.2765
46	20185	15484.8	6515.2	19.5396
47	20623	16000.1	5999.9	20.8648
48	21061	16523.9	5476.1	22.2541
49	21499	17056.4	4943.6	23.7095
50	21937	17597.4	4402.6	25.2330
51	22375	18147.0	3853.0	26.8266
52	22813	18705.3	3294.7	28.4923
53	23251	19272.1	2727.9	30.2323
54	23689	19838.9	2161.1	32.0486
55	24127	20414.2	1585.8	33.9434
56	24565	20998.2	1001.8	35.9189
57	25003	21590.8	409.2	37.9772
58	25301	22000.1	0.1	39.6809

2.2. TSS Satellite

The satellite for the first three missions will be 1.6 meter diameter sphere in shape with a total mass of 500 kilograms. There will be several booms attached for antennas and detector mounting. The surface of the electrodynamic mission satellite will be conducting to provide a means of collecting electrons at the satellite end and also to prevent differential charging at the high voltages attained by the satellite (over 5000 volts.)

The satellite will have a switch for connecting the tether to the satellite structure similar in function to the switch on the Deployer. The tether entrance to the satellite will be through a high voltage connector and then carried to the switch assembly and to the scientific instruments.

The TSS-S switch will be opened only when current is not flowing in the tether and can therefore is not required to have a hot switching capability. When the switch is open, it must not leak more than one microampere of current since field aligned currents on the order of a few microamps per square meter are known to produce current driven plasma instabilities. In order to control the instabilities and the environment around the satellite, it is necessary to reduce the spurious flux density on the magnetic field flux tube passing through the satellite to less than the flux known to produce instabilities. Thus, the leakage resistance of the satellite tether switch must be greater than 10^{10} ohms.

Once the satellite switch has been opened, the tether and satellite potentials can be expected to be different -- either because of leakage to the tether or because of active experiments conducted on the deployer side of the tether. Thus, the satellite switch must be able to withstand closing a 5000 volt circuit where the load capacitance is equal to the capacitance of the satellite with respect to the surrounding plasma. An important question for the first electrodynamic tether mission will be the time history of the current to the satellite after switch closure since the development of the sheath, the onset of instabilities, and the interaction of the satellite with the ambient plasma are of fundamental importance in understanding the behavior of the electrodynamic TSS.

The TSS satellite will include several booms. Two of the booms will be deployable to a distance of about 5 meters on each side of the satellite. Although the boom surfaces will be coated with nonconducting materials, the surfaces will probably increase the effective current collecting surface of the satellite since the surfaces in the presence of a plasma will not support a large tangential electric field. Because the booms represent a sizeable increase in the exposed surface area and the capacitance of the satellite, they will be important in determining the current collection capability of the satellite for both pulse and dc characteristics.

The surface of the satellite is required to be coated with a conducting material so that the voltage drop across the surface is small compared to several volts. When the satellite is at high potential, it is important that there be a very small fraction of this voltage across the painted surface of the satellite since otherwise a breakdown condition may ensue. The science requirement for the surface is a separate issue since one purpose of the satellite is to provide a collecting surface for electrons.

At the time the satellite switch is closed, a large current spike can be expected inside the satellite. The satellite capacitance to the surrounding plasma is one of the parameters which should be studied both theorectically and experimentally prior to the flight. The tether will appear as a transmission line with an electrical length of about 100 microseconds and an impedance of less than 200 ohms. With a tether voltage of 5000 volts, it is possible to get a 25 amp current spike with time constants on the order of a few nanoseconds, depending on the internal capacitance of the satellite and other parameters associated with the switch. Since this current spike is carried on the tether through the satellite, it is necessary to completely shield the tether from other cables and instruments inside the satellite. The tether should be carried in solid shielded cable (such as semirigid coax.)

The high voltage connectors used on the satellite are required to completely seal the tether center conductor from the surrounding plasma and the satellite except at the one location on the surface of the satellite where the tether is electrically connected (through the satellite tether switch.) For practical reasons, the tether connection to the outside of the satellite is necessary in order to permit testing of the satellite high voltage system and to provide for simple connection of the tether to the satellite during integration. Internally, HV connectors protect the satellite components from the high voltages and emi which will be present on the tether during some periods of operation.

2.3. Tether

Several materials have been proposed for the electrodynamic tether. Although the scientific requirements specify a very low value for the leakage through the tether insulation to the center conductor, this requirement is also necessary for operational considerations. Leakage through the tether implies that whenever the tether is connected -- either to the satellite or to the orbiter -- currents will flow through the system uncontrolled.

Pinholes in the surface of the tether may result in a continuous series of pinhole type breakdowns which generate a large amount of high frequency noise. This noise would possibly interfere with the satellite command and telemetry system rf links.

Dielectric surfaces at high potentials in space plasma do not have the same characteristics as one might expect from experience with dielectrics in atmospheric environments. At high positive potentials, dielectrics do not support large tangential electric fields; dielectric surfaces can carry surface currents in the presence of a plasma. The tether surfaces should be studied prior to the mission and measurements should be made during the deployment phase of the mission to determine the extent to which the tether surface will support a leakage current from the plasma to the orbiter. This current is not controllable and is unrelated to the position of the tether switches. It may, however, depend upon the relative voltages of the conductors in the system and thereby permit some degree of study and control.

3. Operational Characteristics

3.1. Voltages

The driving voltage in the tether is produced by the relative motion of the tether and the ionospheric plasma in the presence of the earth's magnetic field. As seen from the tether system and the orbiter, the plasma flows past the orbiter and appears to be driven by an electric field which exists everywhere in space and has a value equal to $-VB\cos\theta$, where **V** is the velocity of the orbiter with respect to the ionosphere and θ is the angle between the velocity vector and the earth's magnetic field vector **B**. As the orbiter plys its way around on orbit, the magnitude of **B** changes and the angle between **B** and **V** varies, producing an emf which varies as shown in Figure 3-1.

During deployment, the voltage between the two ends of the tether will increase linearly with the deployed length. At 20 km, the maximum voltage encountered will be 5000 volts. This voltage depends upon the particular orbit and the presence of ionospheric electric fields at high latitudes may appreciably increase this maximum voltage in future missions with higher inclinations. At low inclination orbits, ionospheric electric fields are negligible for this purpose.

The appearance of the tether voltage at various places in the tether system depends upon a number of different circumstances. When the satellite relay is closed, the satellite will nominally be at a floating potential of about -0.5 volts relative to the local plasma. As seen from the orbiter rest frame, the tether is all at one potential (with the exception of resistive voltage drops) and the orbiter end of the tether in the absence of a current in the tether system will carry the full VxBL tether voltage of -5000 volts relative to the plasma surrounding the orbiter. The tether, connected to instrumentation in the payload bay of the orbiter, appears to be a cable which is connected to a negative, high voltage, current limited power supply. As current is drawn from the tether, voltage drops appear at the surface of the satellite, in the resistive loss in the tether, and the remainder appears as electron beam energy in the Core Electron Gun. It is not obvious that this system is stable; current variations may occur in the tether resulting from the nonlinear, time dependent interactions of the satellite, tether, deployer reel impedance, and Core Electron Gun.

When current is drawn from the tether, the satellite will attain some relatively positive potential relative to the surrounding plasma and collect electrons. The heat produced by the electron bombardment of the satellite is approximately equal to the current multiplied by the satellite voltage. At full deployment, with a satellite potential of 1000 volts and a maximum current of 0.5 A, electron bombardment contributes 500 watts to the surface of the satellite. The total emf tether voltage is 5000 volts with about 1000

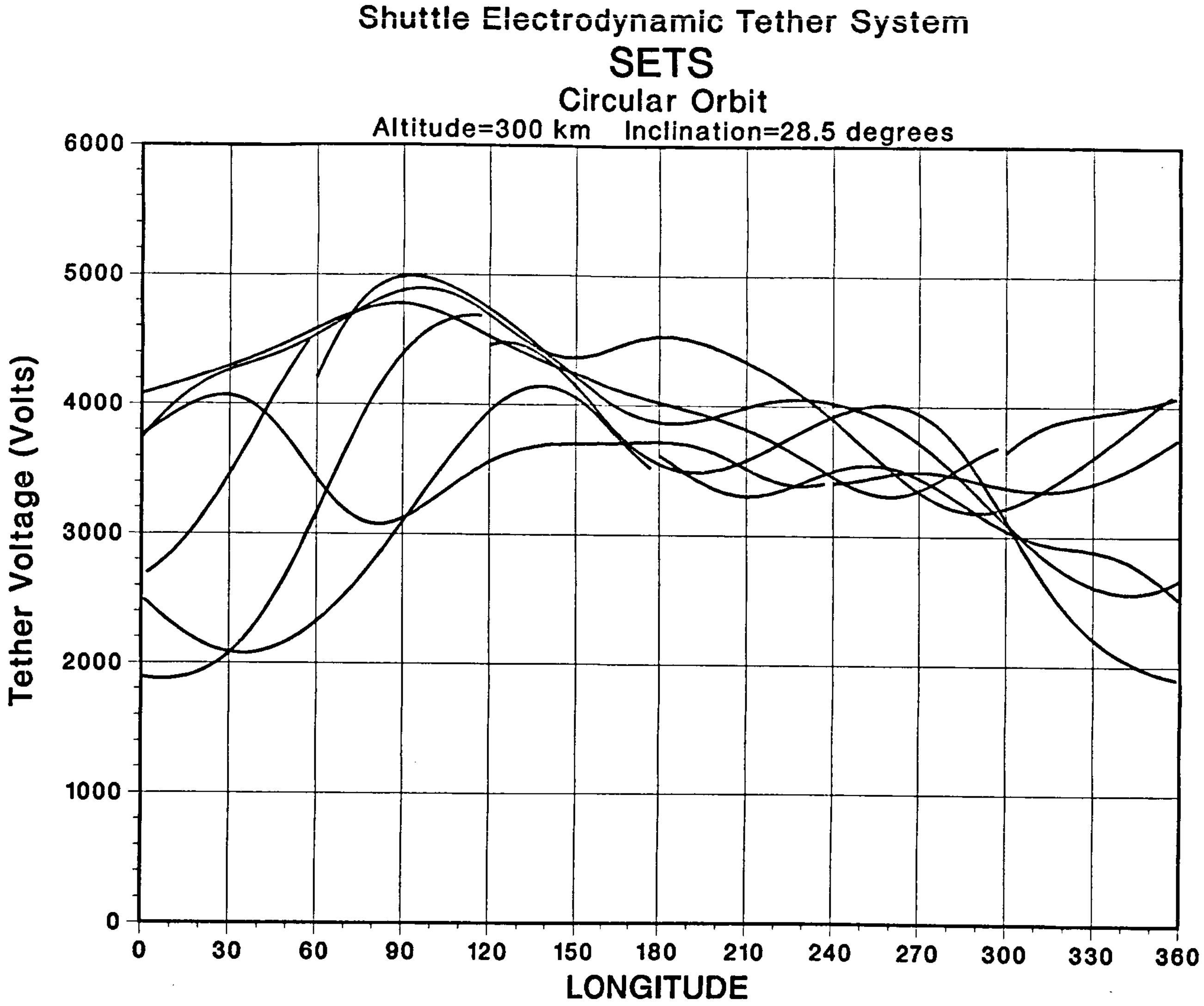

Figure 3-1:
Voltage produced by a 20 km electrodynamic tether at 160 nm altitude in a 28.5 degree inclination orbit. The six curves correspond to different values of the ascending node; one curve for each 60 degrees shift in the ascending node to give a survey of the different orbits encountered.

volts in the tether IR drop and the remainder 3000 volts dropped in the CEG electron beam. Heating is only present while current is flowing in the system, and since the tether current can be controlled, the heating of various components, including the satellite, can be managed operationally.

Another factor to consider with respect to the electron bombardment of the satellite is the effect this bombardment has on the surface characteristics. Energetic electron bombardment is one of the most effective methods for cleaning materials. The electrons can be considered to be a very high temperature gas; at one thousand volts, the effective electron temperature is 12 million degrees kelvin. An electron will have hit every square angstrom of satellite surface after 130 amp seconds (e.g., 100 mA for 1300 seconds.) Testing of the satellite surface characteristics should take into account this bombardment by electrons.

A similar effect is produced by the continuous bombardment by atomic oxygen which has a relative energy of 5 eV with respect to the satellite and has a much higher mass than electrons which is more effective in cleaning the surface. These effects have been an important topic of study since the observations on STS-3 in 1982 where paints were degraded, kapton turned to powder, and aluminum spheres were completely denuded of their colloidal graphite coating.

The maximum tether voltage from velocity and magnetic field effects is very well known and can be modeled accurately. The value of 5000 volts used in this report will change somewhat depending upon the exact orbit, the length of the tether, the direction of the tether relative to the local vertical, and (for modeling calculations) the model used for the earth's magnetic field. These variations are of only minor interest with respect to the overall design of the system since substantial margins are needed. There is one source of voltage, however, which is not known, can be many times larger than the 5000 volt tether voltage, and is therefore certainly not neglible; the tether reel is a large solenoid with an inductance of 40 henrys when fully wound. When the tether is almost fully deployed, with 2 km remaining on the reel, the inductance is still about 0.2 henrys.

The voltage produced by changing the tether current from 0.5 amps to zero in 1 millisecond (similar to the proposed characteristics of the Core electron gun) is 100 volts. If a switch is used to interrupt the circuit, or a break on the deployer side of the tether reel occurs in the tether, the interrupt time may be 10 microseconds and the induced voltage is then 10 kV.

The inductance in the tether reel has one positive effect on the system design. If a breakdown of some type should occur, for example, an arc in the electron gun head between the cathode and orbiter ground, the tether reel inductance can be expected to rapidly shut down the arc. Vacuum arcs have onset times in the range of 100 ns to 10 υs and can be extinguished in times of a few microseconds for currents in the range of a few amperes. Thus, we might expect that an arc in the core electron gun would last for less than 20 microseconds and put a charge of less than 100 microcoulombs on the orbiter.

For an orbiter capacitance of 1 microfarad, the instantaneous voltage of the orbiter would be 100 volts. (VCAP measurements on STS-3 indicate for positive voltages that the orbiter capacitance may well be larger than one microfarad.)

3.2. Currents

The maximum current which can be produced by the electrodynamic TSS depends upon several elements; the satellite sheath, tether resistive drop, and the core electron gun beam energy. The voltage drop from the sum of these three elements (plus any open switches in the system) will equal the VxB voltage. Table 2 gives the maximum voltage and current for the tether system where the ambient electron density is taken to be relatively high.

3.3. Energy storage

Energy is stored in the TSS in the tether capacitance and in the reel inductance. The capacitance per unit length of the tether can be estimated by assuming that the outside diameter of the tether is the outer conductor where the plasma supplies the charges necessary. In this case, the capacitance per unit length of the tether is on the order of 250 pf/m, and the capacitance of the fully deployed tether is 5 microfarads. At 5000 volts, the energy stored is 20 joules. The electrical length of the tether corresponds to a time constant of about 100 microseconds, so the average power to dump the tether, assuming no losses in the tether itself, is 20 kW.

The tether reel inductance has a maximum value of 40 henrys. At 50% deployment, this value drops to 10 H. For a current of 0.5 A, the energy stored in the tether reel is about 1 joule.

4. Sequence of operations

Several of the operational characteristics of the electrodynamic TSS will not be known until the first mission, since this is one of the objectives of the first mission. Testing of subsystems can and should be used to qualify the parts of the TSS for high voltage, leakage, emi, and other parameters applicable to the predictable operation of the TSS. Theoretical calculations can provide some insight to the limits of the parameters which are likely to be encountered, and in some cases, there exists substantial knowledge from previous flights about these parameters. The primary unknown factors which will be encountered on the first mission are:

1. the impedance characteristic of the tether, particularly the capacitive energy storage,

2. the current collection capability of the orbiter and the possible enhancement when the Core electron gun or the SETS FPEG electron gun are emitting a beam,

Table 3-2

Tether Deployed	Maximum VxBL	Tether Current	Sheath Drop	Tether IR Drop	CEG Beam Volts
21836.2	5459.1	0.615	662	1353	3446
21664.8	5416.2	0.609	654	1340	3424
21485.6	5371.4	0.603	647	1327	3401
21298.8	5324.7	0.597	639	1313	3379
21104.3	5276.1	0.590	631	1298	3352
20902.1	5225.5	0.583	622	1283	3326
20692.2	5173.1	0.576	613	1267	3299
20474.8	5118.7	0.568	603	1250	3268
20249.4	5062.3	0.560	593	1232	3237
20016.4	5004.1	0.552	583	1214	3207
19776.0	4944.0	0.544	574	1197	3176
19528.0	4882.0	0.536	564	1179	3144
19272.5	4818.1	0.527	553	1159	3109
19008.4	4752.1	0.518	542	1140	3074
18736.9	4684.2	0.509	531	1120	3038
18457.7	4614.4	0.500	520	1100	3002
18171.1	4542.8	0.490	508	1078	2962
17877.0	4469.2	0.480	496	1056	2921
17574.3	4393.6	0.470	484	1034	2881
17265.1	4316.3	0.460	472	1012	2840
16947.3	4236.8	0.449	459	988	2794
16623.2	4155.8	0.438	445	964	2748
16290.4	4072.6	0.427	432	939	2702
15949.0	3987.3	0.416	419	915	2655
15601.2	3900.3	0.405	407	891	2608
15244.8	3811.2	0.393	393	865	2557
14882.0	3720.5	0.381	379	838	2504
14510.5	3627.6	0.369	365	812	2452
14132.7	3533.2	0.357	351	785	2398
13746.2	3436.6	0.345	337	759	2344
13351.2	3337.8	0.333	324	733	2289
12947.5	3236.9	0.320	309	704	2229
12539.6	3134.9	0.307	294	675	2169
12123.1	3030.8	0.294	280	647	2107
11698.0	2924.5	0.281	265	618	2044
11264.3	2816.1	0.268	251	590	1981
10822.0	2705.5	0.254	236	559	1911
10375.5	2593.9	0.241	222	530	1845
9920.3	2480.1	0.228	208	502	1778
9456.6	2364.1	0.214	193	471	1705
8984.2	2246.1	0.200	178	440	1630
8507.6	2126.9	0.187	165	411	1558
8022.4	2005.6	0.173	151	381	1480
7528.6	1882.1	0.159	137	350	1399
7026.2	1756.5	0.145	123	319	1315
6515.2	1628.8	0.132	110	290	1235
5999.9	1500.0	0.118	96	260	1146
5476.1	1369.0	0.105	84	231	1061
4943.6	1235.9	0.092	72	202	971
4402.6	1100.6	0.078	60	172	870
3853.0	963.2	0.066	49	145	778
3294.7	823.7	0.053	38	117	672
2727.9	682.0	0.041	28	90	567
2161.1	540.3	0.030	20	66	460
1585.8	396.4	0.020	12	44	351
1001.8	250.4	0.011	6	24	236
409.2	102.3	0.003	1	7	99
0.1	0.0	0.000	1	7	99

3. operational aspect of the measurement of orbiter potential relative to the surrounding plasma,
4. the current voltage characteristic of the satellite, and
5. surface leakage from the tether to the orbiter even when the tether switch is open.

The operational sequences should be chosen to bootstrap knowledge of the tether system as the mission progresses from checkout through deployment, on station operations, and retrieval.

4.1. Checkout

The checkout phase is used to assure the proper system operation. The earlier the checkout is performed and the more experience gained in the operation of the tether system during the stowed or checkout phases, the greater is the knowledge and confidence in the status of the system. Checkout items should include not only basic voltage, current, temperature, and status checkout, but also the on orbit interaction of the operational orbiter with the tether system. orbiter generated emi, for example, will produce voltage noise in the large tether reel, which is an antenna for magnetic field noise in the range of less than one hertz up to tens of kilohertz. It will be important to differentiate between ordinary orbiter noise and voltages associated with the deployment of the tether. orbiter magnetic noise will be produced by electrical system operation, pumps, power supplies, thruster firings, and attitude changes (attitude changes result in a time varying magnetic field in the tether reel as a result of the earth's magnetic field.)

4.2. Deployment

As deployment progresses, the voltage produced by the system increases linearly at a rate of between 0.1 V/m and 0.25 V/m depending upon the instantaneous position and velocity of the orbit. Thus, the lowest voltages, and therefore the lowest stored energies and currents, will be encountered during the first part of the deployment phase. It is for this reason that operations should be performed throughout the first stages of deployment to reduce the uncertainties in the TSS operations listed above.

Operation of the Core electron gun at low voltages will also increase the outgassing of the electron gun heads and reduce the possibility of breakdown arcs.

4.3. Full Deployment

At full deployment, the maximum voltage will be applied to the system and the maximum energy will be stored in the tether capacitance. Many of the scientific aspects of the system and the operational characteristics can be determined at slightly lower voltages, e.g., during the last deployment stop at 16 km where the voltage maximum will be 4000 volts instead of the ultimate 5000 volts for full 20 km deployment. Currents in the system will also be lower, although the inductance of the tether reel mechanism will be much higher.