

Disturbance of Electronics in Low-Earth Orbits by High Energy Electron Plasmas

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ABSTRACT

Electrical disturbances caused by charging of cables in spacecraft can impair electrical systems for long periods of time. The charging originates primarily from electrons trapped in the radiation belts of the earth. The model Space Electrons Electromagnetic Effects (SEEE) is applied in computing the transient charge and electric fields in cables on spacecraft at low to middle earth altitudes. The analysis indicated that fields exceeding dielectric breakdown strengths of common dielectric materials are possible in intense magnetic storms for systems with inadequate shielding. SEEE also computes the minimal shielding needed to keep the electric fields below that for dielectric breakdown.

INTRODUCTION

Electrical Charging Electromagnetic Pulse (ECEMP), caused by the charge accumulated in the system components, can impair electrical components in space-based systems for prolonged periods of time. In space, the charging originates mostly from electrons trapped in the earth's radiation belts penetrating deep into the materials of electrical systems, including its insulating materials. When the charge is coupled to sensitive circuit boards, damages can be irreversible. Observations of internal charging in space environments indicate that the electric field intensity can approach the dielectric breakdown strength for materials commonly used in electrical cables, impairing the electronics for long periods of time [1], [2].

The development of modeling tools as an aid in designing electrical systems immune to ECEMP is thus critical, especially for high performance systems and ones in orbit for long periods of time. Modeling tools such as ESADDC and DICTAT have been developed

that incorporate much of the relevant physics [3], [4]. Each of these tools has their own individual merits. This paper presents another modeling tool, Space Electrons Electromagnetic Effects (SEEE) developed at Boeing. The paper presents model results for the charge and electric fields in cables onboard spacecraft at low to medium altitude orbits around the earth during peak magnetic storming. The results show that the electric fields in the dielectric can exceed the dielectric breakdown strength and that the fields can remain at high levels as long as an hour after the storm event ends.

The remaining paper is divided into three sections. The next section discusses the algorithms for the major components of SEEE. The section afterwards presents the results obtained from SEEE for spacecraft during peak magnetic storm events. The last section summarizes the capabilities of SEEE as an aid to the aerospace industry in the design of cables reducing or eliminating ECEMP in space-based systems.

METHODS

The SEEE model components can be divided into three categories illustrated in Figure 1. The model components shown are:

1. modeling the insulating materials as resistors and capacitors in a circuit (the circuit model),
2. computing the electron fluence (electrons/s/unit area) during peak solar or magnetic storm events (the electron fluence model),
3. computing the charge density and dose rate delivered to the cable materials (the transport model)

Each component is described in greater detail in the following subsections.

CIRCUIT MODEL – The largest amount of code to SEEE is devoted to the circuit model. Each dielectric material is modeled as a capacitor in parallel to a resistor much like the RC circuit described in elementary physics and engineering textbooks. The entire cable is regarded as a series of such RC circuits. The charging/discharging equations differ from the treatment of the problem in textbooks for the RC circuit in that the resistance varies with time due to the variation of the conductivity with the electric field intensity. The increase in the conductivity becomes important in many insulators for electric field intensities above 5 MV/m. Field intensities at such levels can occur in space due to the small size of the cables and the high fluence levels of electrons during magnetic storms. Accounting for field variations of the conductivity, the charge in a dielectric can be shown to vary with time as:

$$Q(t) = \dot{Q}_0 \int_{t_0=0}^{t_0=T_R} dt_0 \exp\left\{-\frac{1}{\epsilon} \int_{t_0}^t \sigma[E(t')] dt'\right\}, t > T_R, \quad (1)$$

$$Q(t) = \dot{Q}_0 \int_{t_0=0}^{t_0=t} dt_0 \exp\left\{-\frac{1}{\epsilon} \int_{t_0}^t \sigma[E(t')] dt'\right\}, t \leq T_R$$

In the above equation, T_R is the period of time the cable is irradiated, σ is the electrical conductivity of a cable material, ϵ is its permittivity, $E(t)$ is the electric field in the material as a function of time, and $\dot{Q}_0$ is the rate of charge produced in the material as the electrons penetrate into the material. Equation (1) is derived in Appendix A. The electric field corresponding to the charge computed from equation (1) is then computed by applying Gauss's law. The value for $\dot{Q}_0$ in equation (1) is computed as:

$$\dot{Q}_0 = \int_{E_e} V_D(E_e) \frac{e\Phi(E_e)}{R_e} dE_e \quad (2)$$

where e is the charge of an electron, R_e is the range in meters of the electrons of energy E_e (MeV) through a material, $\Phi(E_e)$ is the differential electron fluence (electrons/cm² area/s/MeV), and V_D is the charged volume of the dielectric. In the case of a cable with just one dielectric material, the charged volume in the case where the electron entirely penetrates the dielectric layer is the geometric volume:

$$V_D = \pi(R_{OUTER}^2 - R_{INNER}^2)L, R_e \geq R_{OUTER} - R_{INNER}$$

where R_{INNER} , R_{OUTER} , and L are, respectively, the values for the inner and outer radius and length of a cylindrical shell of dielectric. When the electron does not fully penetrate the layer, the charged volume is:

$$V_D = \pi(R_{INNER}^2 + 2R_e R_{INNER})L, R_e < R_{OUTER} - R_{INNER}$$

The charged volumes of a cable with multiple dielectrics are computed in a similar manner.

The electrical conductivity σ is the sum of the field induced conductivity (FIC), σ_{FIC} , and the radiation induced conductivity (RIC), σ_{RIC} :

$$\sigma = \sigma_{FIC}(E(t)) + \sigma_{RIC}(D) \quad (3)$$

Note the time variation of the FIC through the electric field intensity E .

The FIC is computed using the Adamec & Calderwood [5] relationship:

$$\sigma_{FIC} = \sigma(T) \left[\frac{2 + \cosh(\beta_F E^{1/2} / 2kT)}{3} \right] \left[\frac{2kT}{eE\delta} \sinh\left(\frac{eE\delta}{2kT}\right) \right] \quad (4)$$

where:

$$\sigma(T) = \sigma_{\infty} \exp\left(-\frac{E_A}{kT}\right). \quad (5)$$

The remaining symbols in equations (4) and (5) are defined below.

E = electric field (V/m),

T = temperature (degrees K),

E_A = activation energy of the material (eV),

e = charge of an electron,

δ = fixed jump distance (fixed at 1×10^{-10} m),

K = Boltzmann's constant (1.381×10^{-23} J/K),

σ_{∞} = constant.

In practice, the constant σ_{∞} is determined from equation (5) from the conductivity σ_{SET} known at specific temperature T_{SET} in data handbooks. With derived value for σ_{∞} substituted into equation (5), one obtains:

$$\sigma(T) = \sigma_{SET} \exp\left(\frac{E_A}{kT_{SET}}\right) \exp\left(-\frac{E_A}{kT}\right) \quad (6)$$

The RIC depends on the dose rate D (rads/s) though the power law relationship:

$$\sigma_{RIC}(D) = \kappa D^{\Delta} \quad (7)$$

In the above equation, κ ($\Omega^{-1}m^{-1}rad^{-1}s$) and Δ (dimensionless) are constants that depend on the specific material. Ahrens and F. Wooten have compiled log plots of the RIC as a function of the dose rate for a variety of insulators [6]. These plots were referenced to compute the κ and Δ supporting our analyses.

ELECTRON FLUENCE MODEL – The electron fluence model chosen for the analysis was the worst case electron environment model FLUMIC (Fluence Model for Internal Charging). The model consists of fits to the most intense electron fluence levels observed from 1987 to 1998. Data from GOES-7 and the LANL Energetic Spectrometer for Particles (ESP) on a number of geostationary spacecraft were used.