EFFECTS OF SPACECRAFT POTENTIAL ON
SECONDARY ELECTRON YIELDS IN GEOSYNCHRONOUS ORBIT

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Abstract

Surface charging due to interactions with the earth's plasma is a hazard for orbiting spacecraft. Secondary electron (SE) emission is an important physical process in spacecraft charging. Current spacecraft charging models do not consider the SE energy or angular distributions and their implications for estimating the return of SE to the spacecraft. Comprehensive work on the application of SE energy and angular distributions to spacecraft charging has been published [*Nickles et al., 1999*] and part of that work is summarized here. The application of SE energy distributions to the case of positive charging in geosynchronous orbit is discussed and shown to impact the cutoff voltages required to assume that secondary electron yields are effectively zero. The ramification of the SE angular distribution for cases of negative charging in geosynchronous orbit is also briefly discussed.

Spacecraft Charging

Spacecraft are subjected to a harsh environment in orbit around the earth. Along with orbital debris, intense sunlight and high vacuum, spacecraft are exposed to the earth's plasma of electrons and ions. The incident fluxes of charged particles from the plasma and the subsequent emission of charged particles by the various spacecraft surfaces are all sources of current between the neutral plasma and the spacecraft. As a result, the spacecraft adopts a potential(s) to stop the flow of charge. The spacecraft can have varying potentials between surfaces (differential charging) and in relation to the neutral plasma (absolute charging). While absolute charging is relatively harmless, differential charging can lead to damaging arc discharges, interfere with charged particles measurements and enhance particle deposition and impact damage [*Hasting and Garrett, 1996*].

SE Emission and Spacecraft Charging

Secondary electrons (SE's) are electrons emitted from a material due to electron or ion beam bombardment and their emission is an important physical process in spacecraft charging. Materials in close proximity with differing SE emission characteristics can cause differential charging that results in arc discharges. The different SE emission properties of the cover glass and metal interconnects in solar arrays is thought to be the main cause of arc discharge damage to the cover glass. SE emission is also thought to be the central process in the "snapover" phenomenon that causes erratic current collection [*Thomson, 1999; Hasting and Garrett, 1996*].

Secondary Electron Emission

Again, secondary electrons (SE's) are emitted from spacecraft surfaces in response to incident electrons or ions from the plasma environment. Since the SE current due to electron bombardment is typically larger than those due to ion impact, we will only consider SE emission as a result of incident electrons. Incident (or primary) electrons that are reflected or scatter out of the material are referred to as backscattered electrons (BSE's). The elastic BSE's have energies near the primary electron's energy, while electrons emitted from the material (SE's) are theorized to have very low emission energies.

Since electrons are indistinguishable particles, a SE is differentiated from a BSE by convention, at 50 eV of energy. The SE energy distribution is then the low energy subset (0-50 eV) of all the emitted electrons. Figure 1 shows a typical SE energy distribution. Notice that the SE energy distribution is sharply peaked at low energies (maximum energy $E_{max} \sim 1\text{-}5$ eV for most materials [*Seiler 1983*]), which makes the arbitrary definition for SE (electrons with < 50 eV) seem reasonable. Chung and Everhart [*1974*] have derived a semi-empirical theory for the SE energy-distribution (assuming normal incidence electrons)

$$\frac{d\delta(E)}{dE} = \frac{k}{E_{beam}} \frac{E}{(E+\phi)^4} \qquad (1)$$

where k is a normalization constant and ϕ is the work function of the emitting surface. In addition to the energy distribution of SE's, there is also a distribution of the initial angles that SE's are emitted from a surface.
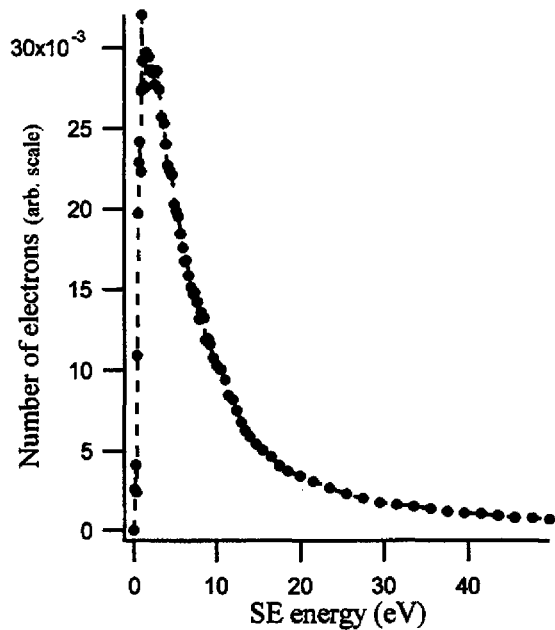
Figure 1. Typical SE energy distribution data. Gold sample using a 1500 eV incident electron beam [Nickles et al., 1999].

SE emission angles follow a Lambert cosine distribution [*Jonker 1951*], as shown in Figure 2.

The secondary electron yield δ is the total number of secondary electrons emitted per incident primary electron. Resolving a material's SE yield in energy or emission angle results in the SE energy or angular distributions. The SE yield is then the integral of these energy and/or angular distributions for the emitted SE, normalized by the incident beam current.

SE Yields and Spacecraft Charging Models

The SE yield is used to calculate the SE current that results from a given flux of primary electrons into a spacecraft surface. The SE yield depends on the primary electron's energy and angle of incidence, but more importantly, the SE yield depends on the emitting material. Adjacent surfaces with different SE yields can result in differential charging.

The current versions of NASA's spacecraft charging analyzer program (NASCAP) rely on experimental values for the SE yield, but do not incorporate information about the emission energy or angle of SE's [*Mandell et al., 1993*]. Since a charged spacecraft can create large electric fields that will deflect SE's, another aspect to consider in spacecraft charging is the return of deflected SE's to their emitting surface or other parts of the spacecraft before they reach the neutral plasma.
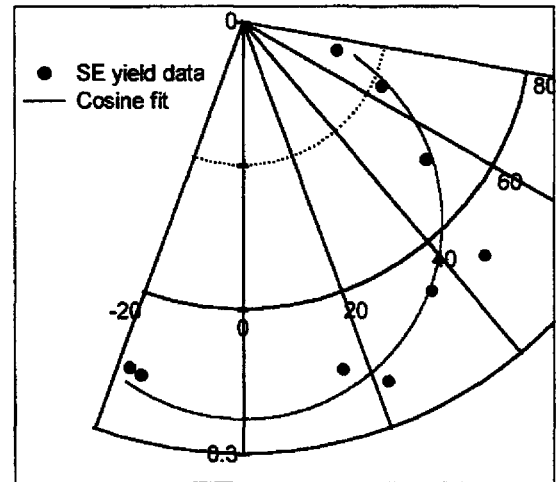

Figure 2. Typical SE angular distribution data [Nickles et al., 1999]. The angle-resolved SE yield is measured through a detector aperture located at fixed angles in relation to the sample surface.

These SE return currents could affect the ultimate charge on the spacecraft. The initial energy and/or emission angle of a SE may need to be considered to calculate whether a given electric or magnetic field will return a SE to the spacecraft.

The work presented here is an introduction to the implications of the SE emission energy and angular distributions on the modeling of spacecraft charging. Specifically, we consider the impact of the SE energy distribution on the SE yield of a positively charged emitting surface of the spacecraft. Consideration of the SE angular distribution in cases of negative charging is summarized. The scope will be further limited to charging scenarios in geosynchronous orbit (GEO) for brevity. More comprehensive work on this subject is available [*Nickles et al., 1999*].

Given the extremely low magnetic field strengths in GEO (~1 milliGauss), we can neglect the effects of magnetic fields on SE's and concentrate on charge induced electrostatic fields. The case where the emitting surface has a positive potential with respect to the neutral plasma will be discussed in detail, then the negative potential case will be considered. We conclude with a discussion of the implications for spacecraft charging in GEO.

SE Return in Cases of Positive Surface Potential

When an emitting surface of SE's has a positive potential with respect to the neutral plasma, we expect that the resulting electric field will slow the SE and

return some of them to the emitting surface. SE returning to their emitting surface will effectively decrease the SE yield that would have been measured from an unbiased surface. For example, surface potentials above +50 volts will retain all the SE's since they have < 50 eV of energy by definition. Any surface charged above +50 volts can therefore be assumed to have a SE yield of zero.

By considering the SE energy distribution, we can refine our estimate of the positive voltage that effectively reduces the SE yield to zero. The low energy peak in the SE energy distribution (see Figure 1) implies that this voltage cutoff for the SE yield could be significantly below +50 volts. The calculation of the effective SE yield as a function of positive surface potential is straightforward given some simplifying assumptions. Although SE's emitted at oblique angles will return to the emitting surface more readily than those emitted perpendicular to the surface, we will ignore the influence of the SE angular distribution and assume that all the SE are emitted perpendicular to the surface. If we also assume that the electric fields resulting from the surface potential are perpendicular to the emitting surface, then all SE with energy below $|eV_{bias}|$ will return to the surface. The effective SE yield δ_{eff} as a function of positive voltage bias V_{bias} is then given by integrating the SE energy distribution of Eq. 1 over the range of escaping SE energies (between eV_{bias} and 50 eV):

$$\delta_{eff}(V_{bias}) = \int_{eV_{bias}}^{50eV} \frac{d\delta(E)}{dE} \cdot dE \qquad (2)$$

The result is shown in Figure 3 for previous work on polycrystalline gold [*Nickles et al., 1999*].

The analysis above results in a significant reduction in our estimate of the positive potential necessary to cutoff the SE yield of a surface. Notice that $\delta_{eff}(V_{bias})$ decreases to <10% of the original SE yield for V_{bias}>20 volts. Inclusion of the SE emission angle in the calculation has been done elsewhere [*Nickles et al., 1999*] and results in a slightly lower estimate for the cutoff voltage. The estimated cutoff voltage can be extrapolated to other materials by considering the variability in SE energy distributions [*Seiler 1983*], which leads to an estimate of 10 to 35 V to reduce δ_{eff} to less than 10% of the unbiased SE yield.

SE Return in Cases of Negative Surface Potential

A negative surface potential acts to accelerate SE's away from the emitting surface. Concerns that an accelerating electric field might increase the SE yield are
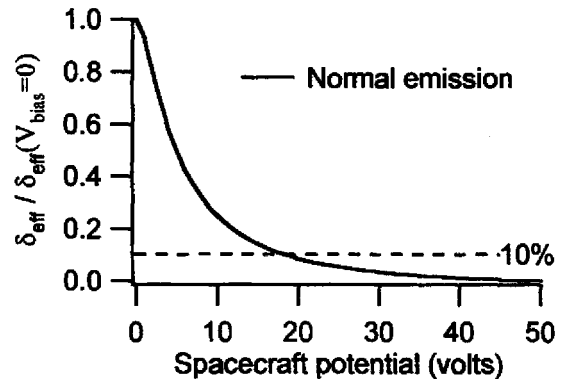

Figure 3. Effective SE yield of polycrystalline gold (as a percentage of the original SE yield) as a function of positive potential with the simplifying assumption that the SE emission is normal to the surface [Nickles et al., 1999].

unfounded. In most cases, the SE yield is not enhanced by the presence of external electric fields that are induced by spacecraft charging.

The concern in these cases is that a SE emitted at an oblique angle could be re-adsorbed by a nearby surface, especially in a confined space. To include this current in spacecraft charging models, the path of SE's would need to be modeled and would entail considerable effort. A simplifying assumption would be to take the SE's paths to follow the electric field lines. For large negative potentials, the SE's could be assumed to follow the electric field lines after negligible distances and would simplify analysis.

Work has been done to address this concern by modeling and experimentally measuring how the SE angular distribution is modified by negative surface potential [*Nickles et al., 1999*]. The result is an estimate that SE's will be confined to within ±30° of electric field lines after traversing a negative potential difference of 20-150 V.

The implications of these results for spacecraft charging depends on the specifics of the plasma environment, which we now consider for typical cases of positive and negative charging in geosynchronous orbit.

Conclusions for Spacecraft Charging in GEO

Spacecraft in geosynchronous orbit (GEO) typically encounter both positive and negative charging during their orbit. When spacecraft in GEO are exposed to sunlight, photoemission plays a large role in charging [*Whipple, 1981*]. Since the charge neutral sunlight removes electrons from the spacecraft, photoemission tends to charge surfaces positive. Recall that positive

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surface potentials will retain SE's and effectively reduce the SE yield. Notice that the opposing currents are a self-limiting mechanism for the charging level of the spacecraft. If observed positive charging levels in GEO were greater than our estimate for the cutoff of the SE yield (10-35 volts), then spacecraft charging models could safely assume the SE emission current is zero and simplify the charging analysis. Sunlit spacecraft in GEO typically reach positive potential of only a few volts [*Garrett, 1981*], so the SE yield is only reduced by ~35%. The SE energy distribution is crucial to the analysis of spacecraft charging at this level. In fact, the positive cutoff voltage may directly influence the ultimate level of positive charging for sunlit spacecraft in GEO.

The other case of negative charging occurs when spacecraft in GEO enter the earth's shadow. Eclipsed from the sun, the positive charging effects of photoemission are gone. To compound the propensity for negative charging, the spacecraft are also in the earth's magnetotail, which exposes the spacecraft to high energy electron fluxes during solar activity. Kilovolt negative charging levels are typical of GEO spacecraft in the earth's shadow [*Garrett, 1981*].

Since SE's have very low energies, the high levels of negative charging observed in GEO would seem to substantiate the assumption that SE's follow electric field lines as they leave the spacecraft. The important consideration is the length scale over which the negative potential is dropped. GEO has a very low plasma density in comparison to other earth orbits, which results in a very long length to the neutral plasma and a lower electric field strength, even though the spacecraft has a large negative potential. Assuming a field strength of 500 volts/m, the previously cited result implies that SE's that have traversed less than ~20 cm are not necessarily confined to within 30° of the electric field line. Calculation of SE return to adjacent surface confined within ~20 cm may require knowledge of SE energy and angular distributions.

Acknowledgments

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