AIAA 96-0143

Spacecraft Charging, An Update

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34th Aerospace Sciences
Meeting & Exhibit
January 15-18, 1996 / Reno, NV

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(Invited Review Paper)

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Nearly twenty years after the landmark SCATHA program, spacecraft charging and its associated plasma interactions continue to be major issues for Earth-orbiting spacecraft. Although typically thought of as a surface effect on geosynchronous spacecraft, internal charging and low-altitude phenomena are increasingly causing concern. Since the time of SCATHA, spacecraft charging investigation efforts were focused on surface effects and spacecraft design issues. Today a growing proportion of spacecraft anomalies are believed to be caused by internal charging effects (charging and ESD events inside **the spacecraft** Faraday cage). This review will, following **a brief summary of the state of the art in surface charging, concentrate on the problems introduced by penetrating electrons ("internal charging") and related processes (buried charge and deep dielectric charging) and on the issues tied to the dense, low altitude plasma environment and the auroral zone. Likewise, with the advent of tethered spacecraft and the deployment of the International Space Station (shortly), low altitude charging has taken on a new significance and urgency.**

Introduction

Garrett[1] reviewed the field of spacecraft charging as of 1980. Spacecraft charging, defined in that review as the buildup of charge on spacecraft surfaces or in the spacecraft interior, has been of concern to users and operators of spacecraft since the first days of the space age. In the original review, the study of spacecraft charging was characterized by four phases. The first phase, the "pre-space age", was primarily concerned with the theory of simple probe charging and with rocket measurements of charging in the ionosphere. It ended in 1957 with the launch of Sputnik. The brief second phase was marked by the formal foundations of charging theory (at least in the ionosphere) and by the first tentative measurements by satellites. The third phase, in the early 60's, was characterized by the first accurate measurements of charging on spacecraft and rockets. Self-consistent models were developed and factors such as secondary emission and photoelectron currents were included in these models. It ended roughly in 1965 with the publishing of E. C. Whipple's thesis[2] on spacecraft charging. That thesis and reviews by Brundin,[3] Bourdeau,[4] and others established the basic components of charging theory and the range of observations. The fourth phase, from 1965 to 1980, was characterized by increasingly more sophisticated models of spacecraft surface charging, in-situ measurements, and definition of the space plasma environment. Giving impetus to the study of spacecraft charging, the first in-situ observations of kilovolt potentials at geosynchronous orbit were reported by DeForest[5] in 1972. This period ended with the flight and analysis of the SCATHA (P78-2) spacecraft. Reviews by Garrett[1] and Whipple[6] summarized the major theoretical and observational findings of the period. The engineering implications of these findings were summarized in the NASA Spacecraft Charging Design Guidelines and MIL STD 1541 A.*

This review will provide an overview of the changes in the field of spacecraft charging between 1980 and the present--other papers in the session will review these changes in detail. The 15 years between the original review in 1980 and now mark the fifth "age of charging". Although the changes since 1980 have in general been in emphasis, there has been a major shift in attitude vis a vis surface charging versus internal charging caused by penetrating electrons--whereas the former was always an important process, in recent years it has become increasingly clear that, as external charging is now routinely addressed in spacecraft design, a growing proportion of spacecraft anomalies are now believed to be caused by "internal" charging (defined as charging inside the Faraday cage of the spacecraft). Likewise, with the importance of the Space Station to the national space program, the charging effects of low Earth orbit have become of increasing concern. Finally, the continuing desire to use high voltages in space and to utilize tethers have in particular led to growth in these areas doring the fifth period.

Surface Charging

Surface charging in this paper refers to charging effects and electrostatic discharge effects on the outside of the spacecraft "Faraday cage". It is now universally recognized as an important design consideration for spacecraft. Surface charging is defined by the current balance equation:

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$$I_T(V) = I_E(V) - (I_I(V) + I_{SE}(V) + I_{SI}(V) + I_{BSE}(V) + I_{PH}(V)) \qquad (1)$$

where

V = surface potential relative to space
I_T = total current to spacecraft surface at V;
= 0 at equilibrium when all the current sources balance
I_E = incident ambient electron current
I_I = incident positive ion current
I_{SE} = secondary emitted electron current due 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

Fig. 1[9] is an approximation of the expected range of the threat in terms of surface potential (in the absence of photoemission) as a function of altitude and inclination. The primary region of surface charging is, as has been recognized for many years, in and near geosynchronous orbit. This region was extensively mapped by the SCATHA satellite. The characteristics of this environment have been presented in a series of descriptive “atlases”.[10-15] Of increasing interest, however, is the portion of the charging environment below 1000 km in the polar regions. Although not as dramatic as geosynchronous charging, “low altitude” surface charging in this region is more common than originally thought (see Section IV).

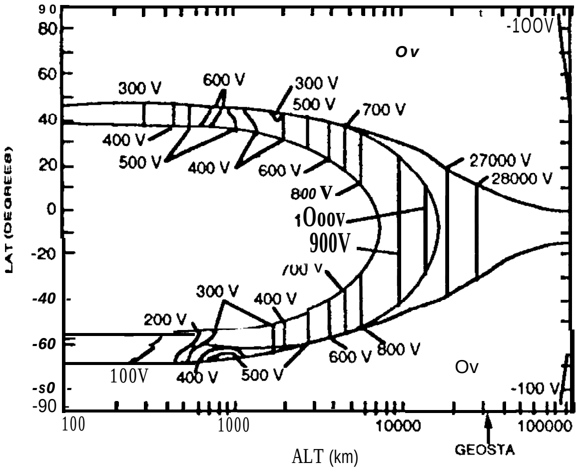

Fig. 1 Surface potential contours (in the absence of sunlight) as a function of altitude and latitude.[9]

The surface charging environment has been mapped out for other planets--surface potentials have been estimated for example for Jupiter.[16] In support of such predictions, the Voyagers have observed large surface charging throughout the solar system--tens of kV at Jupiter[17] and -400 V at Uranus.[18] Many interplanetary spacecraft are now, as a result, designed to minimize surface charging as a matter of course. These design techniques are based on design guidelines and standards defined in NASA 2361[7] and MIL-STD 1541A.[8] The methods for controlling and mitigating surface charging were the direct outgrowth of the SCATHA experience. Actual flight experience over the last decade has repeatedly demonstrated the value of these methods. Indeed they have consistently proven to be successful in limiting the effects of surface charging. Coupled with newly developed materials and appropriate spacecraft design considerations, surface charging can be controlled over the regions marked off in Fig. 1,

Although it is still difficult to adequately predict geomagnetic activity with anything more than a half to one hour lead time, it has proven possible, based on in-situ measurements, to estimate absolute surface charging levels with some accuracy from measurements of the plasma (note: differential potentials are another matter altogether and require sophisticated codes such as NASCAP to provide satisfactory results). In Garrett et al.,[19] data from plasma sensors on one geosynchronous spacecraft were successfully used to determine charging levels at another spacecraft. These measurements, which can be had in near-real time, can be used to estimate charging levels at other spacecraft within several hours of local time around the observing spacecraft. This capability is demonstrated in Fig. 2 where data from one spacecraft (the USAF Defense Support Program or DSP satellite) are used to estimate potentials on the near-by ATS-6. Of interest is that this was done with only three electron energy channels. The results imply that surface charging is primarily a function of the large fluctuations in electron current at energies of a few 10’s of keV and that it is possible to provide a “spacecraft surface charging index”.

Internal Charging

Internal charging as used here refers to the accumulation of electrical charge on the interior of a spacecraft due to the penetration of high energy ($E > 100$ keV) electrons. During the Voyager 1 passage by Jupiter on September 5, 1977,[20],[21] 42 identical electrical anomalies were observed. These were subsequently attributed to internal charging. In particular, it was postulated that ~MeV electrons had penetrated the surface of a cable and built up charge sufficient to cause arcing. Analysis of SCATHA, CRRES, and DSP data[22] showed similar effects. Laboratory studies by Leung,[23] Frederickson,[24-26] and others demonstrated that internal (also called buried) charging was a potential source of discharges. As a result, a series of internal charging experiments were flown on the CRRES spacecraft in 1990-1991 .[26] These experiments, which exposed a variety of configurations of isolated conducting surfaces and dielectrics to the Earth’s radiation environment, clearly demonstrated the reality of this effect. Over 4000 pulses were detected during the 13 months lifetime of the CRRES spacecraft. As in the case of SCATHA for surface charging, CRRES marked a watershed in the study of internal charging.

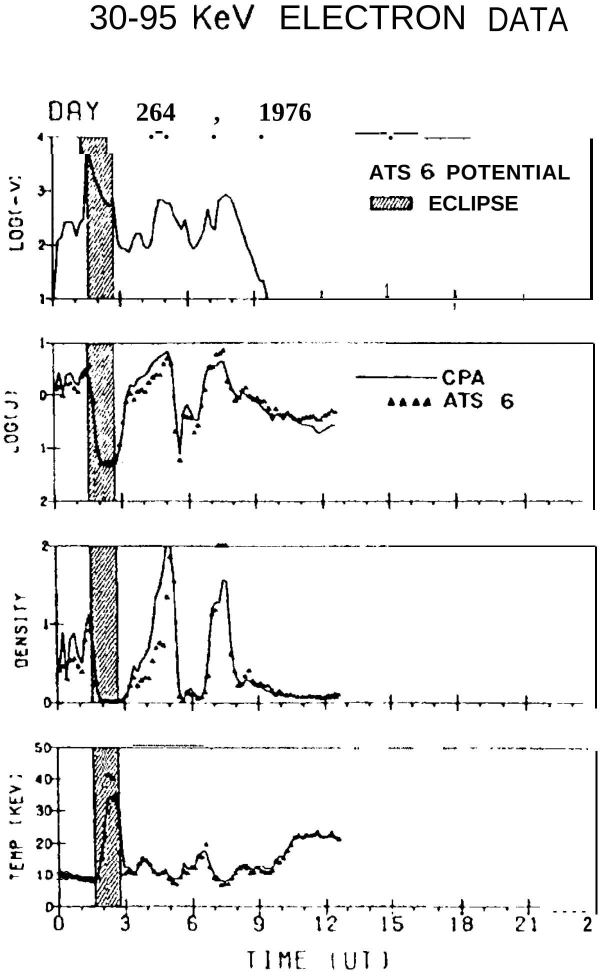

Fig. 2 Measurements of the 30- to 80-keV electron channels from the DSP CPA instrument compared with the plasma and charging environment at ATS 6.[19]

Except for bulk conducting materials, charge will be deposited over a finite depth--indeed, any particle with energy over a few eV will penetrate the surface. The depth of penetration and charge deposition is a function of stopping power, the energy of the impinging particles, and any electric fields normal to the surface (see Fig. 3 for the penetration depth of energetic electrons and protons in aluminum). A common spacecraft surface configuration that will exhibit this behavior consists of an exposed dielectric material with a conducting backing connected to the spacecraft ground. Charge will accumulate (or diffuse away) in the dielectric over time as a function of the conductivity of the material and the imposed electric fields. If the charge accumulating in the dielectric induces a field greater than the breakdown strength of the material (typically of the order of 10^5 to 10^6 V/cm), a discharge can occur within the material or from the interior of the dielectric to one of its surfaces.

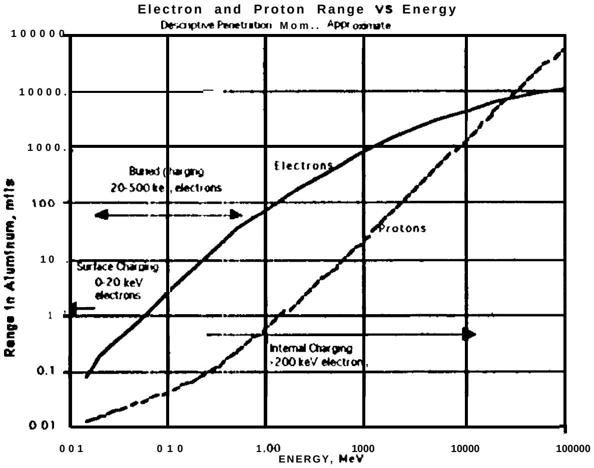

Fig. 3 Electron and ion penetration ranges in aluminum.

The computation of internal charging resembles surface charging calculations with the inclusion of space charge. The basic problem is the calculation of the electric field and charge density in a self-consistent fashion over the three-dimensional space of interest. The primary difference between the two is the role that the conductivity of the material plays in the process. Poisson's equation must be solved subject to the continuity equation in the dielectric. As a simple example, consider a one-dimensional, planar approximation at a position X in the dielectric. The equation at X is then:

$$\varepsilon(dE/dt) + \sigma E = J \qquad (2)$$

where E is the electric field at X, t is time, σ is the conductivity in $(\text{ohm-m})^{-1} (= \sigma_o + \sigma_r)$. Here σ_o is the dark conductivity, σ_r is the radiation induced conductivity,[27] ε is the dielectric constant. J is the incident particle flux (current density) at X including primary and secondary particles. A solution of this equation for σ and J independent of time is:

$$E = E_o \exp(-\sigma t/\varepsilon) + (J/\sigma)(1 - \exp(-\sigma t/\varepsilon)) \qquad (3)$$

where E_o is the imposed electric field at $t=0$.

Although an approximation, these two equations demonstrate the basic features of radiation induced charging. In particular, they demonstrate the importance of the charging time constant ($\tau = \varepsilon/\sigma$). For many materials, τ ranges from 10 s to 10^3 s. Some common space dielectric materials have even longer constants. In regions where the dose rate is high (enhancing the radiation conductivity), the E field comes to equilibrium rapidly. In lightly irradiated regions, where the time constant is long (the dark conductivity dominates), the field takes a long time to reach equilibrium. Depending

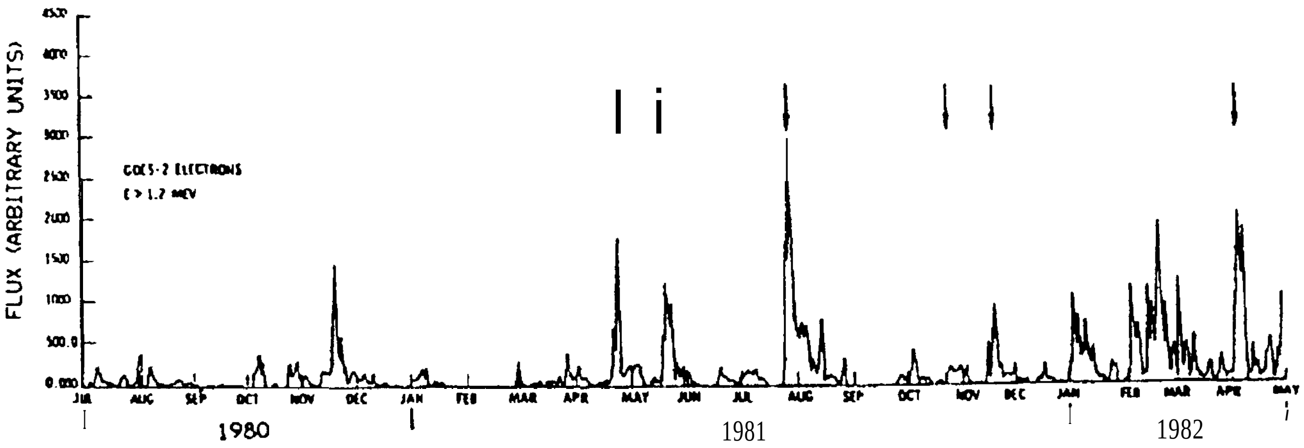

Fig. 4 GOES-2 E **> 1.2 MeV electron flux at geosynchronous orbit between July 1980 and May 1982 compared with star-sensor anomalies on the DSP satellite.**[22]

on the dielectric constant, as a rule of thumb, 10^{10} to 10^{11} electrons/cm^2 on the interior of a spacecraft may cause internal discharges. Electron energies of importance are between 100 keV to 3 MeV. Charging times at these energies and the fluxes at geosynchronous orbit would be about 3 to 30 hrs. At lower charging rates, material conductivity often leaks off the charge so that internal charging would not be a problem. In Fig. 4, measurements of the E > 1.2 MeV electrons at geosynchronous orbit by the GOES-2 satellite between July 1980 and May 1982 and star-sensor anomalies on the DSP satellite are seen to be well correlated confining this proposition.[22]

As of this date, detailed and specific published guidelines have not been formulated for preventing or controlling internal charging. Although many of the procedures for limiting surface charging can be applied to internal charging, there are issues specific to internal charging that are not covered in 2631 or in MIL-STD 1541 A. There is not yet a consensus in the spacecraft engineering community as to what and to what degree design features are necessary to limit internal charging effects. This lack of consensus has resulted in several spacecraft suffering upsets that might have been avoided if proper guidelines had been in place. Recently, two Anik spacecraft apparently suffered serious consequences as a result of this lack of consistent guidelines. On January 20 and 21, 1994, the Anik-E1 and E2 spacecraft suffered serious upsets within hours of each other that resulted in brief loss of one and a six month outage to the other. Subsequent analysis has implicated internal charging as the cause.

As in the case of surface charging, there are currently on station several geosynchronous monitors that can be used to provide a real-time "internal charging index" (Fig. 4). When the flux exceeds a critical number for a given spacecraft (this number is very dependent on spacecraft design), arcing may occur.

Low Altitude Charging

Spacecraft orbiting at low altitudes must also be concerned with charging. At this time, the threat is not as well defined from a design standpoint as it has been for surface and internal charging. Because of the complex magnetohydrodynamic flow fields and, with Space Station and similar large bodies, the effects of structure size and shape in high density plasmas, hypersonic plasma interactions at low altitudes have always presented an analytic challenge. With the proliferation of super computers and massively parallel processors, a number of spacecraft charging problems at low altitudes are for the first time yielding to numerical analysis. Intricate geometries, magnetic fields, changing composition, and imposed potentials can now all be effectively modeled. As outlined in Hastings'[28] recent review, low altitude charging analysis is coming of age.

Turning to the basic physics, the low altitude charging problem is best represented by the movement of a body through a dense, cool ionospheric plasma. For a typical spacecraft, its characteristic dimensions are, in contrast to geosynchronous orbit, quite large compared to the plasma debye length. This factor makes current flow computations for complex geometries and field configurations difficult. However, the basic variations can be illustrated for the current flow to a flat plate. In the absence of externally-imposed fields or currents (i.e., particle beams), the current flow to a planar surface on a spacecraft in the ionosphere as a function of angle relative to the velocity angle can be expressed by:

$$I_i = \alpha q n_i A_i \left[v_s \cos\theta (1/2 + 1/2 \, @\text{-}(x)) + \frac{-x^2}{2\sqrt{\pi}} \right] \tag{4}$$

where:

$$x = \frac{v_s \operatorname{Cos}\theta}{a} - \left(\frac{qV}{kT_i}\right)^{1/2}$$

θ = angle between sensor normal and velocity vector
A_i = collection area
a = grid transparency function
a = most probable ion thermal velocity
v_s = spacecraft velocity
q = charge
T_i = ion temperature
k = Boltzmann constant
n_i = number density

The current predicted by this equation[29,30] is plotted as a function of angle relative to the spacecraft velocity vector in Figure 5. It illustrates the characteristic "ram-wake" variation in the current with angle. Similar predictions for a cylindrical geometry,[31] as a function of altitude (and hence composition), are compared with actual data from measurements on a small spacecraft[32] in Fig. 6. The agreement is quite good and demonstrates how current flow varies dramatically with angle and composition. When magnetic fields, imposed potentials, and complex geometries are also included, the difficulty of the problem changes dramatically and can seldom be addressed analytically as above.

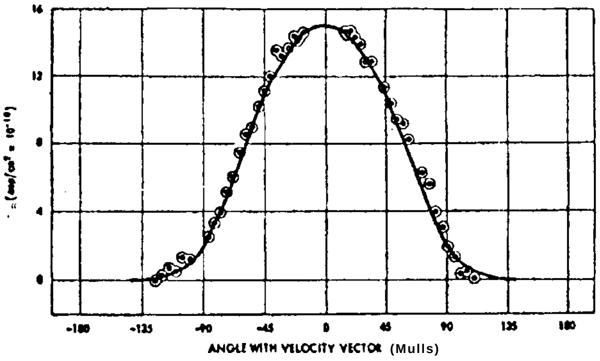

Fig. 5 Positive ion current density versus angle to the satellite velocity vector at 3.6 km/s.[30]

As a sample of the difficulties that a typical problem can introduce, consider a large biased solar panel in low Earth orbit. Figure 7 is a plot of the plasma flow field for a large flat plate (representing say a large Space Station solar array panel) at low altitudes. This figure[33] illustrates several possible variations. The first frame (Fig, 7a) is for an unbiased plate in a low altitude ionospheric plasma at -Mach 8. Next, a small, isolated body is inserted in the flow field behind the plate and allowed to float to an equilibrium potential. This alters the flow field slightly (Fig. 7b). Next, an externally imposed current source is applied (an auroral particle beam such as observed at high inclinations). The main plate does not alter its potential significantly but the smaller body, because it is shielded from the ionospheric plasma, begins to charge. As it does so, it significantly alters the wake flow (Fig. 7c). In Fig. 7d, a potential difference is applied between the plate and the small body (this might correspond to a crew module biased relative to the main arrays). As the potential difference is increased, the flow field becomes even more altered.

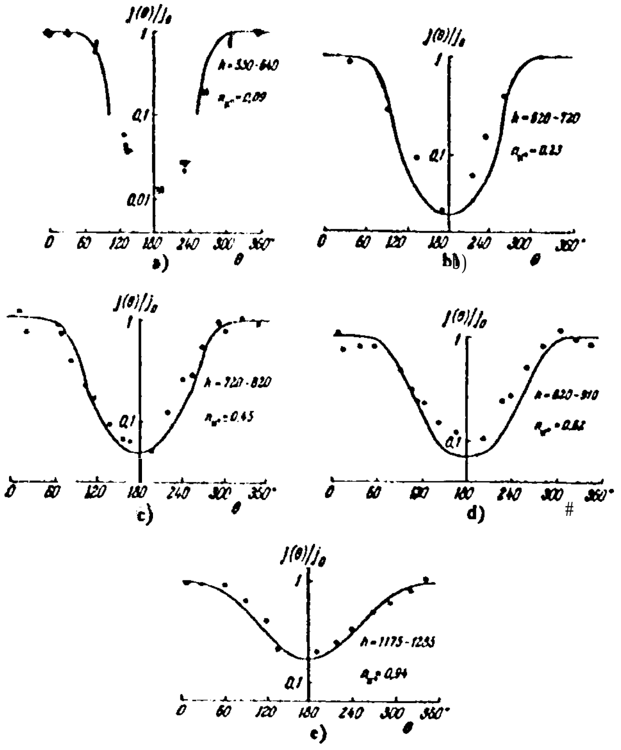

Fig. 6 Normalized electron current versus angular position of the plasma probe on Explorer 31.[32]

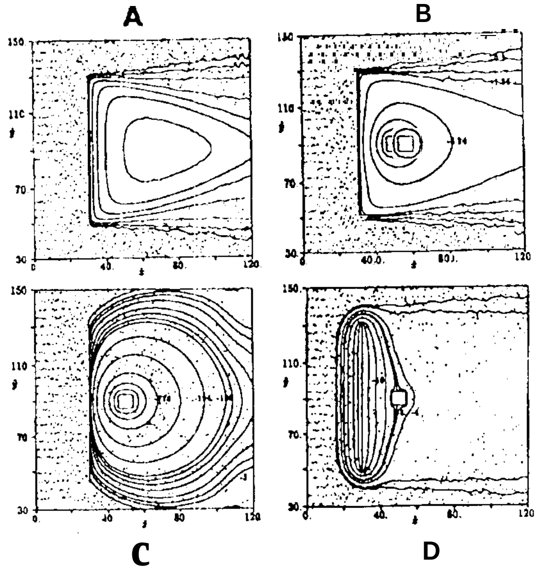

Fig. 7 Low altitude potential and ion flow contours for four different conditions (see text) .33

The calculations just presented barely introduce the rich variety of low altitude plasma interactions now being studied. Consider the growing interest in space tethers. Multi-km long thin conducting cables are now possible. Given the interesting and useful applications that the dynamics of these structures imply, NASA and the DoD have initiated several studies of the electrodynamics of tethers. One interest here is the use of these tethers to generate electricity. The basic principle is well known and contained in the Lorentz relationship:

$$V = \vec{v}_s \times \bar{B} \cdot \bar{L} \tag{5}$$

where:
B = the magnetic field (vector)
L = the tether length (vector)

For a conducting object in low Earth orbit, the VXB electric field varies from a low of about (O. 1 V/m) at the equator to a maximum of (0.3 V/m) over the polar caps. As Eq. 5 states, the potential depends on the orientation of the tether relative to the VXB electric field vector. For a 10 km tether (easily possible with present technology), a potential difference of up to 30,000 V is possible. Problems arise, however, in achieving the current flow necessary to utilize the energy as it is not clear that a sufficient ion current is possible without resorting to an ion thruster or similar emission device.[28] This is an ongoing topic of research and debate.

Over the last few years, experimental work in low altitude charging has concentrated on monitoring charging events on the low altitude (800 km), polar orbiting DMSP satellites. Papers[34] have reported potentials ranging from a few hundreds of volts to over a kV. It now appears that far from being a very rare event, moderate charging events (i.e., above the -200 to 500 V differential potentials normally believed to be the minimum necessary to cause arcing) are relatively common for polar orbiting spacecraft (note there have been few reports of anomalous spacecraft events attributed to this environment, however). Given adequate measurements of ionospheric and geomagnetic activity, it should be possible to determine the occurrence of such events in real time as in the case of geosynchronous charging as the two are intimately connected,

Another area of low altitude charging interest is that associated with induced potentials. In a series of rocket and satellite experiments, the DoD and NASA have completed several interesting studies over the last decade into the effects of induced high potentials on solar arrays and of plasma beams on spacecraft potentials, Intended primarily to parametrize the ranges over which exposed high potential surfaces can be biased before arcing sets in and to demonstrate control of the discharge process, two series of experiments stand out. The first of these are the ongoing solar array experiments associated with the PASP Plus APEX satellite experiment.[35] Launched into a 363 by 2550 km elliptical orbit on August 3, 1994, by a Pegasus rocket, this experiment consisted of a collection of several types of solar array cells. Ranging from solar concentrators to representative samples of the Space Station arrays, the cells were biased over a range of voltages (±500 V) and their current collection and arcing characteristics measured. in particular, the electron current collected by the se-called snap-over phenomena for positively biased solar arrays[23,36] was studied. Likewise, arcing for large negative potentials were also monitored. The results are still being analyzed, however.[3]5

The final low altitude charging experiments of interest are those associated with the Ballistic Missile Defense Organization's SPEAR Program.[37] In a series of three launches between 1987 and 1993, rockets were used to characterize the ability of a power system to maintain high voltages (upwards of 40 kV) in a dense ionospheric plasma (-200 to 300 km). These rocket flights were very successful in demonstrating the generation and control of multi-kV potentials in dense, ionospheric plasma. Careful, ground-based studies permitted accurate modeling of the subsequent observations and detailed evaluations of a variety of techniques for controlling, measuring, and establishing high potentials in space without the need for heavy insulation relative to the plasma. These results promise a new era in the utilization of high voltage systems in space.

Conclusions

To summarize, the study and analysis of spacecraft charging over the last fifteen years has demonstrated a growing maturity. Surface charging is recognized as a serious operational threat to spacecraft and useful design guidelines are in place for its mitigation that were made possible in large part by the success of the SCATHA program. Internal charging has grown noticeably more important as a source of charging/arcing. With the flight of CRRES and its internal charging experiment, flight confutation now exists of this Phenomenon over the entire radiation belts. At least for geosynchronous orbit, it is currently possible to provide a real-time internal charging index. Unfortunately, no consistent, formal internal charging design guidelines exist. Mitigating design rules now in use. by a few knowledgeable engineers need to be consolidated and improved for use in the public domain. Finally, low altitude charging effects are slowly yielding to detailed computer analysis and experiment. Theory and evidence are converging on consistent models and techniques. Successful conclusion of this process promises major advances in the utilization of the low altitude space environment. In particular, the use of tethers and of high voltage systems now appear possible if proper consideration to the details is 'maintained. The last fifteen years has thus seen significant and meaningful progress in an important scientific and engineering area of research--spacecraft charging.

Acknowledgments

This work was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

[1]**Garrett,** H. B., "The Charging of Spacecraft Surfaces," *Rev. Geophys.*, Vol. 19, 1981, pp. 577-616.

[2]**Whipple,** E. C., "The Equilibrium Electric Potential of a Body in the Upper Atmosphere," NASA X-615-65-296, NASA, 1965.

[3]Brundin, C. **L.,** "Effects of Charged Particles on the Motion of an Earth Satellite," *AMA Journal,* Vol. 1, 1963, pp. 2529-2538.

[4]**Bourdeau,** R. E., "On the Interaction Between a Spacecraft and an Ionized Medium," *Space Sci. Rev.*, Vol. 1, 1963, pp. 719-728.

[5]**DeForest,** S.E., and **C.E. McIlwain,** "Plasma Clouds in the Magnetosphere," *J. Geophys. Res.*, Vol. 76, 1971, pp. 3587.

[6]**Whipple,** E. C., "Potentials of Surfaces in Space," *Rep. Prog. Phys.*, Vol. 44, 1981, pp. 1197-1250.

[7]**Purvis,** C. K., **H.B.** Garrett, **A.C.** Whittlesey, and NJ. Stevens, "Design Guidelines for Assessing and Controlling Spacecraft Charging Effects," NASA Technical Paper 2361, NASA, 1984.

‘Anon., "Electromagnetic Compatibility Requirements for Space Systems," **MIL-STD** 1541A, United States Air Force, U.S. Government Printing Office, 1987.

‘Evans, R., **H.B. Garrett,** S. Gabriel, and **A.C.** Whittlesey, **"A** Preliminary Spacecraft Charging Map for the Near Earth Environment" *Spacecraft Charging Technology Conference,* Naval Postgraduate School, 1989.

[1] ‘Garrett, **H. B., E.G.** Mullen, E. Ziemba, and S.E. DeForest, "Modeling of the Geosynchronous Plasma Environment, 2, ATS-5 and ATS-6 Statistical Atlas," AFGL-TR-78-0304, AFGL, 1978.

[11]**Garrett,** H. B., **R.E. McInerney, S.E.** DeForest, and B. Johnson, "Modeling of the Geosynchronous Orbit Plasma Environment-Part 3, **ATS-5** and ATS-6 Pictorial Data Atlas," AFGL-TR-79-O015, AFGL, 1979.

[12]**Garrett,** H. B., **D.C.** Schwank, and **S.E.** DeForest, "A Statistical Analysis of the Low-energy Geosynchronous Plasma Environment--I. Electrons," *Planet. Space Sci.,* Vol. 29, 1981, pp. 1021-1044.

[13]**Garrett,** H. B., **D.C.** Schwank, and **S.E.** DeForest, "A Statistical Analysis of the Low-energy Geosynchronous Plasma Environment--II. Protons," *Planet. Space Sci.*, Vol. 29, 1981, pp. 1045-1060.

[14]**Mullen,** E. G., D.A. Hardy, **H.B.** Garrett, and **E.C. Whipple, "P78-2** SCATHA Environmental Data Atlas," *Spacecraft Charging Technology 1980,* **NASA/AFGL,** NASA CP218UAFGL-TR-81 -0270, 1981.

J ‘Mullen, E. G., and **M.S. Gussenhoven,** "SCATHA Environmental Atlas," **AFGL-TR-83,** AFGL, 1983.

[16]**Divine,** T. N., and **H.B.** Garrett, "Charged particle distributions in Jupiter's magnetosphere," *J. Geophys. Res., VOL* 88, Sept. 9, 1983, pp. 6889-6903.

[17]**Khurana,** K. K., **M.G. Kivelson, T.P.** Armstrong, and **R.J.** Walker, "Voids in Jovian Magnetosphere **Revisted:** Evidence of Spacecraft Charging," *J. Geophys. Res.*, Vol. 92, No. A12, 1987, pp. 13,399-13,408.

[1] ‘Bridge, H. S., *et al.,* **"Plasma** Observations Near Uranus: Initial **Results** from Voyager 2," *Science,* Vol. 233, **July,** 1986, pp. 89-93.

[19]**Garrett,** H. B., **D.C.** Schwank, P.R. Higbie, and **D.N.** Baker, "Comparison Between the 30-80 **keV** Electron Channels on ATS-6 and 1976-059A During Conjunction and Application to Spacecraft Charging Prediction," *J. Geophys. Res.*, Vol. 85, 1980, pp. 1155-1162.

[20]**Leung,** P., **A.C.** Whittlesey, **H.B.** Garrett, **P.A.** Robinson, Jr., and **T.N.** Divine, "Environment-Induced Electrostatic **Discharges** as the Cause of Voyager 1 **Power-**On Resets," *J. Spacecraft,* Vol. 23, No. 3, May/June, 1986, pp. 323-330.

[21]Whittlesey, A. C., and P. **Leung,** "Space Plasma Charging--Lessons **from** Voyager," *AIAA 25th Aerospace Sciences Meeting, January 12-15,* Reno, NV, **1987.**

[22] **Vampola, A.L.,** "Thick Dielectric Charging on High-Altitude Spacecraft," *J. Electrostatics,* Vol. 20, 1987, pp. 21-30.

[23]**Leung,** P., "Discharge Characteristics of a Simulated Solar Array," *IEEE Trans. Nucl. Sci.,* **Vol. NS-30,** 1983, p. 4311.

[24]**Frederickson,** A. R., "Radiation Induced Dielectric Charging," in *Space Systems and Their Interactions with the Earth's Space Environment*, **H.B.** Garrett and **C.P.** Pike, Editors, AIAA Press, NY, 1980, pp. 386-412.

[2]‘Fredrickson, A. R., "Electrostatic Charging and Discharging in Space Environments," ***Proc. 10th Inter. Symp.*** *Discharges and Electrical Insulation in Vacuum, 1983.*

[2]"Fredrickson, A. R., E.G. **Holeman,** and E.G. Mullen, "Characteristics of Spontaneous Electrical Discharges of Various Insulators in Space Radiation," ***IEEE*** *Trans. Nut. Sci.*, Vol. V-39, No. 6, December, 1992.

2 [7]**Frederickson, A.R., D.B. Cotts, J.A. Wall, and F.L.** Bouquet, *Spacecraft Dielectric Material Properties and Spacecraft Charging*, **AIAA** Progress in **Aeronuatics** and Astronautics, Vol. 107, **AIAA,** Washington, D. C., 1986.

[28]**Hastings,** D. E., "A Review of Plasma Interactions with Spacecraft in Low **Earth** Orbit," *J. Geophys. Res.*, **Vol.** *100,* **No.** A8, August, 1995, pp. 14,457-14,483.

[2]9Whipple, E. C., and **L.W.** Parker, "Theory of an Election Trap on a Charged Spacecraft," *J. Geophys. Res.*, **Vol. 74,** 1969, pp. 2962-2971.

[30]**Bourdeau, R.E., J.L. Donley, G.P. Serbu,** and **E.C. Whipple, "Measurements** of Sheath Currents and Equilibrium Potential on the Explorer VIII Satellite," *J. Astron. Sci.*, Vol. 8, 1961, pp. 65-73.

[31] Gurevich, A. V., L.P. Pitaevskii, and V.V. Smimov, “Ionospheric Aerodynamics,” Sov. *Phys. Usp. (Eng. Trans.)*, Vol. 99(1-2), 1970, p. 595.

[32] Samir, U., and G.L. Wrenn, “The Dependence of Charge and Potential Distribution Around a Spacecraft on Ionic Composition,” *Planet. Space Sci.*, Vol. 17, 1969, p. 693.

[33] Wang J., P. Leung, H. Garrett, and P. Murphy, "Multibody-Plasma Interactions: Charging in the Wake,” *J. Spacecraft*, Vol. 31, No. 5, September-October, 1994, pp. 889-894.

[34] Gussenhoven, M. S., “High Level Spacecraft Charging in the Low Altitude Polar Environment,” *J. Geophys. Res.*, Vol. 90, 1985, p. 11009.

[35] Guidice, D., P. Severance, H. Curtis, and M. Piszczor, “Investigation of Space-Environment Effects on Photo-Voltaic Technologies by the PASP Plus Experiment”, AIAA 95-0371, *33rd Aerospace Sciences Meeting and Exhibit*, January 9-12, Reno, NV, 1995.

[36] Stevens, NJ., “Review of Interactions of large Space Structures with the Environment,” in *Space Systems and heir Interactions with Earth’s Space Environment*, H.B. Garrett and C.P. Pike, Editors, AIAA Press, New York, 1980, pp. 437-454.

[37] Rustan, P., H.B. Garrett, and M.J. Schor, “High Voltages in Space, Innovation in Space Insulation,” *IEEE Trans. Elec. Insulation*, Vol. 28, No. 5, October, 1993, pp. 855-865.