

Electrodynamic-Tether Time-Domain Reflectometer for Analyzing Tether Faults and Degradation

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Abstract. We propose using time-domain-reflectometry (TDR) systems to locate and track faults along electrodynamic tether (EDT) systems. Inclusion of a TDR on long-duration EDT missions would facilitate tracking of the expected performance degradation due to faults caused by hazards such as micrometeors. The TDR technique has long been an effective tool for determining the location of loads and faults along common transmission lines (TLs) such as coaxial cables. Also sometimes known as pulse reflectometry, TDR works by sending an impulse down a TL and recording the reflected energy as a function of time. Measurement of the reflected TDR waveform provides insight into the physical structure of the TL and any loads, *i.e.*, faults, along its length. In addition, the delay between launched and reflected signals determines the location of the load or fault. Hence, the TDR technique requires knowledge of the propagation characteristics of the TL under test. To examine the feasibility of extending the technique to EDTs we use a previously developed model for the tether transmission line. This model has temporal, and hence spatial, limitations, which may be overcome with enhancements to the tether TL model. We present some general parameters governing the development of such a tether TDR system as well as computer simulations of the TDR system's response.

INTRODUCTION

Electrodynamic tether (EDT) systems have been proposed for long-duration missions, those lasting several months to many years (Hoyt, 2000; Santangelo and Johnson, 2000; Vas et al., 2000; Santangelo et al., 1999). These future EDT missions are of much longer duration than those of past and present missions, which were designed to last days or weeks. Although still a concern for short-duration missions, these longer missions will provide an especially harsh environment with respect to orbital debris and atomic oxygen flux, which will impact tether survivability. Wider and/or multistrand tethers (Forward, 1992) may help mitigate against premature severing of the tether; however, the severity of the environment and resulting tether performance degradation will be difficult to determine without some type of active monitoring equipment.

The need for a system to measure the health of the tether is demonstrated by the expected wear and tear due to the EDT system's orbital environment. Similar to the tether configuration employed on the upcoming ProSEDS (Propulsive Small Expendable Deployer System) mission (Johnson et al., 1998), these future EDT missions will employ partially bare, partially insulated configurations. It is estimated that the insulated tether portions could receive hundreds to thousands of micrometeorite hits over the course of a year mission. Although each of these hits may only be the size of a pin hole, some may be larger affecting the integrity of the tether and its operational capability.

One proposed solution for monitoring the tether degradation is the use of time domain reflectometry (TDR), which can be used to locate the position(s) of the breached insulation. The basic tether TDR concept was demonstrated by (Bilén, 1998) and continues to be an area of active interest (Bilén et al., 2000). Running the tether TDR system during a sequence as part of a generic mission profile (each sequence would take $\lesssim 1$ s) would allow for the determination of degradation as a function of time. The tether acts as a transmission line (TL) transferring energy from one point to another. If we first determine the TL properties of the tether, we can then locate the position of any "loads" along it, and pin holes that allow current to leak from the tether to the plasma can be considered as loads (Figure 1).

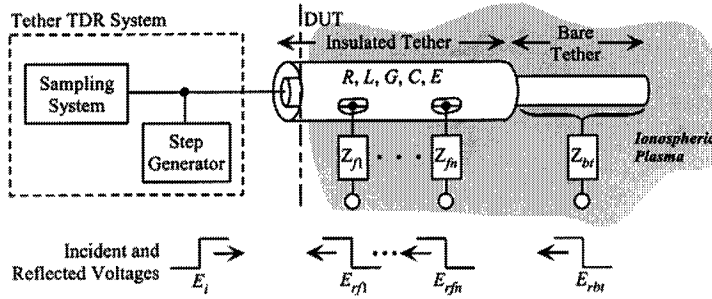


FIGURE 1. Schematic of the Tether TDR System.

In this paper, we will present first an introduction to TDR and how it might be used as a system for EDTs. We then present a previously developed TL model of the EDT and a sample computer simulation in a TDR configuration. We follow with a discussion of the open issues for development of future EDT TDR systems and finish with a summary.

TIME-DOMAIN REFLECTOMETRY ALONG EDTS

Time-domain reflectometry, also sometimes known as pulse reflectometry, is a technique that consists of launching an impulse down a transmission line and recording the reflected energy—the “echo”—as a function of time. The measurement of the reflected TDR waveform provides insight into the physical structure of the device under test (DUT), which may be the transmission line itself (Hsue and Pan, 1997), devices and parasitics positioned along the length of the line (Dascher, 1996), or devices at the end of the line (He et al., 1994). The characteristics of the DUT(s) can be determined from knowledge of both the incident and reflected signals. The TDR technique has the advantage of being able to accurately model nonlinear devices. With modern systems such as network analyzers, the TDR technique is often accomplished by applying a fast Fourier transform (FFT) to frequency-domain data. While the FFT technique has found much utility, especially for microwave-circuit measurements, the “old” method of applying an actual pulse continues to find areas of use, and may indeed be necessary depending on the TL and load characteristics.

Referring again to Figure 1, let us examine the TDR system and operation in more detail. The TDR system itself consists of a step generator to “launch” incident energy down the tether, denoted E_i , and a sampling system to measure the reflected energy. The reflected energy might occur at any fault in the insulated tether (denoted $E_{r1} \dots E_{rn}$) and from the impedance mismatch at the transition to and along bare tether portion of the tether (E_{rbi}). The temporal location of the reflected energy determines the fault’s spatial location through the relation

$$d_f = v_{\text{prop}} \frac{t}{2}, \quad (1)$$

where v_{prop} is the propagation velocity along the tether TL, and t is the transit time from the monitoring point to the load and back again, hence the factor of $1/2$ in Eqn. (1). The shape of the reflected waveform is also valuable since it reveals both the nature and magnitude of the mismatch. The reflection coefficient, Γ , at a discontinuity on a TL is given by the equation

$$\Gamma = \frac{E_r}{E_i} = \frac{Z_L - Z_0}{Z_L + Z_0}, \quad (2)$$

where Z_L is the load impedance and Z_0 is the tether’s characteristic TL impedance, which must be known. In this case, $Z_L = Z_{f1} \dots Z_{fn}$ or Z_{bt} for each of the faults and bare tether portion, respectively.

TDR ON DYNAMIC TETHER TRANSMISSION LINES

Signals, or perturbations, take a finite amount of time to propagate along a tether and, depending on their voltage level and spectral content, tend to affect the surrounding ionospheric plasma as they travel. This interaction, in turn, affects the tether’s transmission-line (TL) characteristics. Under negative high-voltage excitation the sheath is dynamic and nonlinear—unlike the assumptions generally used for low excitation voltages, those being static sheath size or linearized sheath characteristics. Because the plasma effectively forms the outer conductor (James et al., 1995), the geometry of the plasma–conductor system is not rigid and this dynamic and nonlinear sheath fundamentally changes

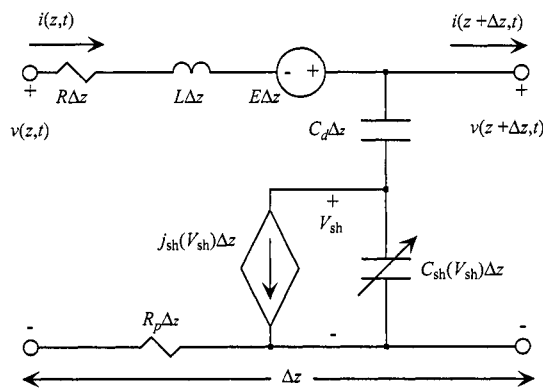


FIGURE 2. Tether Incremental Circuit Model Showing R , L , E , C_d , R_p , $C_{sh}(V_{sh})$, and $j_{sh}(V_{sh})$ Per Unit Length, Δz .

the nature of EM propagation along electrodynamic tethers. Previous tether TL models (Arnold and Dobrowolny, 1980; Osmolovsky et al., 1992) assume, as a first-order approximation, that the plasma-sheathed tether can be modeled as a simple rigid coaxial cable. While this has proven acceptable for short tethers (Bilén et al., 1995), an improved model was developed for longer deployed tether lengths, primarily to account for the higher induced voltages and the dynamic sheath.

Bilén and Gilchrist (2000) derived a transient plasma-sheath model by analytical means and verified the model by experiments and PIC simulations. The model is valid in the frequency regime between the electron and ion plasma frequencies ($\omega_{pe} \gg \omega \gg \omega_{pi}$), and for large negative applied voltages, $|V_a| \gg kT_e/q$. In this frequency regime, the model describes the ion-matrix-sheath radius as a function of applied voltage, $r_{sh}(V_a)$. This voltage-dependent sheath model was employed as the basis of a nonlinear EDT TL model using the Tethered Satellite System (TSS) tether (Bonifazi et al., 1994) as an example. In effect, the model of the tether-plasma system is of a “non-static” coaxial transmission line, *i.e.*, a transmission line with voltage-dependent (“nonlinear”) parameters. In the frequency range $\omega_{pe} \gg \omega \gg \omega_{pi}$, the tether’s E - and B -fields are contained locally, which allows an effective capacitance and inductance per unit length to be defined for the tether. In this model, the E -field is contained within the sheath region (as shown by Bilén (1998)), which allows an effective capacitance to be defined. The effective inductance is due to the locally contained B -field and takes into account the location of the plasma return currents. The inductance-per-unit-length parameter generally has been neglected in previous TL models of EDTs. For example, (Arnold and Dobrowolny, 1980) exclude inductance and so avoid integrating the rate of change of current in their computer model. Osmolovsky et al. (1992) include the inductance term in a generalized description of their model, but then set the inductance parameter to zero before performing calculations. In general, the absence of an inductance term in these previous models is justified because those models are not concerned with examining electromagnetic-signal propagation effects.

The incremental circuit model of the electrodynamic tether (Fig. 2) consists of the elements R , L , E , C_d , R_p , $C_{sh}(V_{sh})$, and $j_{sh}(V_{sh})$ per unit length, Δz . The values for R , L , E , C_d , and R_p are fixed values that are either measured or calculated. The remaining two, $C_{sh}(V_{sh})$, and $j_{sh}(V_{sh})$, are varying parameters that depend on V_{sh} , the sheath voltage. The other varying parameter is a current-per-unit-length term that also depends on sheath voltage. The functional form for this term is that of OML electron current collection. Since there is no (or very little) ion current collection, then for $V_{sh} < 0$, $j_{sh} = 0$. More details on the derivations and descriptions of each of these components may be found in Bilén (1998) and Bilén et al. (2000).

Tether Characteristic Impedance and Propagation Velocity

Using circuit parameters for capacitance and inductance per unit length, we can calculate the classical characteristic impedance of and propagation velocity along the tether transmission line. Since the capacitance is a function of voltage, then both impedance and propagation velocity are functions of voltage. Assuming $G = 0$ (insulated tether, no faults), $R \ll \omega L$, and $L = \text{constant}$, then the characteristic impedance is given by

$$Z_0(V_a) \simeq \sqrt{L/C(V_a)} . \quad (3)$$

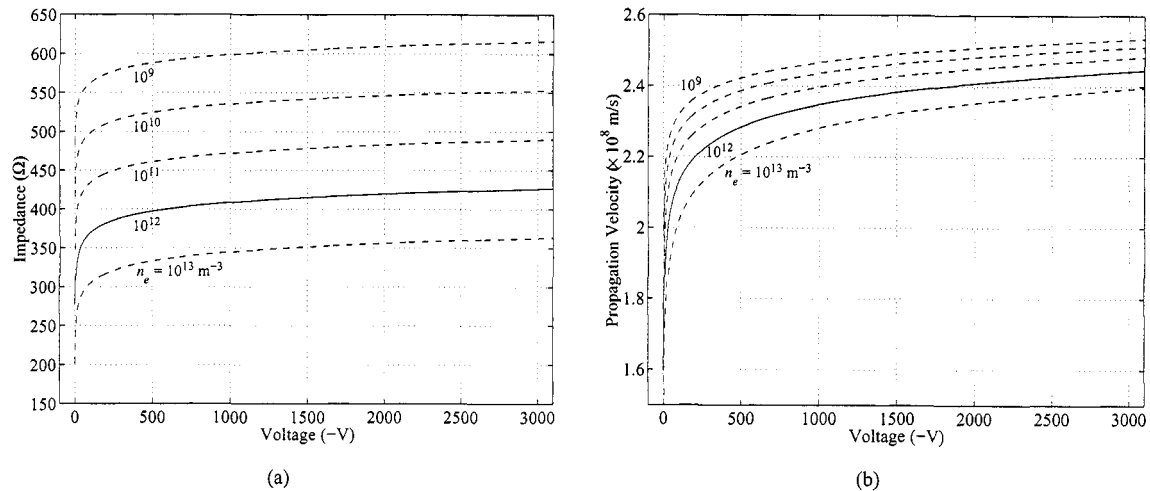


FIGURE 3. Plot of Tether Transmission-Line (a) Impedance and (b) Propagation Velocity vs. Applied Voltage for Cylindrical Tether Geometry for Various Plasma Densities. Solid Line Represents an $n_e = 10^{12} \text{ m}^{-3}$ Plasma.

Eqn. (3) is plotted in Fig. 3(a) for several values of plasma density; the figure clearly shows that as n_e decreases, Z_0 increases. The propagation (phase) velocity for the tether transmission line is given by

$$v_{\text{prop}}(V_a) = 1/\sqrt{LC(V_a)}. \quad (4)$$

Eqn. (4) is plotted in Fig. 3(b) for several values of plasma density; the figure clearly shows that as n_e decreases, v_{prop} increases. Several researchers have reported on propagation velocities along plasma-immersed conductors. For example, James (1993) experimentally determined a small-signal group speed $v_g = 0.6c \simeq 1.8 \times 10^8 \text{ m/s}$ for sheath waves along the OEDIPUS–A 958-m tether. This measurement agrees well with this model, given the appropriate parameters for their system; however, their model was based on a voltage-independent (*i.e.*, fixed) sheath distance.

Computer Simulation

Transient simulations of the circuit model were performed using HSPICE, which is similar to the standard Berkeley SPICE. The entire tether circuit is assembled as a ladder network of N incremental sections of length chosen such that $\Delta z \ll \lambda$. A choice of 4-m increments for Δz yields a minimum of 40 increments per wavelength. A circuit consisting of $N = 5000$ increments was used, which equates to an 20-km-long tether. This length was chosen for two reasons: 1) 20-km is the length of practical tether systems such as TSS and 2) this length allows the applied pulses and sinusoidal waveforms to be adequately resolved at different sections along the transmission line.

For tether systems, there are several methods for producing tether voltage modulations, *i.e.*, forced oscillations, which include 1) periodically producing current increases, decreases, or breaks; 2) varying the source and/or load impedances; and 3) changing parameters and control voltages of the contactors and emitters. For these circuit simulations, we utilize a voltage source controlled by pulse and sinusoidal functions. The shortest pulse length that can be launched onto this transmission-line model is on the order of $\tau_a = 1\text{--}3 \mu\text{s}$ for an $n_e = 10^{12} \text{ m}^{-3}$ plasma. This pulse length, in turn, places a lower limit on the spatial resolution of any TDR measurements. To get an idea for what kind of resolution is possible with a TDR measurement, a 3- μs , –500-V pulse traveling $\sim 2.3 \times 10^8 \text{ m/s}$ yields a minimum spatial resolution $\gtrsim 700 \text{ m}$. To achieve better spatial resolution, an enhanced EDT circuit model is needed—one that can handle much faster rise- and fall-times

As a sample simulation of a TDR system, we describe the following result. Figure 4 shows a simulation wherein a pulse was launched along a lossless tether TL that had a step discontinuity in plasma density (from $n_e = 10^{12} \rightarrow 10^{10} \text{ m}^{-3}$) at section $N = 3000$; the value of Z_L was left at the $Z_0(0)$ value of the first portion of the line. Although somewhat artificial, such a situation could occur if the upper half of the tethered system were to fly into a deep density depression with sharply defined features. The simulation results show very clearly two return pulses, the first is due to the change in plasma density at $N = 3000$ and the second is due to the mismatch at the load. Referring to Eqn. (2), we see that

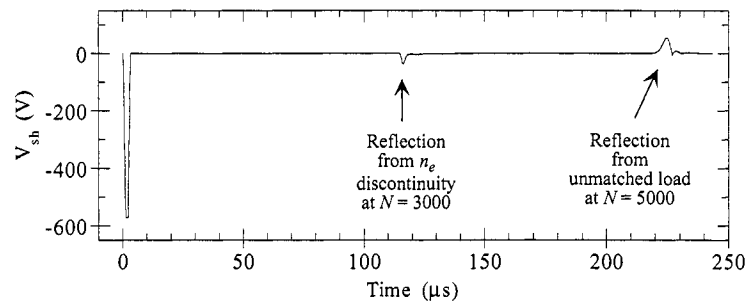


FIGURE 4. Time-Domain-Reflectometry Simulation with a Pulse Along a Lossless Tether Transmission Line that had a Step Discontinuity in Plasma Density and an Unmatched Load Impedance.

these reflections make sense in the classic sense of TDR. As plasma density decreases, Figure 3(a) shows that Z_0 increases. Hence, at the step change in plasma density we would expect a positive Γ , and indeed the return pulse from this discontinuity is the same polarity. Conversely, at the load we would expect a negative Γ , and indeed the return pulse from the load is positive. This simple demonstration shows that TDR applications along tethers may hold promise for future systems.

FUTURE EDT TDR SYSTEM DEVELOPMENT

We briefly present here some open issues that will need to be studied before any TDR system can be fully practicable.

1) What is the appropriate TL model for the EDT in the region of the ionosphere through which the system will be traveling? What are the material effects (*e.g.*, copper, aluminum, insulation) on the TL model? Will sheath-wave models be needed (James et al., 1995)? 2) What size of tether damage (*e.g.*, wire damage, insulation breaches) can be determined via the TDR method? 3) Should the TDR system be solely time domain or should it be a hybrid pulsed-RF system? 4) What is the spatial resolution of the system? (Note, as mentioned this is dependent on the circuit model used.) What resolution is acceptable? 5) What level of on-board processing will be needed to reduce the captured data set? How fast is processed data needed? Can processing be performed on the ground? 6) How does the length of the tether affect the system's response? If the tether is not fully deployed from the deployment device, how should the effect of the deployer be accounted for? How should the launched energy be coupled into the tether? 7) What is the power needed for the launched pulse? 8) How can the tether TL system and the pulse launcher best be impedance matched so that too much energy is not lost is the system-tether transition? 9) What is the propagation difference between the insulated and bare tether sections?

To help resolve some of these open issues, the following experiments and investigations are proposed: 1) Examination of tether TL characteristics under different proposed tether designs and expected plasma environments. 2) Impedance matching techniques between the launcher and tether. 3) Determination of minimum/maximum pin hole size and minimum/maximum number of pin holes that can be detected. 4) Computer modeling (SPICE circuit modeling and others) to simulate the tether system and expected response of the system. This modeling would be based on some previously developed models of the tether-plasma interaction and the experiments proposed here. This modeling would examine both the insulated and uninsulated sections of the tether.

SUMMARY

We propose here the method of using TDR along EDTs as a low cost method for monitoring the tether's health during future long-duration missions. The TDR method deserves serious consideration as it has the potential of providing the desired health information quickly and relatively inexpensively compared with competing ideas. We presented herein some of the TDR system's expected benefits, open issues, and appropriate test schemes to resolve some of the open issues. To demonstrate the promise of the TDR system, we used a previously developed voltage-dependent sheath and EDT TL circuit model that incorporates high-voltage sheath dynamics. The circuit model was implemented using a circuit-simulation program, and a simulation performed showing the potential of a TDR system.

NOMENCLATURE

C_d	dielectric capacitance per unit length, F/m	t	time, s
C_{sh}	sheath capacitance per unit length, F/m	T_e	electron temperature, K
d_t	distance to load, m	V_a	accelerating potential, V
E	tether TL <i>emf</i> per unit length, V/m	v_g	group velocity, m/s
E_i	incident voltage, V	v_{prop}	propagation velocity, m/s
E_r	reflected voltage, V	V_{sh}	potential across voltage-dependent sheath, V
j_{sh}	sheath current density, A/m ²	Z_0	TL characteristic impedance, Ω
k	Boltzmann's constant, 1.38×10^{-23} J/K	Z_f	fault impedance, Ω
l	tether length, m	Z_L	load impedance, Ω
L	TL inductance per unit length, H/m	Γ	reflection coefficient
N	integer, unitless	λ	wavelength, m
n_e	electron plasma density, m ⁻³	τ_a	applied-voltage pulse length, s
q	charge magnitude, 1.602×10^{-19} C	ω	angular excitation frequency, rad/s
R	TL resistance per unit length, Ω /m	ω_{pe}	angular electron-plasma frequency, rad/s
R_p	plasma resistance per unit length, Ω /m	ω_{pi}	angular ion-plasma frequency, rad/s
r_{sh}	ion-matrix-sheath distance, m		

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