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Recommended Citation

Ferguson, Dale C.; Murray-Krezan, Jeremy; Barton, David A.; Dennison, JR; Gregory, Stephen; and Sim, Alec, "On the Feasibility of Detecting Spacecraft Charging and Arcing by Remote Sensing" (2013). AIAA Atmospheric and Space Environments Conference. *Presentations.* Paper 27.
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On the Feasibility of Detecting Spacecraft Charging and Arcing by Remote Sensing

25 June 2013

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

OUTLINE

- Introduction
- Space Situational Awareness
- Terminology Conventions and the Natural Radiation Background
- Glows Due to Electron Impact
- X-rays From Impinging Electrons
- Electromagnetic Emissions from Arcing
  - Radioemission from Arcs
  - Optical Emission from Arcs
  - Optical Emission from Arc-Afterglows
- Conclusions

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Introduction

- High energy electrons, often from GEO storms, cause GEO satellites to charge
  - GEO storms are rapid changes in Earth’s magnetic field when solar plasmas hit the magnetosphere
  - In a GEO storm, a satellite can charge to –20 kV, and satellite surfaces up to 5 kV with respect to each other
  - High electric fields result in arcs, with high currents and radiated signals, causing disruptions in comm signals, latchups of electronic components, short-circuits, and surface property changes
- Satellite behaviors deviating from nominal are called anomalies
  - Anomalies range from simple bit-flips to losses of entire comm circuits or solar array strings/power supplies.
  - Solar arrays are highly sensitive to charging, since they 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
- Small transient arcs on solar arrays can turn into huge solar powered sustained arcs
- Most GEO satellite anomalies occur within a few hours after an eclipse
  - GEO Satellites can only be in eclipse:
    - during two eclipse seasons every year,
    - each lasting about two months at the vernal and autumnal equinoxes, and
    - for a maximum of about 1 hour each day during these seasons

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Introduction (2)

- Deep-dielectric discharges are from (penetrating) electrons of > 2 MeV
  - Electrons build up for hours or days inside electronics until electric fields build up to discharge levels
- Surface discharges are from electrons of 5-50 keV that differentially charge satellite surfaces. When local electric fields build up to discharge levels, an anomaly can occur
  - GEO charging conditions can last for several hours, and then typically abate for a while
- Remotely sensing spacecraft charging and its arcs requires detection of:
  - high energy electrons (or ions) as they hit the spacecraft surfaces,
  - radiated emissions from passage of the electrons through the material, or
  - radiated emissions from the arcs themselves
- Electromagnetic radiation gives the best chance of remote detection because EM waves are insensitive to electric and magnetic fields and charged particle environments

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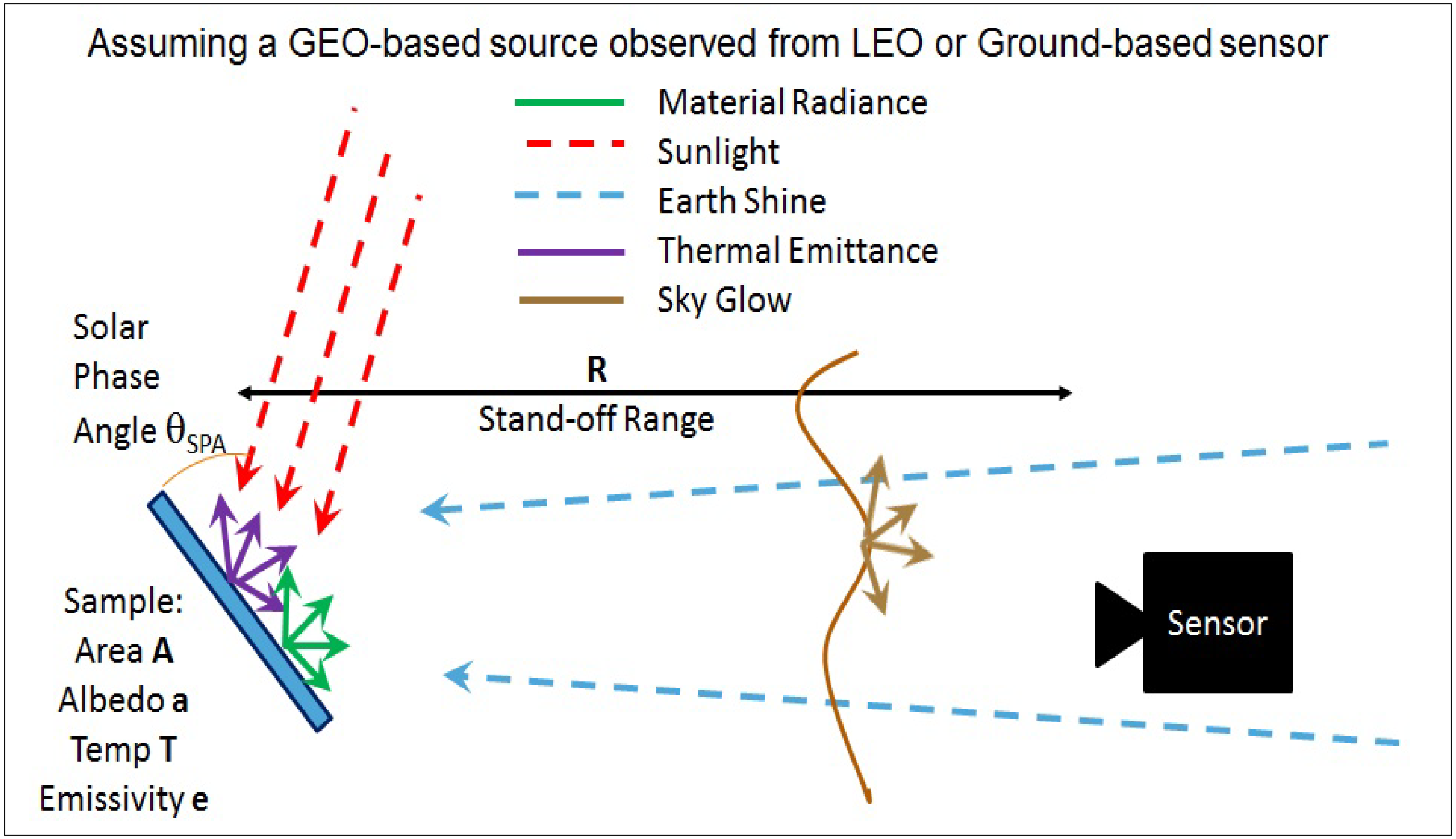
Space Situational Awareness

- SPACE SITUATIONAL AWARENESS (SSA) - the capability to determine what is happening and why on satellites in space
  - Satellite operators need good SSA to diagnose anomalies and plan for events (like meteor showers) when avoidance is necessary
  - Examples of SSA - ground station operators must plan for losing their signals when they are too close to the sun in the sky (during eclipse seasons) or when space weather conditions may cause arcing anomalies on satellites
  - The USAF must maintain SSA to determine if satellite anomalies are due to operations in the space environment or to hostile acts
- > 50 years into the space age, most satellites still do not have sensors to detect:
  - whether they are at dangerous potentials, or
  - when or if they undergo arcing
- Anomaly resolution is hit or miss, and false diagnoses are probably common
- Detection now must be by remote sensing from ground stations or by satellites
- We here examine remote sensing methods to detect satellite charging and/or arcing

Terminology Conventions and the Natural Radiation Background



Assuming a GEO-based source observed from LEO or Ground-based sensor

- Material Radiance
- Sunlight
- Earth Shine
- Thermal Emittance
- Sky Glow

Solar Phase Angle θ_{SPA}

R

Stand-off Range

Sample:
Area **A**
Albedo a
Temp T
Emissivity e

Sensor

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.

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Terminology Conventions and the Natural Radiation Background

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

- L_{Sun} may be found by assuming the observed satellite has an albedo described by:

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

- 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

- Notional observed solar phase angle in our scenario is **θ_{SPA}= 60º**
- For these conditions, **L_{Sun} = 140W/m^2 µm** (3.5x10^{16}photons/s-cm^2-µm) at an optical wavelength near 0.5 µm (green light)
- Using the same assumptions, **$L_{EarthShine}$= 4W/m^2 µm** (1x10^{15}photons/s-cm^2- µm) at an optical wavelength near 0.5 µm
- Expected radiance due to thermal emission, assuming an emissivity of e =1 (!), is

  $L_{Thermal} \leq$ 10^{-37}W/m^2 µm (2.5x10^{-23}photons/s-cm^2- µm) near 0.5 µm

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Terminology Conventions and the Natural Radiation Background

- **Assume**:
  - the observation is conducted from Earth,
  - under good observational conditions, i.e. dark skies of 19th mag/arcsec^2,
  - with a telescope having a field-of-view (FOV) of one minute-of-arc.
  - We then expect that the radiant contribution of sky glow is

    $L_{SkyGlow}$~10^{-16}W/m^{2}mm (2.5x10^{-2}photons/s-m^2- µm) in the optical waveband

- Under the best observational conditions on Earth, zodiacal 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 is ~ 21st mag/arcsec^2**;
    - The background also depends strongly on what stars are in the field of view. For example, if one is observing near a bright star, there will be a high background radiance from starlight

- **$L_{Charging}$** is the radiance due to electron bombardment of the satellite surfaces, primarily the solar panels. An electron bombardment glow is smaller than either **L_{Sun}** or **$L_{EarthShine}$**

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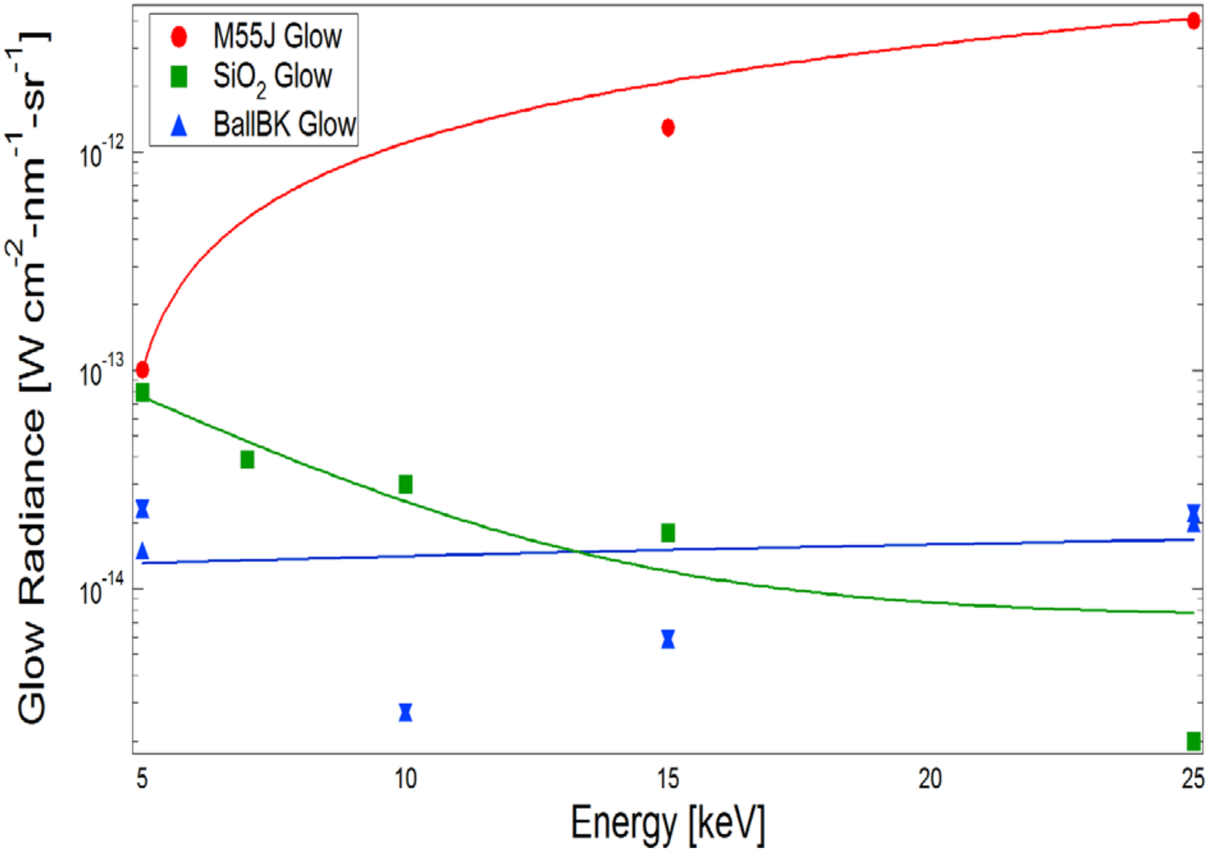
Glows Due to Electron Impact



Glows of M55J (carbon composite), silicon dioxide, and black Kapton for a laboratory beam flux of 10 nA/cm^2

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Glows Due to Electron Impact

- $L_{Charging} = 6.3\times10^{-6}$ 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
  - M55J is widely used in spacecraft design and is likely to be the solar array structural material for many satellites
- Highest GEO electron current fluxes are ~ 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, we find the maximum expected

  $L_{Charging} \leq (6.3\text{x}4/25)\ \text{x}10^{-6}$ or ~ $1\text{x}10^{-6}$ W/m^{2}μm
- For comparison's sake, the total power deposited by collected electrons on a spacecraft is ~$8\text{x}10^{-5}$ W/m^2

Glows Due to Electron Impact

Assume that one can observe the satellite when it is in eclipse. Then,

$$L_{Total} = L_{Charging} + L_{SkyGlow}$$

- As seen from Earth, the satellite charging brightness must compete with the sky glow. Assuming the GEO solar array area is 60 m^2, then at Earth,

$$L_C = L_{Charging} \times A_{array}/(4\pi R^2), \text{ or } L_C \sim 6\times10^{-23} \mathrm{W/m^2\mu m}, \text{ with } R=36\times10^3 \mathrm{km}$$

- $L_{SkyGlow} = 3.4\times10^{-16}$ W/m^{2}µm (8.5×10^{-2}photons/s-cm^2-µm)
  - for a FOV of 1 arcminute
    - our signal-to-noise (S/N) would be only ~2×10^{-7}
  - If we reduce the FOV (or our pixel size) to 1 arcsecond,
    - $L_{SkyGlow} = 9.4\times10^{-20}$ W/m^{2}µm, and our S/N ratio still is only 7×10^{-4}
- Even special materials would not make the glow visible from Earth
  - If each electron yields all its energy in a 1 µm bandwidth, then $L_C = 4.9\times10^{-21}$ W/m^{2}µm, and S/N~ 0.06
- Thus, sky glow <u>severely</u> limits detectability of the electron-produced glow from Earth. Thus, observation from a spacecraft in eclipse is necessary.

Glows Due to Electron Impact

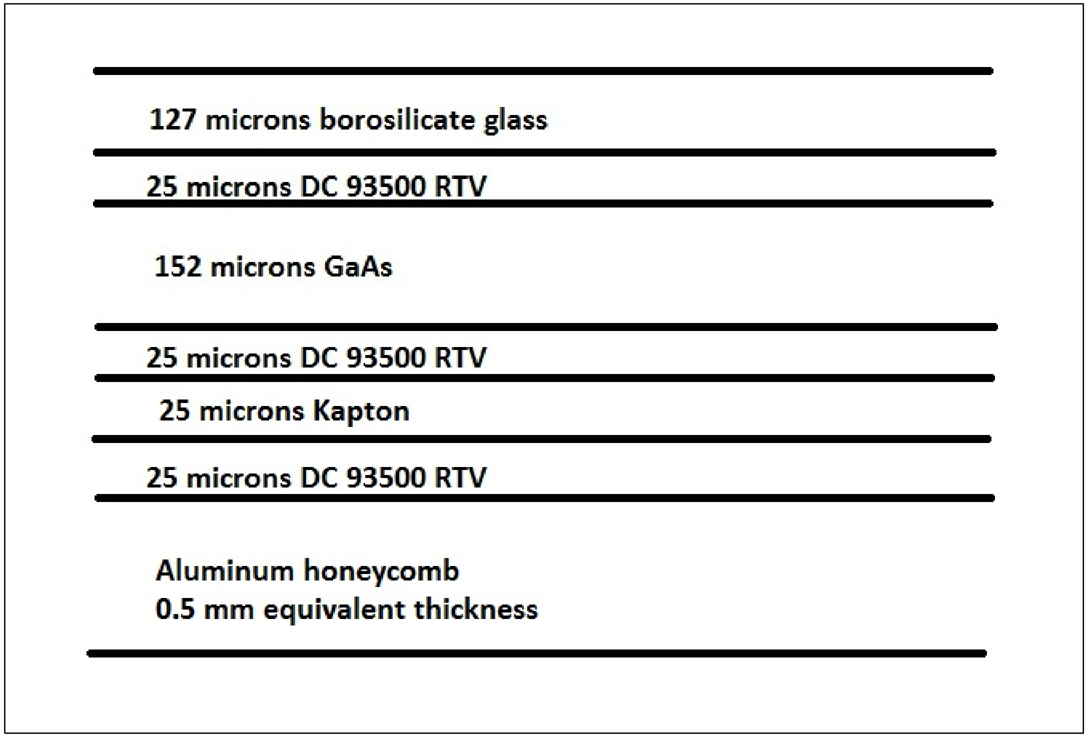
- **From space, and if zodiacal background is negligible, sky glow = 0, so that**

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

- **Unfortunately, zodiacal light for GEO satellite observation is strongest near eclipse seasons, when the satellite is near the ecliptic plane.**

- **$L_{\text{Reflected Sun}}$ is ~ $7.4\text{x}10^5$ L_{Charging}.**
  - **That is ~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.**

X-rays From Impinging Electrons



127 microns borosilicate glass

25 microns DC 93500 RTV

152 microns GaAs

25 microns DC 93500 RTV

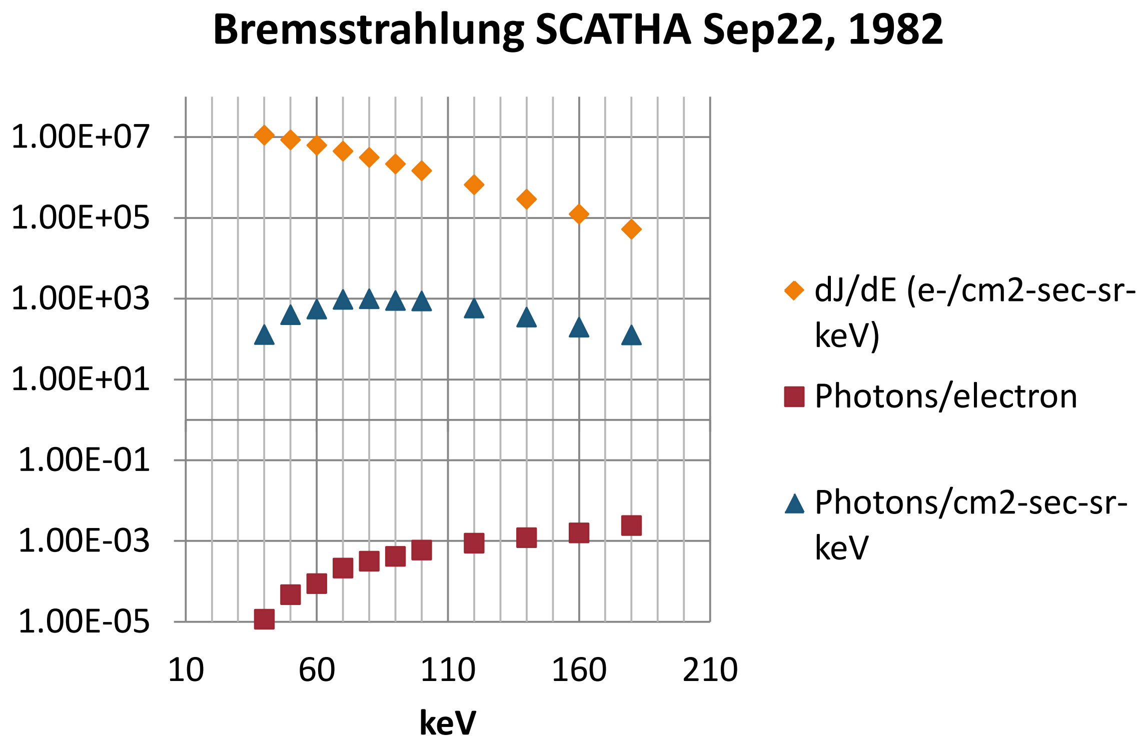
25 microns Kapton

25 microns DC 93500 RTV

Aluminum honeycomb
0.5 mm equivalent thickness

- **Solar array layup considered in doing x-ray bremsstrahlung calculations. Electrons enter from bottom and x-rays exit through top**

X-rays From Impinging Electrons



- **Calculations of bremsstrahlung from solar array layup on previous slide. Electron spectrum measured by SCATHA satellite on Sept. 22, 1982. Yield calculated by MULASSIS (Spenvis)**

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X-rays From Impinging Electrons

- **Integration from 40-80 keV electrons gives a total of about 8x10^{8} photons/m^{2}-sr-sec and with a 2π normalizing factor and 60 m^{2} array, we have from the source 5.6x10^{11} photons/sec**
- **We will have in our sensor at LEO (assuming 1 m^{2} collecting area) about 2.4x10^{-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 improve this number by at least 300 times (by reducing our observing distance to < 2000 km, for instance) we might be able to detect these emissions**

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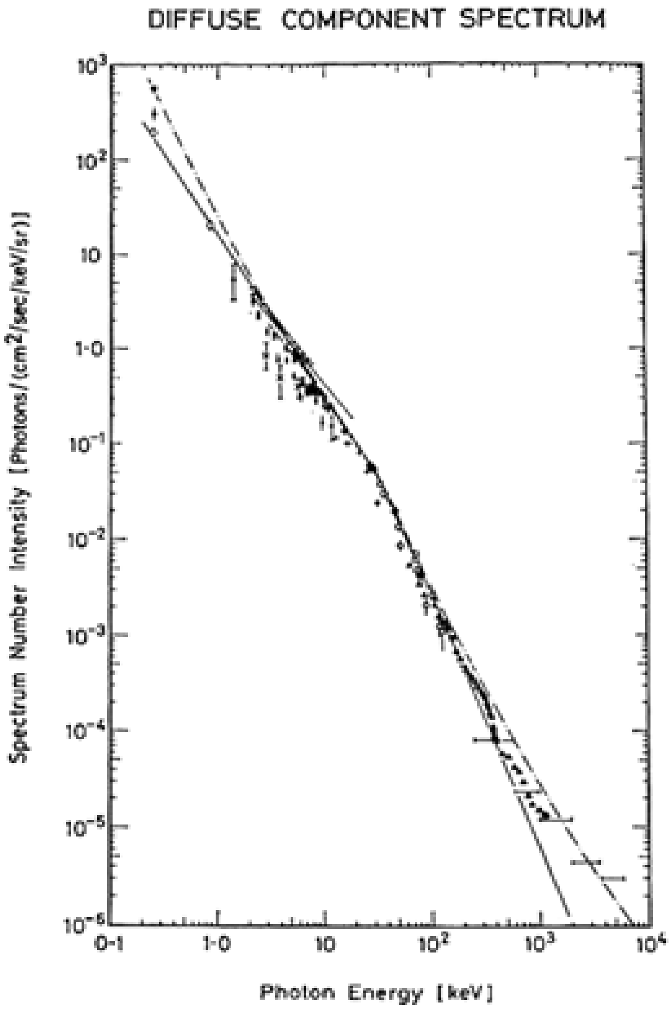
X-rays From Impinging Electrons



Diffuse Cosmic X-ray Background Spectrum

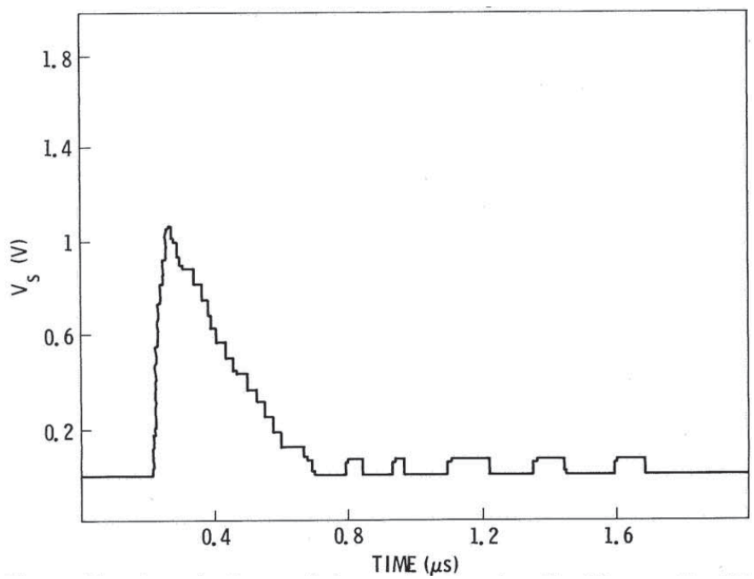
Electromagnetic Emissions from Arcing

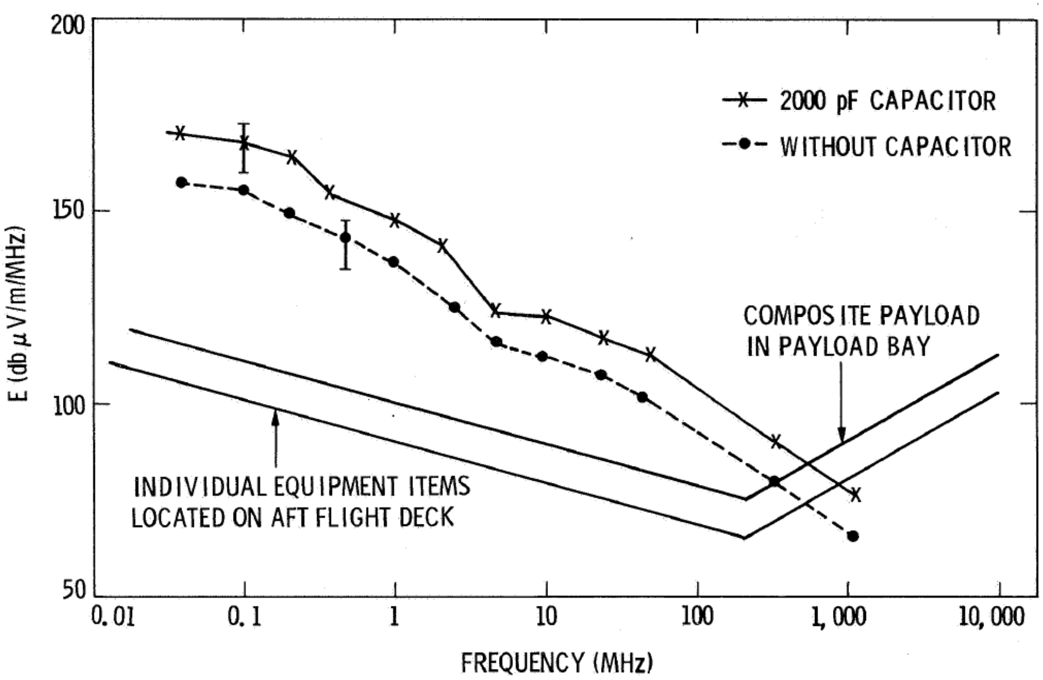
- Would the cosmic x-ray background limit detection of the x-ray signal?
- Strongest x-ray emission from the array will be in the energy range 40-50 keV (from

Electromagnetic Emissions from Arcing

Radioemission from Arcs

- Arcs occur on GEO spacecraft due to the high electric fields from spacecraft charging
- Leung measured radio emission from arcs on solar array samples
  - A 2000 pF capacitor was added to the bias circuit to enable his small (100 cm^2) array results to simulate a larger array





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Electromagnetic Emissions from Arcing

Radioemission from Arcs (2)

- Assume all energy stored in the 2000pF capacitor at 1000 V (0.001 Joule) is dissipated in ~ 0.5 μs, then average power is ~2000 W
- Converting dB μV/m on previous slide to power, we find that at 1 MHz, the peak power (for a fraction of a microsecond) is ~ 3×10^4 W/MHz!
- A large solar array on a GEO satellite has 100 times (200 nF) the 2000 pF capacitance used by Leung, so the peak power of a large array arc at 1 MHz could be 3×10^6 W/MHz
- At a GEO satellite distance, this corresponds to a flux at 1 MHz of 1.8×10^{-18} W/m^{2}Hz, or 1.8×10^4 solar flux units (sfu's)!
  - At 10 MHz, the flux is already down to 1.8 sfu at Earth. However, this flux should be detectable with an uncooled receiver on a 3 m radiotelescope or a cooled receiver on a 1 m telescope
  - These fluxes will appear as short (1 μs or so) bursts of broadband emission, especially using a radio telescope on the night-side of Earth, and thus shielded from the direct solar emissions

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Electromagnetic Emissions from Arcing

Radioemission from Arcs (3)

- 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
  - At 4 meters distance (~ avg 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
- We believe that whether in eclipse or not, satellite arcs are easily detectable by a monitor on-board the satellite or even by a small radio dish on Earth

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Electromagnetic Emissions from Arcing

Optical Emission from Arcs

- **In laboratory experiments, arcs are easily seen by video camera and by eye**

- **Assume 1/10 the energy of the discharge is emitted as light (0.01 J)**
  - **If emitted in 1 μs, and with a bandwidth of 1 μm, we have optical power emitted ~ 10^4 W/μm.**
  - **At GEO distance, on Earth this = 6×10^{-7} W/m^{2}μm**
  - **This is over 9 orders of magnitude brighter than skyglow at 5000 Å, assuming FOV = 1 arc-minute. Put in astronomical terms, the momentary magnitude of the arc should be about -8, compared with the -26 of the sun, -12 for the full moon and -4 for the planet Venus!**

- **Since the energy of a photon at 1 μm wavelength is 2×10^{-24} J, at 1 μm this is 2×10^{11} photons/m^{2}μm-s!**
  - **If the array arcs while the satellite is in eclipse, it should be detectable with even a moderate sized telescope**

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Optical Emission from Arcs (2)

- 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 be ~ magnitude +3, easily detectable in even a small telescope (the limiting magnitude of the human eye is +6)
- 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

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Electromagnetic Emissions from Arcing

Optical Emission from Arcs (3)

- 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 arcminute 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 use 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

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Electromagnetic Emissions from Arcing

Optical Emission from Arc-Afterglows

- **Shortly after the initial arc emissions, solar array surfaces glow continuously for two reasons:**
  - **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**
  - **Some of the cells in the array circuit are back-biased by the arc, and act as light emitting diodes**
- **Both of these types of emissions are broadband and may last for hundreds of microseconds**
- **Arc-caused glows may have a total radiance of ~ 0.016 W, and from a GEO satellite, a radiance at Earth of 1x10^{-18} W/m^2, ~ 360 times (7 mag) brighter than the glow produced by electron bombardment, for a bandwidth of 1 μm**
- **These glows might 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**

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Conclusions

1. **It may be feasible to detect, from LEO and in some cases the Earth's surface, the x-ray, optical and/or radio emissions from GEO satellites as they undergo spacecraft charging and arcing**
2. **The best possibility for detection is from microsecond bursts of light and radio waves from arcing, especially when the arcs occur on large solar arrays**
   a. **Arc-produced radio bursts may be seen by antennae on the arcing GEO satellites**
   b. **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**
   c. **From Earth, optical and radio coincidence techniques may be most useful**
   d. **Solar array back-bias glows may be observed from the ground or from LEO for a few hundred microseconds after an arc**
3. **Glows produced when charging electrons bombard dielectrics in GEO are too weak to be detected from Earth or LEO, although co-orbiting GEO satellites might be more easily able to detect the emissions**
4. **Bremsstrahlung x-rays produced by charging electrons in GEO are too weak to be detected by LEO satellites and would require co-orbiting satellites**
5. **It may be of immediate interest to attempt arc detection from ground-based optical and/or radio telescopes**

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