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On the Feasibility of Detecting Spacecraft Charging and Arcing by Remote Sensing

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It is a sad fact that 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 we examine a few remote sensing techniques that could be applied for detecting spacecraft charging and/or arcing.The first technique considered depends on the fact that when bombarded by high energy electrons, many types of dielectrics emit a glow that could be observed remotely, and would change with the degree of spacecraft charging. Only kilovolt electron strikes are effective at producing the glow. Thus, under geomagnetically calm conditions, if the glow were detected, high energy electron fluxes capable of spacecraft surface charging to kilovolt levels would be indicated. If the space plasma were disturbed, and the spacecraft were thus being charged negatively by a multitude of multi-kilovolt electrons, the ongoing charging would be seen as an enhanced surface glow. Although easily seen in the laboratory, this glow is likely to be too weak to be detected in space except for a satellite in eclipse. However, GEO satellites charge more in eclipse anyway. We will estimate whether the glow can be detected from both Earth and space.

The second technique depends on the fact that when electrons above about 20 keV strike a surface, x-rays are produced (through bremsstrahlung). If immersed in a very high-temperature plasma (like that of the famous Galaxy 15 event or the ATS-6 record charging event) a spacecraft may thus be seen by the x-rays that are produced. It is generally conceded that in eclipse a spacecraft will charge negatively (in volts) up to the electron temperature of the surrounding plasma (in eV). Again, detection in eclipse is probably necessary, since solar x-rays reflected by spacecraft surfaces might make daytime detection impossible. This method would likely only indicate when the most severe charging conditions were ongoing, and would of necessity require detection by an orbiting satellite.

Finally, when spacecraft arc, the arcs produce electromagnetic radiation. On PASP Plus and other scientific satellites, radio waves produced by arcs were used to determine the arc location, for instance. Arcs in laboratory conditions have been detected solely by radio emission, and oftentimes the visible light emitted is used to determine arc location and timing. While the radio noise produced is severe enough close by to produce radio interference in sensitive spacecraft electronics, it is likely to drop off rapidly, and most probably could only be detected by satellites orbiting nearby. However, the light produced may be substantial, and might be detected by a suitably filtered telescope even on Earth. Also, shortly after an arc, solar array surfaces glow for two reasons – firstly, while the arc is progressing, the coverglass surface is positively charged, and glows from electron excitation at its surface. If the arc does not completely discharge the surface, the glow may continue until ambient electrons collected completely neutralize it. Secondly, some of the cells in the array circuit are back-biased by the arc, and act as light emitting diodes. Both of these

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emissions are broadband and may last for hundreds of microseconds. Possibilities for arc detection from Earth-bound optical and radio telescopes will be discussed.

Nomenclature

a = sample effective albedo
A = projected area of sample, relative to observer
a_{Bus} = average, diffuse bus albedo
$a_{SolarPanel}$ = average, diffuse solar panel albedo
A_{Bus} = projected area of satellite bus, relative to observer
$A_{SolarPanel}$ = projected area of solar panel, relative to observer
A_{Total} = total projected area of satellite—bus and solar panel—as seen relative to observer
B = magnetic field strength (Teslas)
e = sample emissivity
L_C = spectral radiance expected from charging effects propagated to the observer location
$L_{Charging}$ = spectral radiance expected from charging effects
$L_{EarthShine}$ = spectral radiance due to Earthshine reflected from of sample
$L_{SkyGlow}$ = radiance estimate resulting from expected sky background, both terrestrial and zodiacal
L_{Sun} = spectral radiance due to sunlight reflected from of sample
L_{Total} = total spectral radiance expected
$L_{Thermal}$ = spectral radiance that results from thermal emittance of sample
R = stand-off range between observer and satellite
σ = parameter that specifies width of notional specular reflection from a reflective sample
θ_{SPA} = solar phase angle
T = sample temperature (Kelvins)

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. It is a sad fact that 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 we examine a few remote sensing techniques that could be applied for detecting spacecraft charging and/or arcing.

But first, we must define a few terms. A satellite is said to be in eclipse when it passes into Earth's shadow. Satellites in GEO (geosynchronous Earth orbit, on the equator at about 36000 kilometers altitude) can only be in eclipse during two eclipse seasons every year, each lasting about two 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, 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, since they typically have:

1. Grounded conductors exposed to the space plasma,
2. Surfaces already at high potentials with respect to each other,
3. Large areas of connected capacitance that can contribute to arc currents,
4. 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. 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 either 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 we will investigate several of these options, to see if remote sensing is feasible. We believe 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

In order to detect electromagnetic radiation from spacecraft, we 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, we will adhere to the conventions in Fig. 1 and Equation 1.

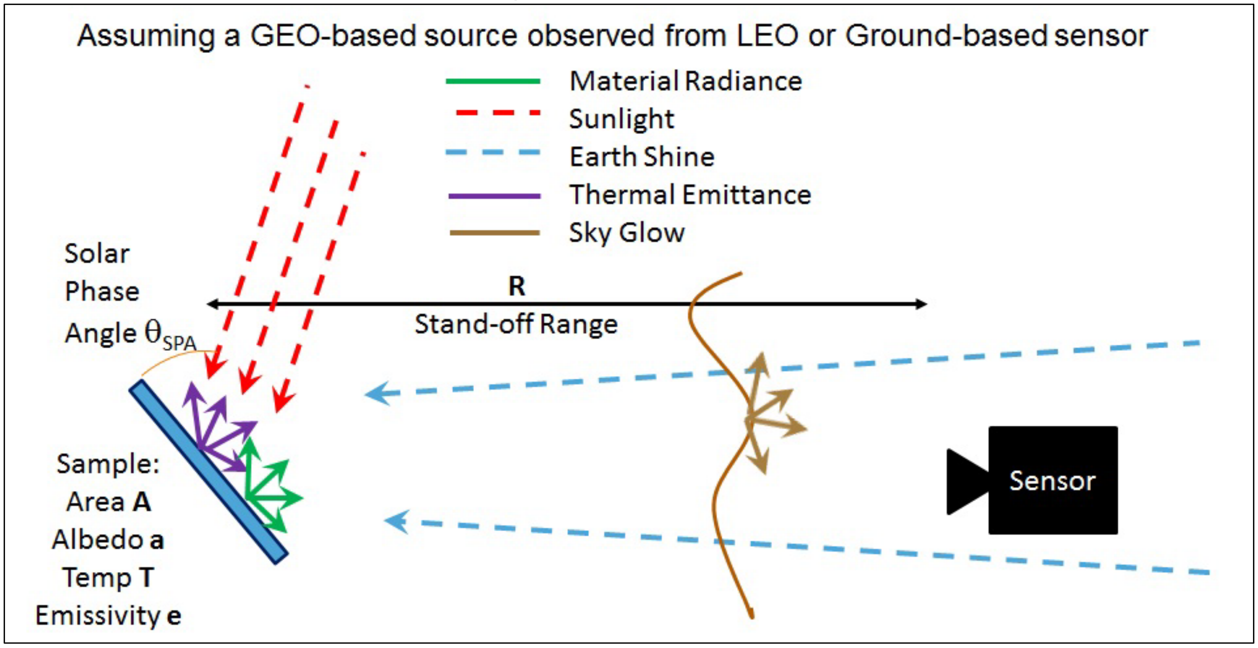

Figure 1. Radiance seen by a sensor at standoff distance R. All except the material radiance are natural background noise. The material radiance is assumed here to be any glow produced over an area by a charging material.

$$L_{Total} = L_{Charging} + L_{Sun} + L_{Earthshine} + L_{Thermal} + L_{Sky\ Glow} \tag{1}$$

When observing a satellite in GEO from a ground-based sensor, the sources of radiance are described mathematically in Equation 1. The terms in Equation 1 are the reflected sunlight, L_{Sun}; the reflected Earthshine incident on the satellite, $L_{EarthShine}$; the thermal emittance, $L_{Thermal}$; and the sky glow $L_{SkyGlow}$. In order to obtain an estimate of each of the contributing radiance terms we make several assumptions which are reasonable for a large GEO synchronous communication satellite, such as one of the DirecTV satellites, observed from a ground-based sensor. The expected radiance due to reflected sunlight, L_{Sun}, is calculated assuming that the observed satellite has an albedo described by the equation:

$$a(\theta_{SPA})=\left[1e^{-\left((\theta_{SPA})/2\sigma^2\right)^2}+\left(a_{SolarPanel}\frac{A_{SolarPanel}}{A_{Total}}+a_{Bus}\frac{A_{Bus}}{A_{Total}}\right)\cos^2\theta_{SPA}\right]. \qquad (2)$$

For a large communications satellite the solar panel and bus sizes (A) and albedos (a) can be approximated as $A_{SolarPanel}$ = 60m^2, $a_{SolarPanel}$ = 0.04, A_{Bus}=10m^2, and a_{Bus}= 0.6. The notional observed solar phase angle in our scenario is θ_{SPA}= 60º. For these conditions, the expected reflected sunlight from the satellite is L_{Sun} = 140W/m^{2}μm (3.5x10^{16}photons/s-cm^2-μm) at an optical wavelength near 0.5 μm. Using a similar set of assumptions, the radiance due to Earthshine can be estimated as $L_{EarthShine}$= 4W/m^{2}μm (1x10^{15}photons/s-cm^2-μm) at an optical wavelength near 0.5 μm. The expected 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 $L_{Thermal}$ ~10^{-37}W/m^{2}μm (2.5x10^{-23}photons/s-cm^2-μm) at an optical wavelength near 0.5 μm.

Assuming that the observation scenario is conducted on Earth, in good observational conditions, i.e. dark skies of 19th mag/arcsec^2, with a telescope that has a field of view equivalent to one minute-of-arc, we should expect that the radiant contribution of sky glow is small, $L_{SkyGlow}$~10^{-16}W/m^{2}μm (2.5x10^{-2}photons/s-m^2-μm) in the optical waveband. Under the best observational conditions on Earth, 21st mag/arcsec^2, zodiacal background light becomes important. In a space-based observational scenario, one would not expect sky glow, but there would still be zodiacal background light. Zodiacal background light has been estimated to be on the order of 21st mag/arcsec^2; however, the background also depends strongly on what stars are in the observatory's field of view. 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 Equation 1, which is one focus of this paper and will be described in more detail in subsequent sections, $L_{Charging}$, is the 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[1], it is known that this term will be small compared with either the reflected Sunlight or Earthshine terms, L_{Sun} or $L_{EarthShine}$.

In summary, when Equation 1 is employed for a scenario where a large GEO-synchronous communication satellite is observed from Earth, the total expected radiance, L_{Total} is dominated by L_{Sun} and $L_{EarthShine}$. In that scenario, the value of L_{Total} corresponds to a visual magnitude M_V ~14 at a solar phase angle of 60º, which is consistent with observational data[2]. Of course observational scenarios where the observed satellite is eclipsed by the 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 utilized in that eclipse scenario, where $L_{SkyGlow}$, $L_{Thermal,}$ and $L_{Charging}$ may be the dominant terms.

III. Glows Due to Electron Impact

Dennison et al[1] have shown that when keV energy electrons bombard dielectric surfaces, they glow. This phenomenon has been seen in the laboratory countless times (see Ferguson et al[3,4]). The GEO environment often is characterized by high fluxes of keV electrons, and these electrons can produce kV of charging on GEO satellites. Especially during geomagnetic storms, it is quite normal that GEO satellites undergo charging to several kV 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 below (figure 4 of Dennison et al[1]), an estimate for the glow brightness is 6.3x10^{-6} W/m^{2}μm for an M55J carbon composite at a current flux at the surface of about 10 nA/cm^2 and a beam energy of about 5 keV. This material is widely used in spacecraft design and is likely to be the solar array structural material for many satellites. The highest electron current fluxes seen in GEO are about 0.4 nA/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[1] , we correct the maximum expected $L_{Charging}$ to be (6.3x4/25) x10^{-6} or ~ 1x10^{-6} W/m^{2}μm. For comparison's sake, we estimate the total power deposited by collected electrons on a spacecraft to be 8x10^{-5} W/m^2.

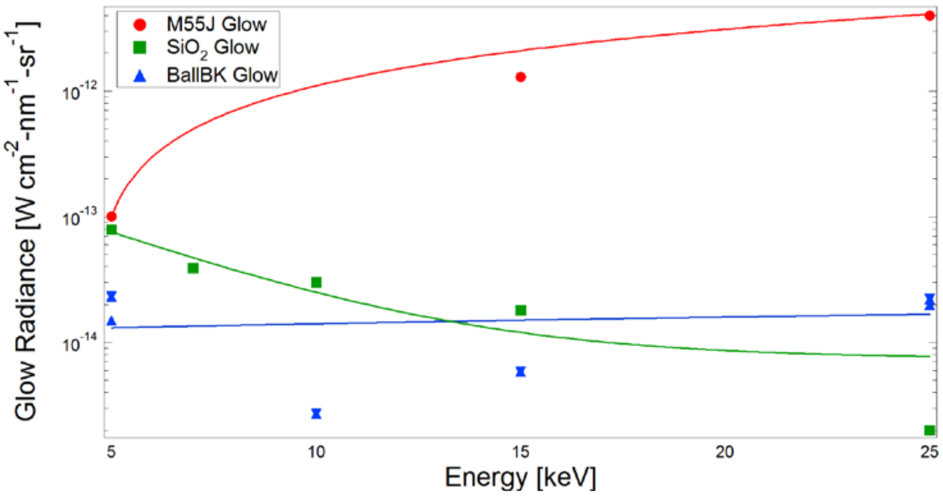

Fig. 2. Glow radiance at 10 nA/cm^2 electron flux.

Since 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. While we cannot eliminate the thermal contribution from the surface, by observing at optical or near infrared wavelengths we can minimize it so it becomes negligible. Finally, from ground-based observations, the sky glow cannot be eliminated, and

$$\mathbf{L_{Total} = L_{Charging} + L_{SkyGlow}.}$$

A complication is that as seen from Earth, the satellite charging brightness must compete with the sky glow. Assuming the area of a solar array in GEO is 60 square meters, at Earth

$$\mathbf{L_C} = \mathbf{L_{Charging}} \mathbf{x}\ \mathbf{A_{array}}/(4\pi\mathbf{R}^2)\text{, or } \mathbf{L_C} \sim 6\text{x}10^{-23}\text{W/m}^2\mu\text{m, where } \mathbf{R}=36\text{x}10^3\text{km.}$$

compared to the skyglow $L_{SkyGlow}$ = 3.4x10^{-16} W/m^{2}μm (8.5x10^{-2}photons/s-cm^2-μm) for a FOV of 1 arc-minute. Our signal-to-noise would be only ~2x10^{-7}. If we reduce the FOV (or our pixel size) to 1 arcsecond, $L_{SkyGlow}$ = 9.4x10^{-20} W/m^{2}μm, and our signal-to-noise ratio still is only 7x10^{-4}. Thus, sky glow 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 μm bandwidth, then L_C at Earth would still be only 4.9x10^{-21} W/m^{2}μm, and our signal-to-noise against sky glow ~ 0.06.

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

$$\mathbf{L_{Total} = L_{Charging}}$$

and our 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.

Our difficulty in seeing the low-level signals of the glow can perhaps be appreciated by comparing the corrected $L_{Charging}$ value with the $L_{Reflected\ Sun}$ value discussed in Sec II. $L_{Reflected\ Sun}$ is about 7.4x10^5 that of $L_{Charging}$. That is about 15 magnitudes brighter (five magnitudes are a factor of 100 in brightness), 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, we only gain 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 minutes 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 radiation can be seen by remote sensing instruments. Typically, bremsstrahlung is strongly peaked in the direction toward which the electron was travelling, 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 layup shown in Fig. 3, this implies, from the NIST tables[4], 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 our atmosphere, so observation must be done by a satellite in LEO or GEO.

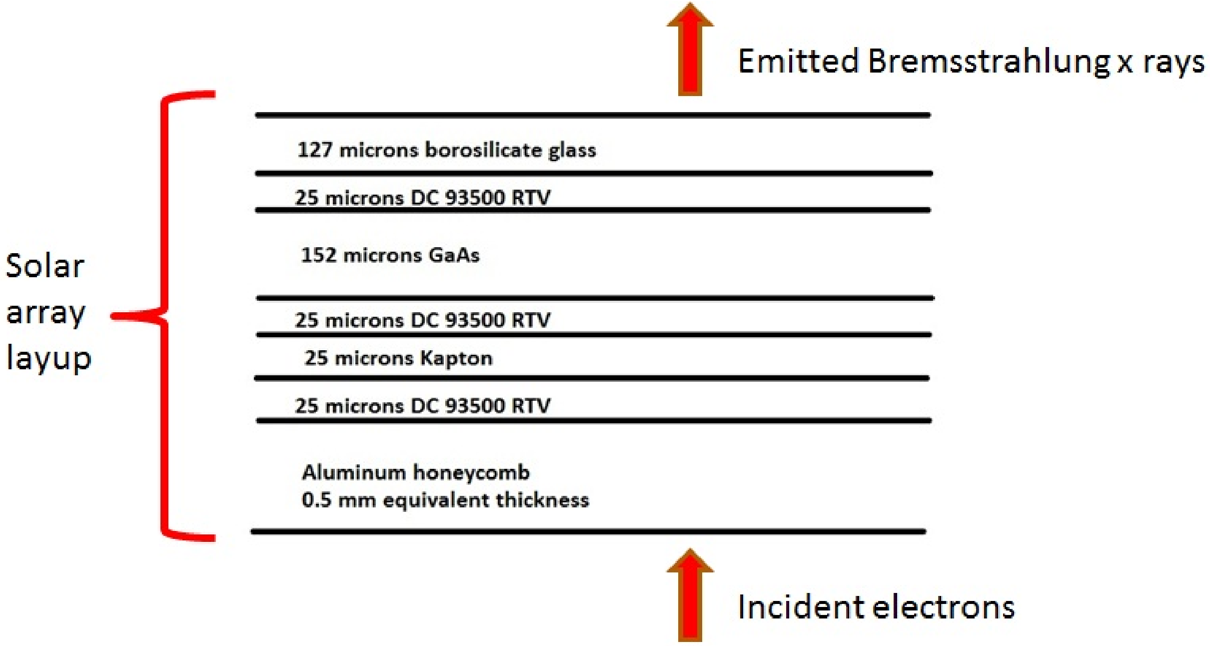

Figure 3. Assumed solar array layup for purposes of electron and x-ray transport.

Let us take, as a worst-case GEO electron spectrum, that of Sept. 22, 1982, as reported by Roeder[6]. In the 40 keV bin, Roeder reports an electron flux of $1.0\text{x}10^7$ electrons/cm^{2}sr-keV-sec. This is $1.0\text{x}10^{11}$ electrons/m^2-sr-keV-sec, or, taking 2π steradians as the normalizing factor, we have $6.28\text{x}10^{11}$ electrons/m^2-keV-sec. Let us assume a 100 keV bandwidth, and that every electron produces one x-ray. At the source this gives us $6.28\text{x}10^{13}$ photons/m^{2}sec over a hemisphere. With a 60 m^2 array, we have at the source about $3.7\text{x}10^{15}$ photons/sec. At a distance of 35000 km (distance from GEO to LEO), this becomes 0.6 photons/m^2 sec at our LEO sensor. Finally, assuming our sensor has a collecting area of 1 m^2, we can get ~30 x-ray photons per minute. For the entire maximum time the array is in eclipse, we 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.

In order to put some realism in our brightness estimate, we considered electrons entering the layup in Fig. 3 from below (because in eclipse, the front of the array is earth-pointing), and used a code called MULASSIS[7] to calculate escaping fluxes. The electron spectrum we used was a single-Maxwellian fit to the Sep. 22, 1982 spectrum. Fig. 4 shows our assumed electron flux spectrum, the photons predicted to be escaping from the layup, and the resultant emitted electron spectrum. Performing a simple integration from 40 keV to 180 keV electrons gives a total of about $8\text{x}10^8$ photons/m^2-sr-sec and with the 2π normalizing factor and 60 m^2 array as above, we have from the source $5.6\text{x}10^{11}$ photons/sec. This is a factor of about $3\text{x}10^4$ down from our estimate above that assumes every electron produces one photon. Now we will have in our sensor at LEO about $2.4\text{x}10^{-3}$ x-ray photons per minute, and during an entire eclipse about 0.18 x-ray photons, not nearly enough to make a detection. If we could improve this number by at least 2.5 orders of magnitude (by reducing our observing distance to 2000 km or less, for instance) we might be able to detect these emissions.

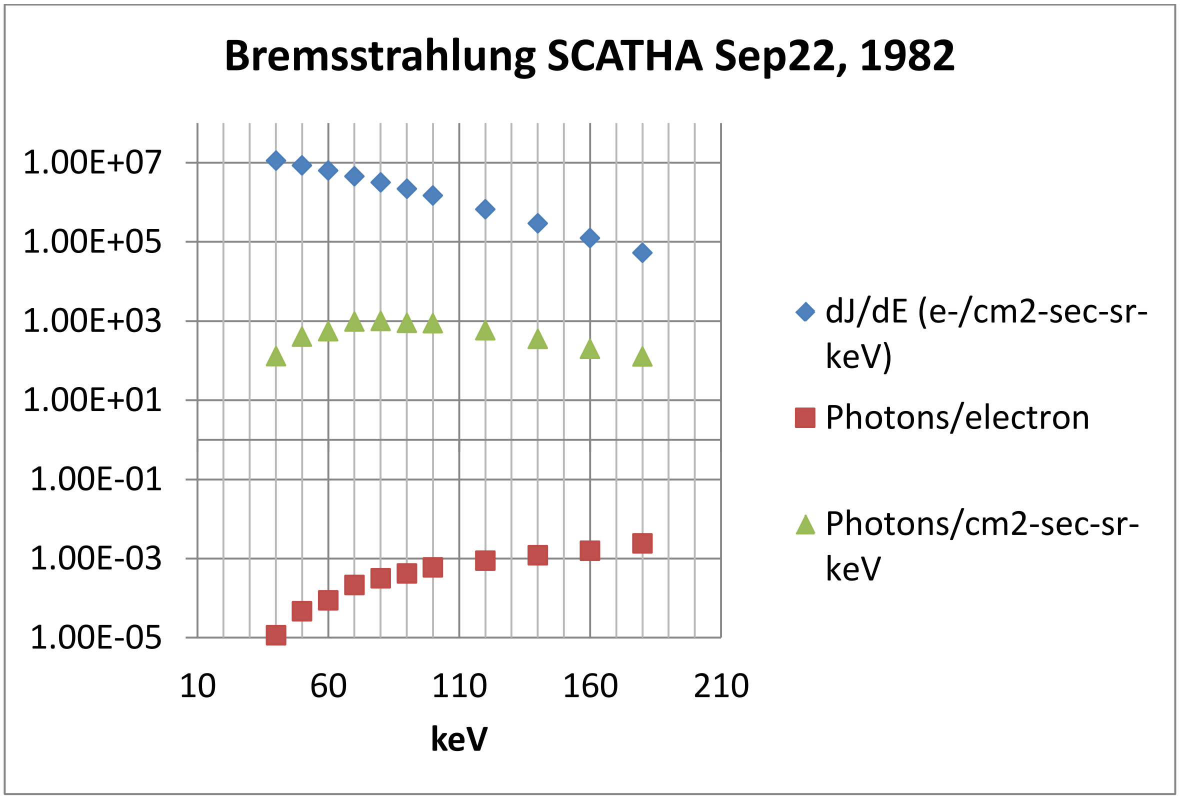

Figure 4. Bremsstrahlung x-rays from an extreme charging electron spectrum[6].

Next we 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[8]. The strongest x-ray emission from the array will be in the energy range 40-50 keV (from our MULASSIS calculations). From Fig. 5, we can see that at 45 keV, the flux is about 0.02 photons/cm^2-sec-keV-sr. This is 200 photons/m^2-sec-keV-sr. Again, assuming a 50 keV bandwidth, we have from the background 10^4 photons/m^2-sec-sr. Now we must make an assumption of the beamwidth of our x-ray telescope. Let us assume 1 square arc-minute. This is 8.46×10^{-8} sr, so in our telescope, we have 8.5×10^{-4} photons/sec-m^2, or in an entire eclipse period, about 3 photons. This gives us a signal-to-noise in our LEO sensor above the diffuse background of about 0.06. So, 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, we require that both the satellite and detector be in either LEO or GEO.

As in our previous calculations, we will want to do this detection when the sensor is in eclipse, so we do not have a noise background of solar x-rays scattered in the atmosphere and when the satellite we are observing is in eclipse, so we get no solar x-rays reflected by the satellite.

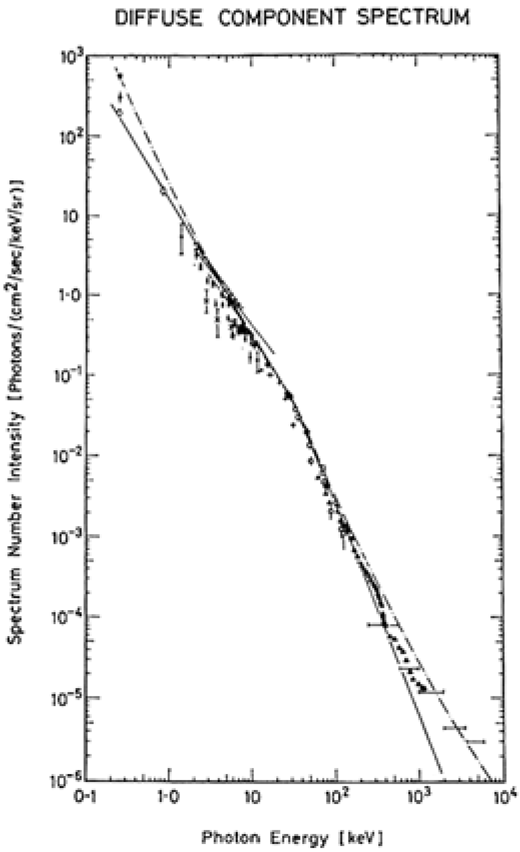

Figure 5. The Diffuse X-ray Background Spectrum.

V. Electromagnetic Emissions from Arcing

A. Radioemission 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 microseconds and the fall time is about 0.3 microseconds. The latter number corresponds roughly to a 3 MHz frequency, and the former a 50 MHz frequency. Frequency content at > 50 MHz must be due to unresolved structure in the voltage profile.

Assuming all of the energy stored in the 2000pF capacitor at 1000 V (0.001 Joule) is dissipated in about 0.5 microsecond, we get an average power of about 2000 W. Converting dB microvolts per meter in Figure 5 to power, we find that at 1 MHz, the peak power (for a fraction of a microsecond) is about $3\text{x}10^4$ W/MHz. This gives about $1.5\text{x}10^4$ W/MHz average power, and thus a "bandwidth" of about $2000/1.5\text{x}10^4 = 0.13$ 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, so we expect that the peak power of a large array arc at 1 MHz could be $3\text{x}10^6$ W/MHz. At a GEO satellite distance, this corresponds to a flux at 1 MHz of $1.8\text{x}10^{-12}$ W/m^{2}MHz = $1.8\text{x}10^{-18}$ W/m^{2}Hz = $1.8\text{x}10^4$ solar flux units (sfu's) = $1.8\text{x}10^8$ Jy, even greater than the signals from the disturbed sun[10]! But at 10 MHz, the flux is already down to $1.8\text{x}10^4$ Jy at Earth. This should, however, be detectable with an uncooled receiver on a 3 m radiotelescope 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[15]. At

4 meters distance (something like an average distance between a solar array arc and the spacecraft antenna), the peak flux would be ~150 W/m^{2}MHz at 1 MHz or 1.5x10^{-13} W/m^{2}MHz at 1 GHz. Thus, we believe that whether in eclipse or not, satellite arcs may be easily detectable by a monitor on-board the satellite or even by a moderate-sized radio dish on Earth.

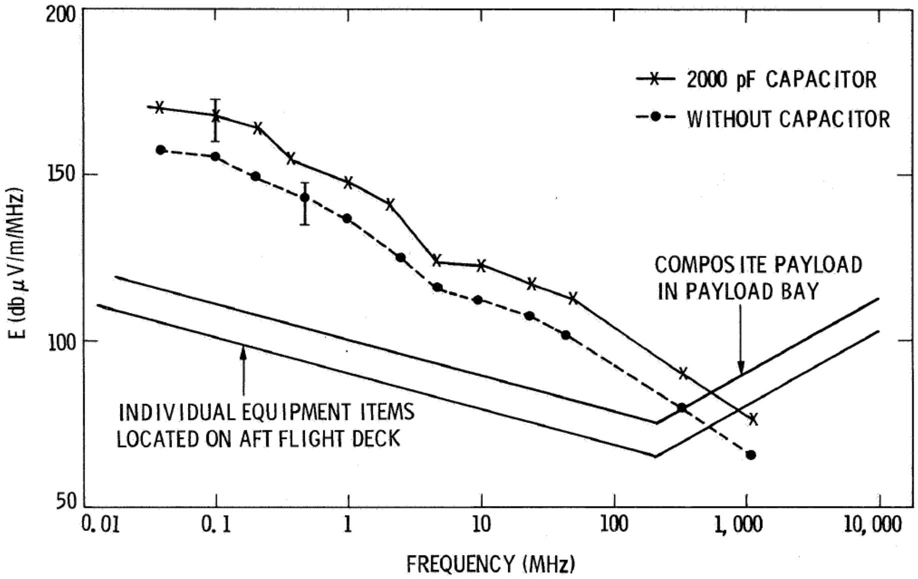

Figure 6. Radio frequency emission from arcs on solar arrays[9]. 2000 pF capacitor was added to simulate a larger array response.

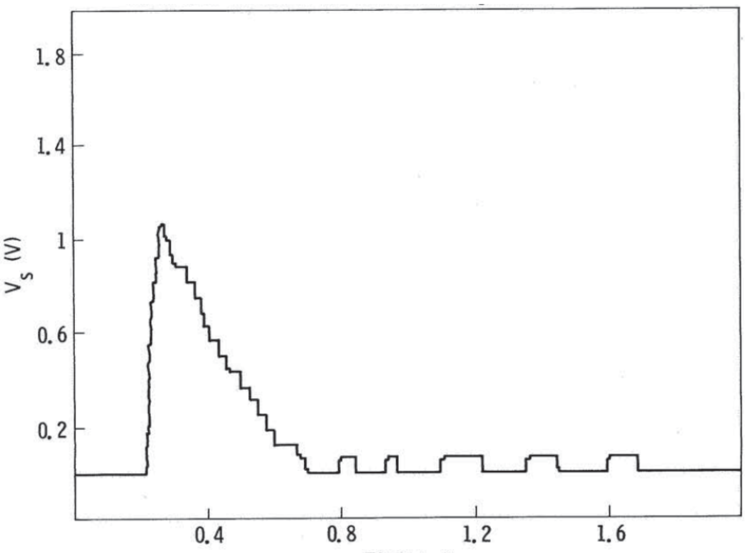

Figure 7. Voltage waveform for one of Leung's arcs[9].

B. Optical Emission from Arcs

We will now treat arcs as seen in visible wavelengths. In laboratory experiments, arcs are easily seen by video camera. 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. For simplicity's sake, let us assume that 1/10 the energy of the discharge is emitted as light. Using the above estimate for dissipated energy on a very large array, we will take 0.01 Joule as our total energy dissipated as light. If this is emitted in one microsecond, and with a bandwidth of 10,000 Å (1 micrometer), we have a power emitted of 10^4 W/μm. At the GEO distance, the flux on Earth becomes $6x10^{-7}$ W/m^2μm. This is over 9 orders of magnitude brighter than skyglow at 5000 Å, assuming a field of view of 1 arc-minute. Put in astronomical terms, the momentary magnitude of the arc should be about -8, compared with the -26 of the sun. Since the energy of a photon at 1 μm wavelength is $2x10^{-24}$ J, the photons received per arc by a ground-based telescope at 1 μm are $2x10^{11}$ photons/m^2μm-s! If the array arcs while the satellite is in eclipse, it should be detectable with even a moderate sized telescope. In nearly direct sunlight, a 60 m^2 array on the satellite itself should reflect only about 3 times more sunlight than the peak of the arc, so detection should be possible even if the arc occurs on a satellite outside of eclipse. This is fortunate, because many satellite anomalies (i.e. arcs) happen just after a satellite leaves eclipse. Assuming that the signal-to-noise ratio is inversely proportional to the exposure time (noise builds up during the exposure), and assuming an exposure time of 1/30 second, the arc should still look to be about magnitude +3, easily detectable in even a small telescope.

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. We suggest 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 field of view (1 arc-minute 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 – firstly, 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[3] 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]. Secondly, 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 reference 12 we can say that the back-bias glow may be comparable to the illumination in a very poorly lit room, which can be estimated[13] as 10 lux (lumens/m^2). For green light[14], 1 lux is 1.464 mW/m^2. Thus, assuming that one quarter of our array is back-biased, we have a total radiance of about 0.016 W, and at a distance of a GEO satellite, a radiance at Earth of $1x10^{-18}$ W/m^2, some 360 times (~7 magnitudes) brighter than the glow produced by electron bombardment, assuming a bandwidth of 1 μm in wavelength. 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.

VI. Conclusions

We have shown that it may be feasible to detect, from LEO and in some cases the Earth's surface, the x-ray, optical and radio emissions from 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 antennae 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. Secondly, the glows produced 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 is 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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