A Preliminary Spacecraft Charging Map for the Near Earth Environment

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ABSTRACT

Spacecraft in the vicinity of the Earth can encounter many different spacecraft charging regions. Although in general each spacecraft along with its particular orbit should be evaluated for charging possibilities a generalized charging map of the magnetosphere can be useful for early evaluation of spacecraft charging. Here, a preliminary worst case charging map for the Earth's magnetosphere is presented for the purpose of providing quick estimates of possible problems. As would be anticipated, high level charging is generally confined to the magnetic field lines that map to the auroral oval and the plasmasheet, and moderate level charging (~100 V) occurs in the Magnetosheath. For the simple charging model considered, charging below 200 km in an auroral arc is in the -10's of Volts range Between 200 km and 2000 km, the charging rises to over -650 Volts. Above 2000 km the charging rises to -1000 Volts at 15000 km. In the plasmasheet (including GEO orbits), charging can be as much as -28,000 Volts.

INTRODUCTION

A generalized map of the near-Earth charging environment, with an estimate of "worst case" charging potentials is produced here for use in early mission development. The map is not to be used for analysis of specific spacecraft charging problems since the environment is much too variable, but as a quick visual aid for estimating whether charging will be of concern for a particular mission. It should also be of general value for discussing spacecraft charging problems with those not familiar with spacecraft charging, because it shows the regions of concern for the Earth environment.

The original impetus for this study resulted from a requirement for order of magnitude estimates of the possibility of ESD problems on some JPL missions. They were high inclination orbit missions which pass through the auroral zones. The time spent on the estimate was limited by the necessity of a rapid response for the projects. The locations of the serious charging levels is believed to be properly presented here (for $K_p = 5$, and local time = midnight) but the actual charging levels may change. Also since these environments are extremely variable, the locations and levels of charging will vary or disappear with different K_p and local times.

CHARGING MODELS

A simple charging model using current balance is used here. Incoming electrons and ions are balanced against backscattering and secondary emission. Photo-emission electrons are included in the model but are set to zero here (midnight - or shadow) to yield worst-case charging estimates. The program interates the potential until, at a particular voltage, these currents are balanced according to

$$I_e = I_I + I_{se} + I_{sI} + I_{BSe} + I_{ph} \qquad (1)$$

where,

I_e = Incident electron current,

I_I = Incident ion current,

I_{se} = secondary emitted electron current due to I_e,

I_{sI} = secondary emitted electron current due to I_I,

I_{BSe} = Back scattered electron current due to I_e,

I_{ph} = photoelectron current.

For this particular study the electron and ion currents are taken from double Maxwellian distributions for the electrons and ions. Assuming that the secondary and backscatter terms can be parameterized, for an ambient Maxwellian plasma,

$$\sum_{i=1}^{2}(A_{ei}\,J_{ei}[1 - Se_i(V,T_{ei},n_{ei}) - BSe_i(V,T_{ei},n_{ei})])\,e^{(qV/kT_{ei})} - \sum_{k=1}^{2}(A_{Ik}J_{Ik}[1 + SI_k(V,T_{Ik},n_{Ik})]\;[1-(qV/kT_{Ik})]) - A_{ph}\,J_{ph}\,f(X_m) = I_T = 0 \qquad \text{for}\,V<0 \tag{2}$$

where

J_{ei} = ambient electron current density,

J_{Ik} = ambient ion current density,

A_{ei} = electron collection area ($4\,\pi\,r_s^2$ for a sphere)

A_{Ik} = ion collection area,($4\,\pi\,r_s^2$ fc · a sphere),

A_{ph} = photoelectron emission area, ($\pi\,r_s^2$ for a sphere),

SE_i, SI_k, BSE_i = parameterized functions for secondary emission due to electrons and ions and backscatter electrons,

J_{ph} = saturation photoelectron flux,

$f(X_m)$ = percent of attenuated solar flux as a function of altitude X_m of center of sun above the surface of the Earth as seen by the satellite and the summation subscripts i and k are for the two Maxwellian populations assumed for the electron and ions respectively.

Equation (2) is appropriate for a small (= 1 to 5 meter diameter), uniformly conducting satellite at geosynchronous orbit in the absence of magnetic field effects.

The charging model is further described in Garrett [1978 a and b], Garrett [1979], Garrett, et al. [1979] and Tsipouras et al. [1975]. It assumes a 1 to 5 meter aluminum sphere but has been validated by comparison to flight data. In general, but not included here, charging levels will also depend on surface electrical properties such as the exact value of the secondary electron emission coefficient, the directionality of the electron or ion fluxes, and the suppression of secondaries by magnetic mirroring.

ENVIRONMENTAL MODELS

Gussenhoven et al. [1985] and Deutsch [1981] are used to define worse case environments in two locations. Gussenhoven et al. [1985] found the highest charging in the aurora to be -679 Volts at 840 km altitude (measurement) and Deutsch [1981] found the highest charging at geosynchronous orbit could be

-28000 Volts in eclipse (calculated from a measured spectrum which charged ATS-6 to 2200 V while it was in sunlight). There is a discontinuity in the model between the plasma sheet and the inner magnetosphere produced by the termination of the low temperature plasma model used for background in the lower magnetosphere.

The auroral zone characteristics are difficult to accurately define. Several approximations were therefore necessary. The diffuse auroral zone is used to define the footprints of the magnetic field lines that carry the auroral electrons that will produce charging. The discrete aurora will produce the charging. A definition of the equatorward boundary of the discrete aurora was not available for this study. The poleward boundary seems not well defined during severe magnetic storms. Below 2000 km, the International Reference Ionosphere (IRI) model is used as a background plasma environment. Grebowosky et al. [1983] finds that there is a general weakening of the ionospheric densities near the poleward boundary of the auroral oval (drop of 1/5 above 1000 km) and Gussenhoven et al. [1985] finds sharper drops near regions of intense KeV electron precipitation (drop of 1/200 above 840 km). To reproduce the charging of Gussenhoven et al. [1985], the IRI densities need to be suppressed by a factor of 500. In general any charging level can be attained by suppressing the ionosphere by an arbitrary amount but the above suppression does not produces densities lower than those recorded in Gussenhoven et al. [1985]. Densities below 400 km are not suppressed because it is not known by measurements that this is the fact although swelling of the neutral atmosphere during storm conditions may accomplish this.

The auroral charging is estimated with a specific electron spectrum from the ATS-6 satellite, Gussenhoven et al. [1985]. In the aurora, the ionosphere which is used as a background (discharging) spectrum is suppressed to match the charging level found in Gussenhoven et al. [1985]. Above 800 km, the ionized hydrogen begins to dominate over ionized atomic oxygen and the charging level is reduced. As the IRI model only goes to 2000 km the plasmasphere model of Chiu et al. [1979] was used for background at higher altitudes (greater than 2000 km). Reiff et al. [1988] concludes that half of the acceleration of the discreet auroral electrons is above 2000 km altitude and Moser et al. [1980] concludes that the bulk of the acceleration is above 4000 km altitude. Here 2000 to 14000 km is used as the acceleration region.

In order to estimate the effect of a parallel electric field, no mirroring is assumed for the auroral electrons. It can be shown that mirroring is suppressed if a sufficiently large parallel electric field exist in the region. Simply, following Chen [1985], the force on a electron in a curved magnetic field with an electric field parallel to the magnetic field is given by

$$F_{\parallel} = -\mu \frac{\partial B}{\partial s} + qE, \tag{3}$$

where,

μ = the magnetic moment and

s = the pathlength along the field line.

The first term is the magnetic mirroring and the second is the electric field. For no mirroring this quantity should remain negative or zero. For this model the acceleration is assumed to be from a simple linear electric field.

The worst case auroral environment is assumed any time a spacecraft is inside the diffuse auroral oval defined by Whalen et al. [1985], where the equatorial boundary in geomagnetic latitude, GMB, is given by,

$$\text{GMB (degrees)} = 72 - 0.9Q - (5.1)\cos((360^\circ/24)lt - 12^\circ) + \alpha K_p, \tag{4}$$

where,

Q = a magnetic index that is generally unknown other than by solving
(range 1 to 8)
for it using this equation.'''

lt = local time of the spacecraft

α = a local time dependent parameter (Whalen et al. [1985]) and

K_p = the magnetic storm index.

The parameters Q and K_p are assumed to be 5 and 6 respectively in this study. The charging environment so defined roughly corresponds to a "worst-case" environment enveloping 95% of the charging events. The poleward boundary is found by measuring the thickness of the auroral oval for the proper local times off Figure 12-7 of Whalen et al. [1985].

Outside the ionosphere, diffuse aurora zone, acceleration region, and the plasmasphere are the plasmapause, the outer magnetosphere and the magnetosheath. The plasmapause is ignored in this study because, at night, it is a thin region without well defined boundaries. It has been modeled for use in a daytime estimate at a later date. The outer magnetosphere is modeled generically (one density/temperature fits all). This model produces no charging. The magnetosheath is the Garrett and Deforest [1979] equatorial model that has been made into a 3-D model by rotating it about the sun-earth axis.

No attempt has been made to account for time variations caused by the orientation of the Earth's magnetic polar axis. The model that produced the map does take these variations into account but to reproduce them in the map would make it too complex and therefore less useful for the stated purpose. The polar cusp is also ignored.

RESULTS

In general, charging is serious only along field lines that map to the auroral zone or inside that zone. This includes the plasmasheet and the magnetosheath regions, any location on a field line that maps down to the auroral zone, and any location past the magnetopause.

The models are constructed so as to reproduce worst case charging for the various regions and not to predict higher levels than has been reported (i.e., since the ionosphere's behavior under these circumstances is not well known, the 600 Volt level for DMSP is fitted and no attempt is made to find a spectrum that will exceed the 600 Volts). This assumption has the result of predicting what level of charging would be experienced at different altitudes for that same spectrum.

The locations for the charging are found for the conditions Q=5 (Q is the magnetic index that defines the auroral oval equatorial boundary) and K_p=5 (K_p is the magnetic storm index). A series of cases have been run at midnight for all latitudes at 281 degrees east longitude (this includes the north magnetic pole) for altitudes up to 100,000 km. The effect of varying the longitude, K_p or local time would be to shift the charging region to follow the footprints of the auroral oval. For sunlight, the map would only be good for parts of the spacecraft that are isolated electrically from the rest of the spacecraft and in shadow.

Charging levels are presented in the contour map accompanying this paper. Two regions are needed to produce the charging levels in the auroral/acceleration zone and the outer plasma sheet. Matching these two models together has not been accomplished yet so there is a region between the models where the charging levels are discontinuous as stated above. This will probably be eliminated in a later version of the model.

USAGE

The original usage intended for this contour map was to advise managers of Earth orbiting satellites whether they should worry at all about spacecraft charging effects, given the proposed altitude and inclination. For that purpose, the contour map has met its goal.

For more specific questions involving specific satellite geometry and materials, charging magnitude, higher intensity storms, probability vs longitude or local time, etc., the manager should request and get a detailed calculation for that case.

It can be seen that many assumptions were necessary to provide the continuity in space from one regime to another, and to make the analytic models match the observed data. These difficulties are presented as a question to our colleagues to expand our knowledge of spacecraft charging environments so we can include them in our model.

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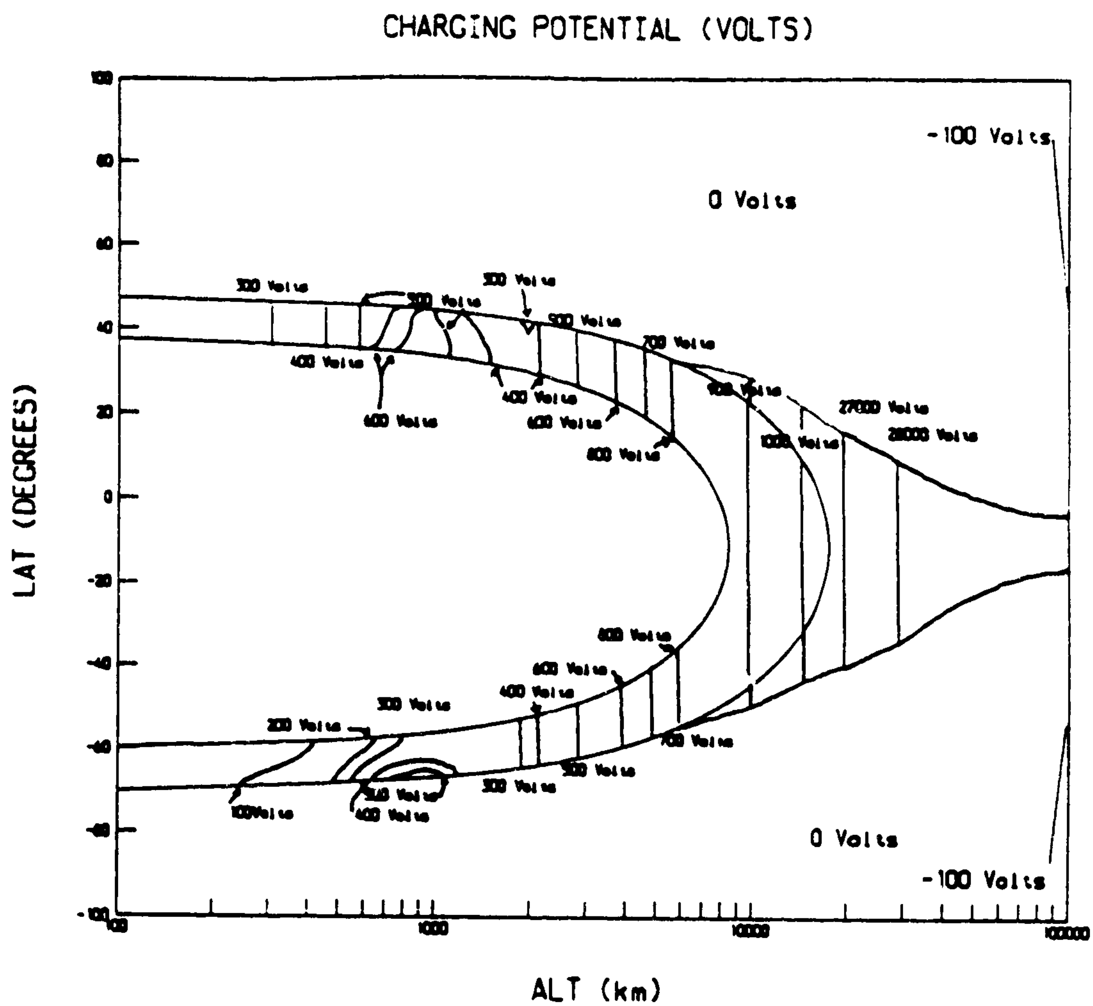
CHARGING POTENTIAL (VOLTS)
-100 Volts
0 Volts
300 Volts
500 Volts
300 Volts
500 Volts
700 Volts
400 Volts
400 Volts
600 Volts
600 Volts
800 Volts
900 Volts
27000 Volts
28000 Volts
1000 Volts
800 Volts
600 Volts
400 Volts
300 Volts
200 Volts
700 Volts
500 Volts
300 Volts
500 Volts
100Volts
400 Volts
0 Volts
-100 Volts
LAT (DEGREES)
ALT (km)
100
80
60
40
20
0
-20
-40
-60
-80
-100
100
1000
10000
100000

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