

# Feasibility of Detecting Spacecraft Charging and Arcing by Remote Sensing

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More than 50 years after the dawn of the space age, most spacecraft still do not have sensors onboard capable of detecting whether they are at potentials likely to put them at risk of severe charging and the concomitant arcing, or, indeed, even capable of detecting when or if they undergo arcing. As a result, anomaly resolution has often been hit or miss, and false diagnoses are probably common. In this paper, a few remote sensing techniques that could be applied for remotely detecting spacecraft charging and/or arcing, and their feasibility, are examined: surface glows from high-energy electron impact, x-rays from bremsstrahlung, and radio and optical emission from arcs and after arcing.

## Nomenclature

$A$	=	projected area of sample, relative to observer, $\text{m}^2$
$A_{\text{Bus}}$	=	projected area of satellite bus, relative to observer, $\text{m}^2$
$A_{\text{SolarPanel}}$	=	projected area of solar panel, relative to observer, $\text{m}^2$
$A_{\text{Total}}$	=	total projected area of satellite (bus and solar panel) as seen relative to observer, $\text{m}^2$
$a$	=	sample effective albedo
$a_{\text{Bus}}$	=	average, diffuse bus albedo
$a_{\text{SolarPanel}}$	=	average, diffuse solar panel albedo
$B$	=	magnetic field strength, T
$e$	=	sample emissivity
$L_C$	=	spectral radiance expected from charging effects propagated to the observer location, $\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$
$L_{\text{Charging}}$	=	spectral radiance expected from charging effects, $\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$
$L_{\text{EarthShine}}$	=	spectral radiance due to Earthshine reflected from sample, $\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$
$L_{\text{SkyGlow}}$	=	radiance estimate resulting from expected sky background, both terrestrial and zodiacal, $\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2}$
$L_{\text{Sun}}$	=	spectral radiance due to sunlight reflected from sample, $\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$
$L_{\text{Total}}$	=	total spectral radiance expected, $\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$

$L_{\text{Thermal}}$	=	spectral radiance that results from thermal emittance of sample, $\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$
$R$	=	stand-off range between observer and satellite, m
$T$	=	sample temperature, K
$\sigma$	=	rms width of specular reflection from sample, deg; rms standard deviation of photon noise, counts
$\theta_{\text{SPA}}$	=	solar phase angle, deg

## I. Introduction

SPACE situational awareness (SSA) is the capability to determine what is happening and why on satellites in space. It is important for satellite operators to have good SSA so that they can respond to anomalies and plan for events (like meteor showers) when avoidance is necessary. Easily understood examples of SSA are when ground station operators plan for losing the signals from their satellites when they are too close to the sun in the sky (during eclipse seasons) or when space weather conditions are likely to produce spacecraft charging arcing anomalies on satellites. The Air Force must maintain SSA to determine whether satellite anomalies are due to operations in the natural environment or to hostile acts. In any case, SSA is of great importance. More than 50 years after the dawn of the space age, most spacecraft still do not have sensors onboard capable of detecting whether they are at potentials likely to put them at risk of severe charging and the concomitant arcing, or, indeed, even capable of detecting when or if they undergo arcing. As a result, anomaly resolution has often been hit or miss, and false diagnoses are probably common. Until spacecraft are routinely launched with charging and arcing monitors, the best that can be achieved is detection through remote sensing, from the ground or by satellites. In this paper, a few remote sensing techniques are examined that could be applied for detecting spacecraft charging and/or arcing.

But first, one must define a few terms. A satellite is said to be in eclipse when it passes into Earth's shadow. Satellites in geosynchronous Earth orbit (GEO, on the equator at about 36,000 km altitude) can only be in eclipse during two eclipse seasons every year, each lasting about 2 months at the spring and autumnal equinoxes, and for a maximum of about 1 hour each day during these seasons. GEO satellites are subject to spacecraft charging, due to fluxes of high-energy electrons onto and beneath their surfaces, usually coincident with geomagnetic storms. Geomagnetic storms are rapid changes in Earth's magnetic field due to impingement of plasmas from the sun on the magnetosphere. During these storms, entire satellites can charge tens of thousands of volts negative of their surrounding space plasma,

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and spacecraft surfaces can charge thousands of volts with respect to each other. The ensuing electric fields can cause local discharges (commonly called arcs), which through their high currents and radiated signals can cause disruptions in command and control signals, latchups of electronic components, short circuits, and even surface property changes. When behavior on a spacecraft suddenly deviates from nominal, the event is called an anomaly. Anomalies range in severity from simple bit flips in nonsensitive circuits to losses of entire command and/or communications circuits or permanent destruction of solar array strings or power supplies. Especially sensitive to spacecraft charging-related anomalies are the solar arrays, because they typically have grounded conductors exposed to the space plasma, surfaces already at high potentials with respect to each other, large areas of connected capacitance that can contribute to arc currents, surfaces always in sunlight, and surfaces always in shade.

It is even possible for small transient arcs on solar arrays to turn into sustained arcs powered by the solar arrays themselves. Most GEO satellite anomalies occur during eclipse seasons, during eclipse and for a few hours afterward. The so-called deep-dielectric discharges are due to very high-energy (penetrating) electrons of 2 MeV and higher. These electrons can build up for hours or days inside spacecraft electronics until the electric field builds up to discharge levels. Surface discharges are due to electrons of 5–50 keV that differentially charge spacecraft surfaces. Again, when local electric fields build up to discharge levels, an anomaly can occur. GEO charging conditions can last for an hour up to several hours, and then typically abate for a while.

To be able to remotely sense spacecraft charging and its discharges, one must be able to detect the high-energy electrons (or ions) as they hit the spacecraft surfaces, to detect the radiated emissions from the passage of the electrons through the material, or to detect the radiated emissions from the arcs themselves. In this paper several of these options are investigated, to see if remote sensing is feasible. It is believed that the detection of electromagnetic radiation gives the best chance of remote sensing because electromagnetic waves are insensitive to the electric and magnetic fields and charged particle environments in which spacecraft operate.

## II. Terminology Conventions and the Natural Radiation Background

To detect electromagnetic radiation from spacecraft, one must have a sensitivity great enough to see the radiation signal and also have a sufficient signal-to-noise ratio to discriminate it from the background. In what follows, the conventions in Fig. 1 and Eq. (1) will be adhered to. All except the material radiance are natural background noise. The material radiance is assumed here to be any glow produced over an area by a charging material.

$$L_{\text{Total}} = L_{\text{Charging}} + L_{\text{Sun}} + L_{\text{EarthShine}} + L_{\text{Thermal}} + L_{\text{SkyGlow}} \quad (1)$$

When observing a satellite in GEO with a ground-based sensor, the sources of spectral radiance are described mathematically in Eq. (1).

The terms in Eq. (1) are the reflected sunlight  $L_{\text{Sun}}$ , the reflected Earthshine incident on the satellite  $L_{\text{EarthShine}}$ , the thermal emittance  $L_{\text{Thermal}}$ , and the skyglow  $L_{\text{SkyGlow}}$ . To obtain an estimate of each of the contributing spectral radiance terms, several assumptions are made that are reasonable for a large GEO-synchronous communication satellite, such as one of the DirecTV satellites, observed from a ground-based sensor. The expected spectral radiance due to reflected sunlight  $L_{\text{Sun}}$  is calculated assuming that the observed satellite has an albedo described by the equation

$$a(\theta_{\text{SPA}}) = \left[ \exp\{-(\theta_{\text{SPA}}/2\sigma)^2\} + \left( a_{\text{SolarPanel}} \frac{A_{\text{SolarPanel}}}{A_{\text{Total}}} + a_{\text{Bus}} \frac{A_{\text{Bus}}}{A_{\text{Total}}} \right) \cos^2 \theta_{\text{SPA}} \right] \quad (2)$$

For a large communications satellite, the solar panel and bus sizes ( $A$ ) and albedos ( $a$ ) can be approximated as  $A_{\text{SolarPanel}} = 60 \text{ m}^2$ ,  $a_{\text{SolarPanel}} = 0.04$ ,  $A_{\text{Bus}} = 10 \text{ m}^2$ , and  $a_{\text{Bus}} = 0.6$ . The notional observed solar phase angle in this scenario is  $\theta_{\text{SPA}} = 60^\circ$ . For these conditions, the expected reflected sunlight from the satellite is  $L_{\text{Sun}} = 140 \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$  ( $3.5 \times 10^{16} \text{ photons} \cdot \text{s}^{-1} \cdot \text{cm}^{-2} \cdot \mu\text{m}^{-1}$ ) at an optical wavelength near  $0.5 \mu\text{m}$ . Using a similar set of assumptions, the spectral radiance due to Earthshine can be estimated as  $L_{\text{EarthShine}} = 4 \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$  ( $1 \times 10^{15} \text{ photons} \cdot \text{s}^{-1} \cdot \text{cm}^{-2} \cdot \mu\text{m}^{-1}$ ) at an optical wavelength near  $0.5 \mu\text{m}$ . The expected spectral radiance due to thermal emission of the notional, large communication satellite, assuming an emissivity even as unrealistically high as  $e = 1$ , gives an upper bound on the value of  $L_{\text{Thermal}} \approx 10^{-37} \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$  ( $2.5 \times 10^{-23} \text{ photons} \cdot \text{s}^{-1} \cdot \text{cm}^{-2} \cdot \mu\text{m}^{-1}$ ) at an optical wavelength near  $0.5 \mu\text{m}$ .

Assuming that the observation scenario is conducted on Earth, in good observational conditions, i.e., dark skies of 19th mag/arcsec<sup>-2</sup>, with a telescope that has a field of view (FOV) equivalent to one minute-of-arc, one should expect that the spectral radiant contribution of skyglow is small,  $L_{\text{SkyGlow}} \approx 10^{-16} \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$  ( $2.5 \times 10^{-2} \text{ photons} \cdot \text{s}^{-1} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$ ) in the optical waveband. Under the best observational conditions on Earth, 21st mag/arcsec<sup>-2</sup>, zodiacal background light becomes important. In a space-based observational scenario, one would not expect skyglow, but there would still be zodiacal background light. Zodiacal background light has been estimated to be in the order of 21st mag/arcsec<sup>-2</sup>; however, the background also depends strongly on which stars are in the observatory's FOV. For example, if one is observing a satellite near a bright star, there will obviously be a high background radiance due to the starlight.

The remaining term in Eq. (1),  $L_{\text{Charging}}$ , which is one focus of this paper and will be described in more detail in subsequent sections, is the spectral radiance due to electron bombardment of the satellite surfaces, primarily the solar panels. In the case of an electron bombardment glow, such as observed in prior laboratory experiments

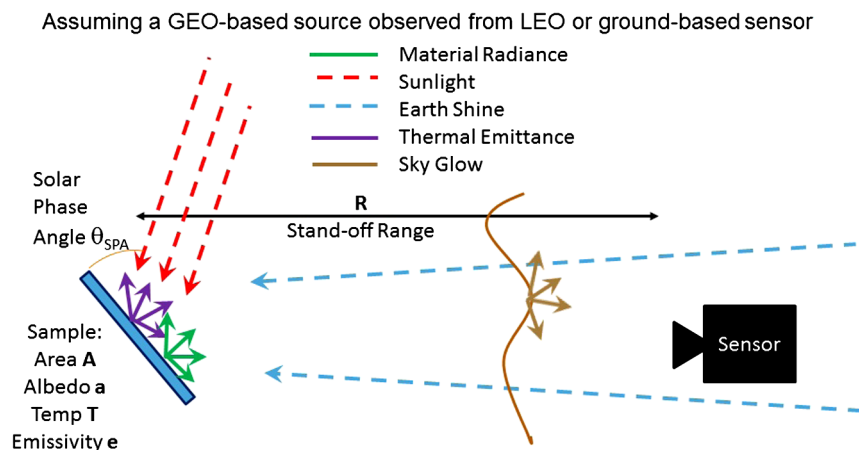


Fig. 1 Radiance seen by a sensor at standoff distance  $R$ .

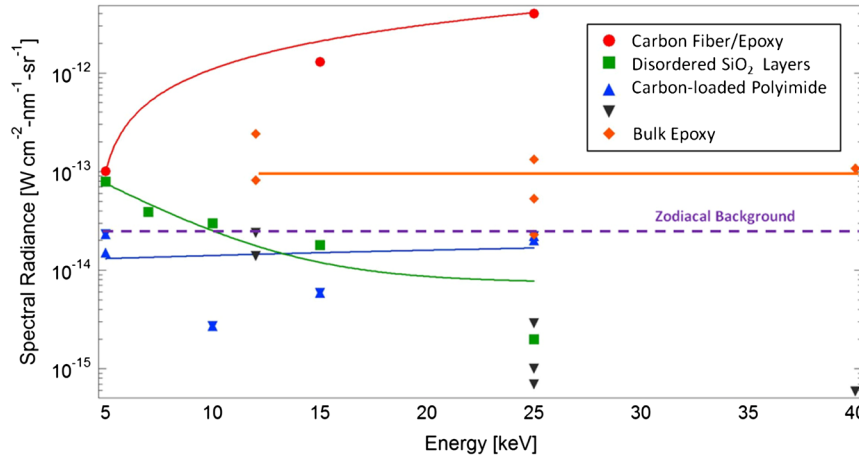


Fig. 2 Cathodoluminescence spectral radiance versus incident electron energy for four spacecraft materials, normalized to  $10 \text{ nA} \cdot \text{cm}^{-2}$  electron power density, with the approximate level of the zodiacal background shown for comparison.

[1], it is known that this term will be small compared with either the reflected sunlight or Earthshine terms,  $L_{\text{Sun}}$  or  $L_{\text{EarthShine}}$ .

In summary, when Eq. (1) is employed for a scenario in which a large GEO-synchronous communication satellite is observed from Earth, the total expected spectral radiance  $L_{\text{Total}}$  is dominated by  $L_{\text{Sun}}$  and  $L_{\text{EarthShine}}$ . In that scenario, the value of  $L_{\text{Total}}$  corresponds to a visual magnitude  $M_V \approx 14$  at a solar phase angle of  $60^\circ$ , which is consistent with observational data [2]. Of course, observational scenarios in which the observed satellite is eclipsed by Earth may be imagined, in which case both illumination of the satellite by the sun and Earth will be eliminated. Equation (1) is general enough to be used in that eclipse scenario, where  $L_{\text{SkyGlow}}$ ,  $L_{\text{Thermal}}$ , and  $L_{\text{Charging}}$  may be the dominant terms.

### III. Glows Due to Electron Impact

Dennison et al. [1,3] have shown that when keV energy electrons bombard dielectric surfaces under space-like conditions, they can emit a continuous glow. This cathodoluminescence spectral radiance can range from  $10^{-9}$  to  $10^{-5} \text{ W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$  for different polymeric, glassy, and multilayer and nanodielectric composite materials (see Fig. 2 and [1,4,5]). This phenomenon has been seen in the laboratory countless times (see [6,7]). The GEO environment often is characterized by high fluxes of keV electrons, and these electrons can produce kilovolts of charging on GEO satellites. Especially during geomagnetic storms, it is quite normal that GEO satellites undergo charging to several kilovolts in eclipse. This charging must be due to collection of keV electrons, which may thus be observed by the glows they produce. From Fig. 2, an estimate for the glow brightness is  $6.3 \times 10^{-6} \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$  for a carbon fiber-epoxy composite at a current flux at the surface of about  $10 \text{ nA} \cdot \text{cm}^{-2}$  and a beam energy of about 5 keV [1]. Similar materials are widely used in spacecraft design and are likely to be used for solar array structural supports for many satellites. The highest electron current fluxes seen in GEO are about  $0.4 \text{ nA} \cdot \text{cm}^{-2}$  at an effective thermal energy of about 20 keV. Taking the glow radiance to be proportional to the beam energy and current flux [4], one may correct the maximum expected spectral power density from  $L_{\text{Charging}}$  to be  $(6.3 \times 4/25) \times 10^{-6} \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$  or  $\sim 1 \times 10^{-6} \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$ . For comparison's sake, the estimate of the total power density deposited by collected electrons on a spacecraft is  $8 \times 10^{-5} \text{ W} \cdot \text{m}^{-2}$ .

Because the glow from an electron-bombarded surface is presumed to be very small, it would behoove us to observe it when the satellite is in the Earth's shadow (eclipse), so that the reflected sunlight and the Earthshine are both near zero. Although one cannot eliminate the thermal contribution from the surface, by observing at optical or near-infrared wavelengths, one can minimize it so that it becomes negligible. Finally, from ground-based observations, the skyglow cannot be eliminated, and  $L_{\text{Total}} = L_{\text{Charging}} + L_{\text{SkyGlow}}$ .

A complication is that as seen from Earth, the satellite charging brightness must compete with the skyglow. Assuming that the area of a solar array in GEO is  $60 \text{ m}^2$ , at Earth

$$L_C = \frac{L_{\text{Charging}} \times A_{\text{array}}}{4\pi R^2}, \quad \text{or} \quad L_C \approx 6 \times 10^{-23} \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1},$$

where  $R = 36 \times 10^3 \text{ km}$  (9)

compared with the skyglow:  $L_{\text{SkyGlow}} = 3.4 \times 10^{-16} \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$  ( $8.5 \times 10^{-2}$  photons  $\cdot \text{s}^{-1} \cdot \text{cm}^{-2} \cdot \mu\text{m}^{-1}$ ) for an FOV of 1 arcmin. The signal-to-noise ratio would be only  $\sim 2 \times 10^{-7}$ . If one reduces the FOV (or the pixel size) to 1 arcsec,  $L_{\text{SkyGlow}} = 9.4 \times 10^{-20} \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$ , and the signal-to-noise ratio still is only  $7 \times 10^{-4}$ . Thus, skyglow severely limits detectability of the electron-produced glow from Earth. Even phosphorescent materials, if they were on GEO spacecraft, would not be very effective at making the glow much more visible from Earth. For example, if each bombarding electron were to yield all its energy in a  $1 \mu\text{m}$  bandwidth, then  $L_C$  at Earth would still be only  $4.9 \times 10^{-21} \text{ W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$ , and the signal-to-noise ratio against skyglow is  $\sim 0.06$ .

If one can make observations from space, and where the zodiacal background is also negligible, the skyglow can be eliminated, so that

$$L_{\text{Total}} = L_{\text{Charging}} \quad (4)$$

and the signal-to-noise ratio is as good as possible. Unfortunately, the zodiacal light background for GEO satellite observation is strongest near eclipse seasons, when the satellite is near the plane of the ecliptic.

The difficulty in seeing the low-level signals of the glow can perhaps be appreciated by comparing the corrected  $L_{\text{Charging}}$  value with the  $L_{\text{ReflectedSun}}$  value discussed in Sec. II.  $L_{\text{ReflectedSun}}$  is about  $7.4 \times 10^5$  times that of  $L_{\text{Charging}}$ . That is about 15 magnitudes brighter (5 magnitudes are a factor of 100 in brightness), and so the maximum brightness of the array glow as seen from Earth is about 29th magnitude. If every bombarding electron could be seen by emitted light, one gains only a factor of about 100, and the glow might be as bright as 24th magnitude. The faintest magnitude limit of the Hubble telescope, for example, is about mag 31, and thus it might just be possible to observe the glow with a long integration time. However, integration times are limited by the length of satellite eclipse (about 70 min at maximum). Co-orbiting telescopes in GEO might be able to more easily observe the emitted radiation.

Glows from ions, if they exist, will be much fainter than those from electrons, because typically ion fluxes onto spacecraft surfaces in GEO are lower by 1.5 orders of magnitude than electron fluxes.

### IV. X-Rays from Impinging Electrons

High-energy electrons, when impinging on materials, produce braking radiation, or bremsstrahlung, as they slow down. This

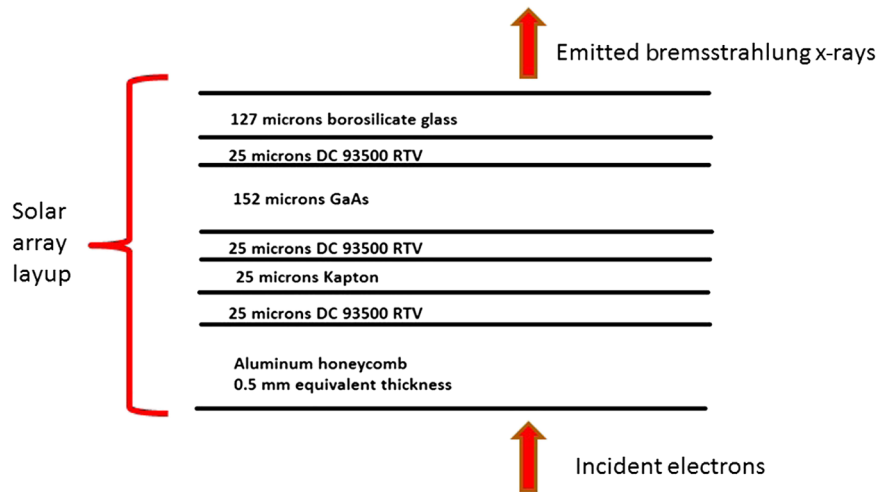


Fig. 3 Assumed solar array layout for purposes of electron and x-ray transport.

radiation can be seen by remote sensing instruments. Typically, bremsstrahlung is strongly peaked in the direction toward which the electron was traveling, and so to be observable from GEO satellites, this radiation must make it through the thickness of the solar array panel. This places a lower limit on the energy of the radiation, and thus of the electrons responsible. However, electrons of very high energy will pass completely through such a panel, and give up little energy to bremsstrahlung. This places an upper limit on the electrons responsible for any observed radiation. For the typical solar array layout shown in Fig. 3, this implies, from the National Institute of Standards (NIST) tables\*\* that most of the observable x-ray radiation will come from electrons in the energy range 20–400 keV. The x-rays produced will be completely absorbed by Earth's atmosphere, and so observation must be done by a satellite in low Earth orbit (LEO) or GEO.

Take as a worst-case GEO electron spectrum that of September 22, 1982, as reported by Roeder [8]. In the 40 keV bin, Roeder reports a differential electron flux of  $1.0 \times 10^7$  electrons  $\cdot$  cm $^{-2}$   $\cdot$  sr $^{-1}$   $\cdot$  keV $^{-1}$   $\cdot$  s $^{-1}$ . This is  $1.0 \times 10^{11}$  electrons  $\cdot$  m $^{-2}$   $\cdot$  sr $^{-1}$   $\cdot$  keV $^{-1}$   $\cdot$  s $^{-1}$ , or, taking  $2\pi$  steradians as the normalizing factor, one has  $6.28 \times 10^{11}$  electrons  $\cdot$  m $^{-2}$   $\cdot$  keV $^{-1}$   $\cdot$  s $^{-1}$ . Assume a 100 keV bandwidth, and that every electron produces one x-ray. At the source this gives  $6.28 \times 10^{13}$  photons  $\cdot$  m $^{-2}$   $\cdot$  s $^{-1}$  over a hemisphere. With a 60 m $^2$  array, one has at the source about  $3.7 \times 10^{15}$  photons  $\cdot$  s $^{-1}$ . At a distance of 35,000 km (distance from GEO to LEO), this becomes 0.6 photons  $\cdot$  m $^{-2}$   $\cdot$  s $^{-1}$  at a LEO sensor. Finally, assuming that the sensor has a collecting area of 1 m $^2$ , one can get  $\sim 30$  x-ray photons per minute. For the entire maximum time the array is in eclipse, one might then see about 2100 photons. This seems like it would be a detectable flux in the absence of a strong x-ray background. However, the assumption that every incident electron produces a detectable x-ray photon is extremely optimistic.

To put some realism in the brightness estimate, consider electrons entering the layout in Fig. 3 from below (because in eclipse, the front of the array is Earthward pointing), and use a code such as MULASSIS†† to calculate escaping fluxes. The electron spectrum used here was a single-Maxwellian fit to the September 22, 1982, spectrum. Figure 4 shows the assumed electron flux spectrum, the photons predicted to be escaping from the layout, and the resultant emitted electron spectrum. Performing a simple integration from 40 to 180 keV electrons gives a total of about  $8 \times 10^8$  photons/m $^2$ -sr-sec, and with the  $2\pi$  normalizing factor and 60 m $^2$  array as above, one has from the source of  $5.6 \times 10^{11}$  photons  $\cdot$  s $^{-1}$ . This is a factor of about  $3 \times 10^4$  down from the estimate above that assumes every electron produces one

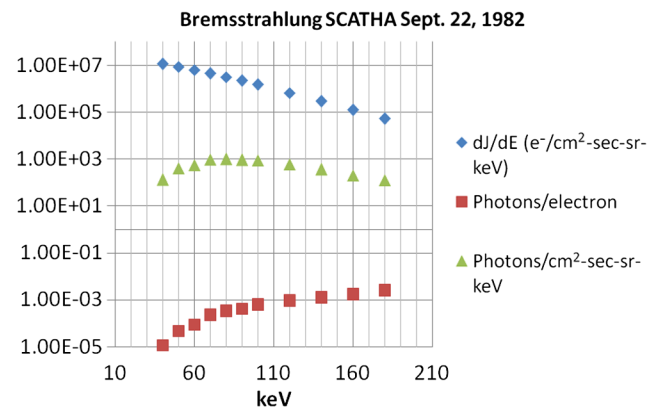


Fig. 4 Bremsstrahlung x-rays from an extreme charging electron spectrum [8].

photon. Now one will have in the sensor at LEO about  $2.4 \times 10^{-3}$  x-ray photons per minute, and during an entire eclipse about 0.18 x-ray photons, not nearly enough to make a detection. If one could improve this number by at least 2.5 orders of magnitude (by reducing the observing distance to 2000 km or less, for instance), one might be able to detect these emissions.

Next, consider whether the cosmic x-ray background would limit detection of the x-ray signal. In Fig. 5 is the diffuse x-ray spectrum seen in space.†† The strongest x-ray emission from the array will be in the energy range 40–50 keV (from the MULASSIS calculations). From Fig. 5, one can see that at 45 keV, the differential photon flux is about 0.02 photons  $\cdot$  cm $^{-2}$   $\cdot$  s $^{-1}$   $\cdot$  keV $^{-1}$   $\cdot$  sr $^{-1}$ . This is 200 photons  $\cdot$  m $^{-2}$   $\cdot$  s $^{-1}$   $\cdot$  keV $^{-1}$   $\cdot$  sr $^{-1}$ . Again, assuming a 50 keV bandwidth, one has from the background  $10^4$  photons  $\cdot$  m $^{-2}$   $\cdot$  s $^{-1}$   $\cdot$  sr $^{-1}$ . Now one must make an assumption of the beamwidth of the x-ray telescope. Assume 1 arcmin $^2$ . This is  $8.46 \times 10^{-8}$  sr, and so in the telescope, one has  $8.5 \times 10^{-4}$  photons  $\cdot$  s $^{-1}$   $\cdot$  m $^{-2}$ , or in an entire eclipse period, about 3 photons. This gives a signal-to-noise ratio in the LEO sensor above the diffuse background of about 0.06. Therefore, x-ray detection at LEO of bremsstrahlung on a solar array in GEO seems impossible. However, a co-orbiting GEO satellite might detect bremsstrahlung from a GEO satellite, or a co-orbiting LEO satellite from a LEO satellite. Thus, one would require that both the satellite and detector be in either LEO or GEO.

As in the previous calculations, one will want to do this detection when the sensor is in eclipse, so that there is no noise background of solar x-rays scattered in the atmosphere, and when the satellite being

\*\*Data available online at <http://physics.nist.gov/> [retrieved 25 August 2014], ESTAR and X-ray Attenuation tables.

††Data available online at <http://www.spenvi.oma.be/help/models/mulassis.html> [retrieved 25 August 2014].

††Data available online at [http://heasarc.gsfc.nasa.gov/docs/objects/background/diffuse\\_spectrum.html](http://heasarc.gsfc.nasa.gov/docs/objects/background/diffuse_spectrum.html) [retrieved 25 August 2014].

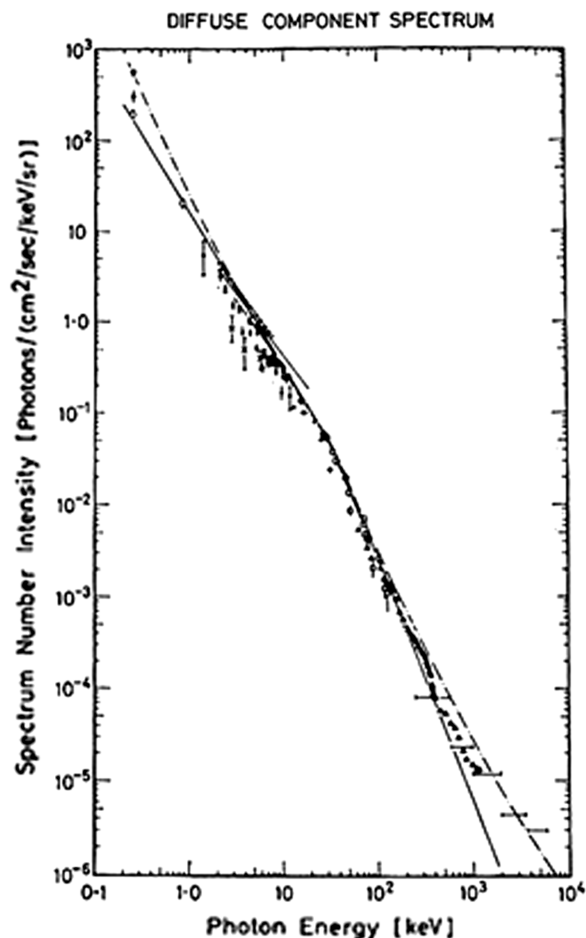


Fig. 5 The diffuse x-ray background spectrum.

observed is in eclipse, so that there are no solar x-rays reflected by the satellite.

## V. Electromagnetic Emissions from Arcing

### A. Radio Emission from Arcs

Arcs occur on GEO spacecraft because of the high electric fields produced by spacecraft charging. Leung [9] has measured radio emission from arcs on solar array samples. Figure 6 shows his results. A 2000 pF capacitor was added to the bias circuit to enable his small array results to simulate a larger array. Of great interest is the very steep spectrum. The electric field strength falls off by about 75 dB from 1 to 1000 MHz. The reason for this is obvious from Fig. 7, where the rise time of the voltage is seen to be on the order of 0.02  $\mu$ s and the fall time is about 0.3  $\mu$ s. The latter number corresponds roughly to a 3 MHz frequency, and the former a 50 MHz frequency. Frequency

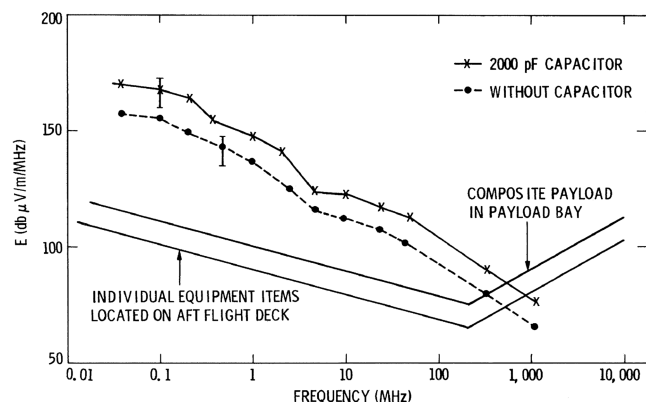


Fig. 6 Radio frequency emission from arcs on solar arrays [9].

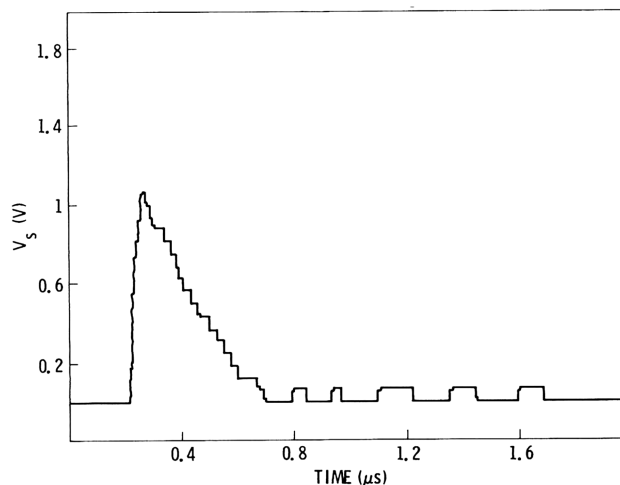


Fig. 7 Voltage waveform for one of Leung's arcs [9].

content at  $>50$  MHz must be due to unresolved structure in the voltage profile.

Assuming that all of the energy stored in the 2000 pF capacitor at 1000 V (0.001 J) is dissipated in about 0.5  $\mu$ s, one has an average power of about 2000 W. Converting dB  $\cdot \mu$ V  $\cdot$  m $^{-1}$  in Fig. 6 to power, at 1 MHz the peak power (for a fraction of a microsecond) is about  $3 \times 10^4$  W  $\cdot$  MHz $^{-1}$ . This gives about  $1.5 \times 10^4$  W  $\cdot$  MHz $^{-1}$  average power, and thus a "bandwidth" of about  $2000/1.5 \times 10^4 = 0.13$  MHz. No wonder the spectrum falls off so fast! Leung estimates that 80–100% of the stored charge is released in a discharge. The discharged capacitance of a large solar array on a GEO satellite is expected to be 100 times (200 nF) the 2000 pF used by Leung, and so one can expect that the peak power of a large array arc at 1 MHz could be  $3 \times 10^6$  W  $\cdot$  MHz $^{-1}$ . At a GEO satellite distance, this corresponds to a differential flux at 1 MHz of  $1.8 \times 10^{-12}$  W  $\cdot$  m $^{-2}$   $\cdot$  MHz $^{-1}$  =  $1.8 \times 10^{-18}$  W  $\cdot$  m $^{-2}$   $\cdot$  Hz $^{-1}$  =  $1.8 \times 10^4$  solar flux units (sfu) =  $1.8 \times 10^8$  Jy, even greater than the signals from the disturbed sun!<sup>§§</sup> But at 10 MHz, the differential flux is already down to  $1.8 \times 10^4$  Jy at Earth. This should, however, be detectable with an uncooled receiver on a 3 m radio telescope or a cooled receiver on a 1 m telescope.

These short bursts of radio emission from arcs must surely be routinely picked up by satellite ground stations, clipped and/or filtered out, and also must be exceedingly strong at the satellite on which they occur. For instance, on PASP Plus and other scientific satellites, radio waves produced by arcs were used to determine the arc location [10]. At 4 m distance (something like an average distance between a solar array arc and the spacecraft antenna), the peak differential flux would be  $\sim 150$  W  $\cdot$  m $^{-2}$   $\cdot$  MHz $^{-1}$  at 1 MHz or  $1.5 \times 10^{-13}$  W  $\cdot$  m $^{-2}$   $\cdot$  MHz $^{-1}$  at 1 GHz. Thus, whether in eclipse or not, satellite arcs may be easily detectable by a monitor onboard the satellite or even by a moderate-sized radio dish on Earth.

### B. Optical Emission from Arcs

The subject now turns to arcs as seen in visible wavelengths. In laboratory experiments, arcs are easily seen by video camera [1,3,5,7,9]. Usually, to allow them to be seen by the unaided eye, a capacitor (33 nF or more) is added to the bias circuit of a small array. With a large array in orbit, this should be unnecessary. Taking the capacitance to space of a spacecraft to be 500 pF, Okumura et al. [11] have reported ground-based results using a 5 m $^2$  solar panel that produced a current of 3.6 A with a rise time of 2  $\mu$ s. Assuming the same fall time, one gets a total energy involved in the arc of 0.012 J. Extrapolating to a 60 m $^2$  array on orbit, this is 0.144 J. Fluorescent bulbs (luminous plasmas) are about 10% efficient at converting electricity to light. Taking 7% of 0.144 J gives 0.01 J as the total energy dissipated as light. If this is emitted in 1  $\mu$ s, and with a

<sup>§§</sup>Data available online at <http://astro.u-strasbg.fr/~koppen/10GHz/basics.html> [retrieved 25 August 2014].



bandwidth of 10,000 ( $1\ \mu\text{m}$ ), there is a differential power emitted of  $104\ \text{W} \cdot \mu\text{m}^{-1}$ . Assuming that the light is emitted uniformly over  $2\pi$  sr (1/2 of the full sky) at the GEO distance, the spectral radiance on Earth becomes  $1.3 \times 10^{-12}\ \text{W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$ . Put in astronomical terms, the momentary magnitude of the arc should be about +10.9. Because the energy of a photon at  $0.5\ \mu\text{m}$  wavelength is  $3.98 \times 10^{-19}\ \text{J}$ , the momentary photon flux received per arc by a ground-based telescope is  $3.3 \times 10^7\ \text{photons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ . Again, assuming that the arc light is emitted mainly in the first microsecond, then one should see about 33 photons  $\cdot \text{m}^{-2}$  from each arc. Assuming only quantum noise (with Poisson statistics), this should be about  $5.7\sigma$  for a  $1\ \text{m}^2$  telescope.

If one defines dark skies as 19th mag  $\cdot \text{arcsec}^{-2}$ , will the normal sky background swamp the signal? Again, assuming a 1 arcmin FOV, this becomes 11 mag  $\cdot \text{arcmin}^{-2}$ , or about the brightness of the arc signal. Thus, one must confine his consideration to an FOV of much less than 1 arcmin, to dilute the background, whereas the arc signal will be undiluted. This should be easily done with a pixelated detector, if each pixel corresponds to only a few arc seconds. For example, a pixel area of  $4\ \text{arcsec}^2$  would give about 2 orders of magnitude less sky background per pixel, reducing the noise per pixel to a level far below that of the arc signal with a  $1\ \mu\text{s}$  time resolution. If one integrates for longer times, the sky background could still be a problem. What about skyglow? Assuming, as above, a 1 arcmin FOV, the result before was that the skyglow was of spectral intensity  $3.4 \times 10^{-16}\ \text{W} \cdot \text{m}^{-2} \cdot \mu\text{m}^{-1}$ . Integrating over  $1\ \mu\text{s}$ , there are only  $8.5 \times 10^{-4}\ \text{photons} \cdot \mu\text{s}^{-1}$  for a  $1\ \text{m}^2$  telescope. One would have to integrate for about 7 ms for the skyglow to contribute  $1\sigma$  to the photon count from an arc. Thus, compared with the ordinary sky background, skyglow is no problem. And, at 21st mag  $\cdot \text{arcsec}^{-2}$ , the zodiacal light is even less of a concern.

Dark current in the sensor needs to be examined. The current produced by the photoelectric effect of 33 photons in  $1\ \mu\text{s}$  is  $5.3 \times 10^{-12}\ \text{A}$ . With a gain of  $10^6$ , one would need a dark current less than about  $10^{-6}\ \text{A}$ . If the array arcs while the satellite is in eclipse, it should be detectable with a moderate-sized ( $1\ \text{m}^2$ ) telescope with a focal plane detector of  $4\ \text{arcsec}^2$  pixel area and  $10\ \mu\text{s}$  time resolution on a night of good seeing ( $<2\ \text{arcsec}$ ). A  $1\ \mu\text{s}$  time resolution might enable partial resolution of the optical pulse shape. Alternatively, a photomultiplier could be used with a  $4\ \text{arcsec}^2$  aperture, but in this case, to look for arcs over a 1-hour period would require arc-second tracking accuracy on an essentially invisible source.

Up to now, only GEO satellites have been considered, but arcs can occur on any satellite if sufficiently differentially charged. Suppose that one were to look for arcs on a GPS satellite, for instance. Aside from the complication that now tracking is very important, GPS satellites (with a 12-hour period) are nearer and the arcs should be brighter. From Kepler's third law, the radius of the orbit of a GPS satellite should be only 0.63 that of a GEO satellite, and thus the (midnight) distance to one overhead would be only about  $19.7 \times 10^3\ \text{km}$ . The arcs, all other things being equal, should then be  $(35/19.7)^2$  brighter, or about 3 times brighter, giving roughly 100 photons per arc. This is some  $10\sigma$  above the quantum noise. All of the other considerations would still apply.

Just as important as how to observe is when to observe. GEO satellites charge more (and arc more frequently) when the high-energy electron flux and electron temperature are higher than normal. Satellite anomalies occur most frequently when the Kp index is high ( $>6$ ) or when it has averaged higher than 4 for a 24-hour period. These time periods usually are preceded by a few days by an Earthward-pointing coronal mass ejection on the sun (CME) or coronal hole ejection on the sun. Thus, the best times to observe satellite arcing are 2–4 days after a CME or coronal hole ejection. In addition, GEO satellites pass through the Earth's shadow only during the so-called eclipse periods near the dates of the vernal and autumnal equinoxes, and GEO satellite arcs are visible only during an eclipse season. GPS satellites do not adhere to this visibility rule. Times of eclipse passage for them must be found from orbital data.

Finally, the arc emissions, by their very transient nature, might be mistaken for local noise or cosmic ray flashes in optical telescopes or for pulsar pulses in radio telescopes. However, if optical bursts are

coincident with radio bursts, arcs could be easily discriminated from natural radio emissions or cosmic ray events. It is suggested here that a commercial satellite ground antenna be used in conjunction with a moderate-sized optical telescope and pointed at GEO satellites one after another as they enter and exit eclipse. With a small optical FOV (1 arcmin or less), a transient pulse monitor, and a sensitive and rapid time response detector, arc pulses should be easily detectable. The radio receiver should have a broad bandwidth and a high-pass filter on the detected output to detect signals coincident in time with those from the optical telescope. Then, coincidences with fluxes above a certain level could be positively identified as arc signatures.

And, depending on the filtering scheme used by GEO satellites, it may be possible to detect arcs on satellite solar arrays by looking for very-short, very-high-amplitude radio pulses in the satellite antennas themselves.

### C. Optical Emission from Arc-Afterglows

There are also light emissions from solar arrays shortly after an arc occurs. Shortly after the initial arc emissions, solar array surfaces glow continuously for two reasons: First, while the arc is progressing, the coverglass surface is positively charged, and glows from electron excitation at its surface. In effect, it undergoes snapover. Ferguson et al. [6] have studied the light emitted by snapped-over surfaces. If the arc does not completely discharge the surface, the glow may continue until ambient electrons collected completely neutralize it [11]. Second, some of the cells in the array circuit are back-biased by the arc, and act as light-emitting diodes [12]. Both of these types of emissions are broadband and may last for hundreds of microseconds.

It is difficult to estimate how bright these arc-caused glows are, but from the figures in [12] one can say that the back-bias glow may be comparable to the illumination in a very poorly lit room, which can be estimated<sup>¶</sup> as  $10\ \text{lumens} \cdot \text{m}^{-2}$ . For green light,<sup>\*\*\*</sup>  $1\ \text{lux}$  is  $1.464\ \text{mW} \cdot \text{m}^{-2}$ . Thus, assuming that one quarter of our array is back-biased, a total power of about 0.016 W, a bandwidth of  $1\ \mu\text{m}$  in wavelength, and a GEO satellite distance, the intensity at Earth is  $1 \times 10^{-18}\ \text{W} \cdot \text{m}^{-2}$ , some 360 times ( $\sim 7$  magnitudes) brighter than the glow produced by electron bombardment. This very rough number may suffice to show that these glows would be possible to detect from large ground-based or LEO telescopes during GEO eclipse. Again, however, telescopes co-orbiting in GEO could more easily see this emission.

Similar long-duration, postarc emissions related to discharges have been observed for several catholuminescent spacecraft materials under electron bombardment in laboratory space simulation experiments [1,5]. These typically have peak spectral radiances of  $10^{-3}$  to  $10^{-7}\ \text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1} \cdot \mu\text{m}^{-1}$  for keV electron bombardment at  $10\ \mu\text{W} \cdot \text{cm}^{-2}$  (representative of severe GEO fluxes), and exhibit  $10^1$ – $10^2\ \text{s}$  decay times [1]. The upper range of these observed emission intensities is of the same order as those estimated above for continuous solar array surface glows.

## VI. Conclusions

It has been shown that it may be feasible to detect, from low Earth orbit (LEO) and in some cases Earth's surface, the x-ray, optical, and radio emissions from geosynchronous Earth orbit (GEO) satellites as they undergo spacecraft charging and arcing. The best possibility for detection is from the microsecond bursts of light and radio waves from arcing, especially when the arcs occur on large solar arrays. The arc-produced radio bursts may also be easily seen by antennas on the arcing GEO satellites. The arcs should be bright enough to be seen (even on a GEO satellite bathed in sunlight) with a moderate-sized telescope from Earth or from LEO. From Earth, optical and radio coincidence techniques may be most useful. Solar array back-bias glows may be observed from the ground or from LEO for a few hundred microseconds after an arc. Second, the glows produced

<sup>¶</sup>Data available online at [http://www.engineeringtoolbox.com/light-level-rooms-d\\_708.html](http://www.engineeringtoolbox.com/light-level-rooms-d_708.html) [retrieved 25 August 2014].

<sup>\*\*\*</sup>Data available online at <http://en.wikipedia.org/wiki/Lux> [retrieved 25 August 2014].

when charging electrons bombard dielectrics in GEO seem to be almost too weak to be detected from Earth or LEO, although co-orbiting GEO satellites might be more easily able to detect the emissions. Finally, the bremsstrahlung x-rays produced by charging electrons are too weak to be detected by LEO satellites and so would also require co-orbiting satellites for detection. It may be of immediate interest to attempt arc detection from ground-based optical and/or radio telescopes.

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