(Abstract No# 169)

The Space Weather Threat to Situational Awareness, Communications, and Positioning Systems

D.C. Ferguson, S.P. Worden, and D.E. Hastings

***Abstract*— A recent space weather headline has cast doubt in the minds of some as to whether space weather is the source of spacecraft anomalies, and thus, whether it is important in the design and operation of critical situational awareness, communications, and positioning systems. In this paper, we reiterate the evidence for the importance of space weather, its role in producing spacecraft and ground anomalies, and the threat it poses to critical systems. In addition, we report new studies broken down by anomaly types and suggest the sources of the anomalies (surface charging or interior charging). Finally, we suggest spacecraft charging and ground effects mitigation strategies for design and operations of systems critical to our modern civilization.**

Keywords—space weather; situational awareness; communications; positioning systems

I. INTRODUCTION

We've known for well over a century that space weather can affect life on earth. These effects are particularly significant for long distance communications systems. Indeed, the enormous solar event of 1859, the Carrington Event knocked out telegraphs throughout North America and Europe. With the advent of space-based communications systems in the last 50 years the potential impact of space weather on long-distance communications has grown significantly. Space-weather induced satellite failures and outages can be devastating on both commercial and military operations. There is also a significant problem with the exponentially growing networks including both space and ground-based links. As with the Carrington event, modern ground based networks are vulnerable to electromagnetic consequences of space weather. In this paper, we review space weather and how it influences crucial military and commercial systems, emphasizing situational awareness, communications, and positioning. The purpose is to counter misleading or false headlines that may give the impression that space weather is not important [1], and to provide solid advice on how to deal with Space Weather threats.

II. SPACE WEATHER – WHAT CAUSES IT

The Sun is a typical G2 type star – a ball of hot plasma about 865,000 miles in diameter (100 times as big as Earth). It is rotating, but instead of rotating like a solid body, it differentially rotates – the rotation period is ~ 25 days at the equator and ~30 days at the poles (average ~ 27 days). It has a magnetic field caused by the dynamo effect. The differential rotation of the plasma (to which the magnetic field lines are attached) twists and untwists the magnetic field lines making the magnetic field increase and decay, and change sign every 11 years (the "sunspot cycle"). When the field is most twisted, it "breaks through" the visible surface, causing sunspots, flares, and coronal mass ejections (CMEs). This is called "solar max", the time of greatest "solar activity". When the field is smooth, there are few or no sunspots, and the solar activity is at a minimum ("solar min"). The earth's space environment is modified by the outflowing "solar wind" on a timescale of minutes to weeks by solar activity. This is called "space weather."

A. Space Weather – The Solar Cycle

In Fig. 1 [2] are the historical solar cycle average yearly sunspot numbers from the beginning of record–keeping in the 1750's. Fig. 2 [3] shows average monthly sunspot numbers for the most recent solar cycles, with speculative estimates for the current cycle (24) and the next (25). In Fig. 3 [4] are the current sunspot measurements for cycle 24.

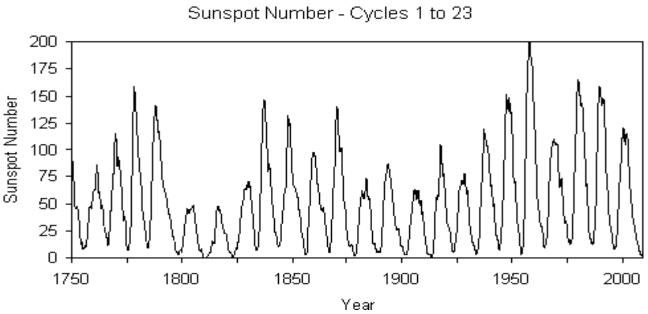

Fig. 1. Historical Solar Cycles

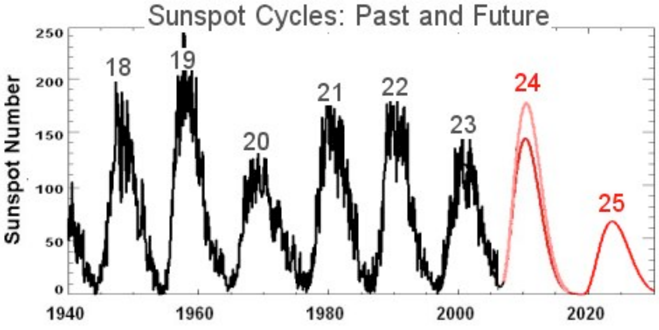

Fig. 2. Recent Solar Cycles – we are in #24 now.

D.C. Ferguson is with the Space Vehicles Directorate, U.S. Air Force Research Laboratory, Kirtland Air Force Base, New Mexico, 87117, USA (email:dale.ferguson@kirtland.af.mil)

S. P. Worden is with the NASA Ames Research Center, Moffett Field, CA, USA, and was formerly a General with the USAF/SMC.

D.E. Hastings is with the Massachusetts Institute of Technology, Cambridge, MA, USA and was formerly the USAF Chief Scientist

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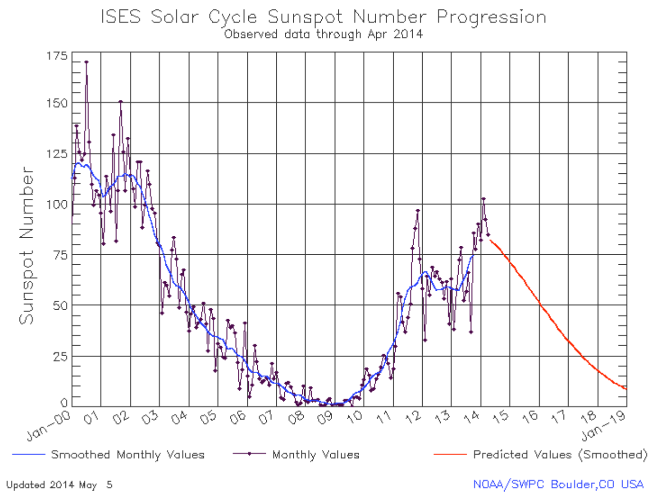


Fig. 3. Current average monthly sunspot numbers with a prediction for the rest of cycle 24.

B. *Space Weather – Phenomenology*

Solar Flares emit copious radio waves, x-rays and relativistic electrons and protons. The x-rays reach Earth and ionize some of the upper atmosphere in only 8 minutes – there is no warning, since we see the flare by light & radio waves that arrive at the same time as the x-rays. Next to arrive are the relativistic protons (Solar Energetic Particles, or SEPs) which can reach Earth in about another 10 minutes. When solar flares erupt, the can also eject large blobs of magnetized plasma called Coronal Mass Ejections (CMEs) traveling at speeds upward of 2×10^6 mph. This means they can hit Earth within 2-4 days.

CMEs are very directional, and most miss Earth entirely. Those that hit can distort the magnetosphere, but to get in must be funneled down through the polar regions. The extra plasma load can stretch the magnetosphere back out away from the sun, and when the magnetic field lines "break," they snap back, accelerating electrons and protons to energies as high as 80,000 keV. This is called a Geomagnetic Storm. GEO satellites (at 6.6 Earth radii) may be impacted within minutes, and the B-field of the whole magnetosphere and ionosphere in ½ hour. Aurorae are caused by the interaction of the entering plasma with Earth's upper atmosphere, causing it to fluoresce like a neon sign.

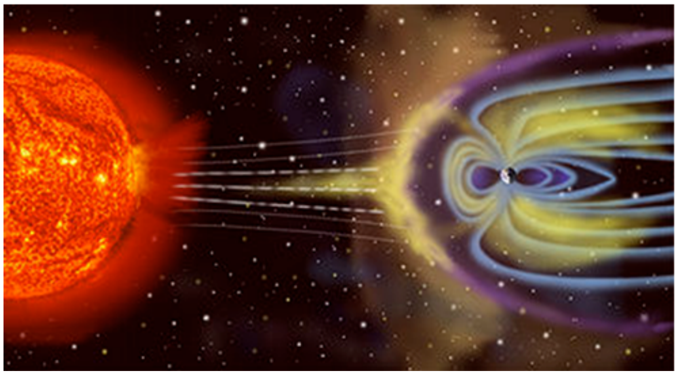


Fig. 4. Schematic of Sun-Earth Interactions [5].

C. *Space Weather – Numbers Used for Solar Activity*

There are several numbers used to characterize the solar activity. Brief descriptions follow:

1) SSN (SunSpot Number) or Z (Zurich SSN) – The number of sunspots visible on the sun's near-side, weighted by areas and groups of spots.
2) F10.7 – The solar flux in the 10.7 cm radio wavelength.
3) Solar Flare X-ray Strength – A, B, C, M, X from weakest to strongest.
4) Kp – planetwide 3-hour disturbance in Earth's magnetic field. Goes from 0-9, ≥5 = geomagnetic storm.
5) Ap – weighted daily average of Kp, nonlinearly related to Kp. Kp of 5 is Ap of 48.
6) Dst – hourly Kp-like average from 4 observatories
7) Solar Wind Speed – 300-2000 km/s, stronger CMEs are ejected with higher speed.
    a. 2 MeV electron flux – can penetrate satellite radiation shielding
    b. 10 MeV proton flux – can penetrate satellite radiation shielding
8) TEC – total electron content. Line-of-sight measure important to radio scintillation.

III. SPACE WEATHER IMPACTS

A. *Impacts on Earth*

Below is a short list of ways that space weather can impact systems on Earth.

1) Power Grid Outages – due to high voltages induced on long power lines by rapid changes in Earth's magnetic field (Dst very high) and the tightly woven power grid. A good example is 13 March, 1989 (cycle 22) – the collapse of Hydro-Québec power grid, putting 6 million people without power.
2) Transportation disruptions – due to navigation and switching problems. A good example is 13 May, 1921 (cycle 15) – the NY Central Railroad was put out of operation due to electrical fires from overstressed electrical transformers. Transpolar flights may be cancelled or rerouted due to space weather radiation fluxes that do not usually reach Earth because they are stopped in the atmosphere. And, instrument landings may be curtailed due to GPS outages from scintillation or GPS malfunctions due to high solar radiation fluxes.
3) Communications and Radar Disruptions. Good examples are the following:
    a) 1-2 September, 1859 (cycle 10) – telegraph outages, fires (the Carrington Event). Largest known historical event.
    b) 13 May, 1921 (cycle 15) – telephone, telegraph and cable outages.
    c) 2 August, 1972 (cycle 20) – telephone outages, components damaged in Canadian overseas cable service.

   d) 4 November, 2003 (cycle 23) – radio blackout
   e) Cell phone, GPS and radar reception may also be compromised

4) Aurorae. Examples follow:
   a) 21 December, 1806 (cycle 5) – first known association of aurorae with magnetic storm.
   b) 1-2 September, 1859 (cycle 10) – aurorae seen as far south as Cuba and Hawaii.
   c) 13 May, 1921 (cycle 15) – aurorae at zenith in Pasadena, CA.
   d) 2 August 1972 (cycle 20) – seen from Illinois to Colorado.
   e) 13 March, 1989 (cycle 22) – seen as far south as Texas [13].

B. Impacts on Satellites

Why are satellite disruptions ("anomalies") important? It is because satellites are the basis of our technological civilization:

- Communications [TV, telephones (land and mobile) – communications satellites]
- Timekeeping (GPS)
- Navigation (GPS)
- Transportation (Air Traffic Control – GPS, train and truck tracking - GPS)
- Agriculture (Planting and harvesting - GPS)
- Wildlife Management (GPS)
- Earthquake, Volcano, Weather and Climate Monitoring (GPS)
- Defense (Surveillance and other intelligence, weapons guidance)

What satellite systems can be affected? All satellite systems, including:

- Power (solar arrays and batteries)
- Payload
- Telemetry (including high-power communications)
- Position and Attitude Control
- Propulsion

1) Sources and Types of Satellite Anomalies

There are two major sources of satellite anomalies, surface charging and deep-dielectric charging. Surface Charging may produce electrostatic discharges (ESDs) and arcing on solar arrays and power cables, and these may reach sensitive spacecraft electronics by radiation or conduction into nearby cables. Surface charging is typically caused by electrons of 5-50 keV energies in GEO, 2-20 keV in PEO, or high voltage arrays in LEO.

Deep Dielectric Charging may produce arcing internally to spacecraft. It is caused by the total dose of electrons of 200 keV to 3 MeV energies, or protons of > 10 MeV energy, or prompt SEPs or X-rays (usually f very high energies), that can pass through spacecraft surface or shielding materials. Interior electronic upsets called Single Event Upsets (SEUs) are caused by the ionization trail of single high energy particles in sensitive electronics.

The types of effects caused by surface or deep-dielectric discharges include transient effects (bit flips in electronics or EMI-produced spurious commands or software upsets) or more permanent damage (arcs, ESDs, and microchannel plate saturation that may damage electronics, and/or cause power cabling or solar array failure). While more rare than transient effects, their permanent nature makes these types of effects devastating to satellite operation.

C. Causes and Effects of Space Weather-Produced Anomalies

Usually, failures of satellite systems to perform or operate properly are called anomalies. In order of their immediacy of effect, these may be caused by the following solar interactions:

- Flares. Flares have an immediate impact on HF radio communications due to ionization in of the D layer in Earth's ionosphere by prompt X-rays. Flares may also produce a long-term impact by heating the upper atmosphere by large fluxes of UV-EUV radiation and this increases atmospheric drag on orbiting satellites.
- The Radio Bursts that often accompany flares can knock out GPS navigation systems and interfere with communications and radar. One example is the large event of 2006 Dec 06 which occurred after the impulsive phase of a flare. It knocked out GPS for 20 minutes and affected cell phone reception. This is a definite issue for the increased use of UAVs and for aircraft landing. Flare prediction is an active area, helped by our new ability to sense far-side activity with the NASA Stereo spacecraft and helioseismology.

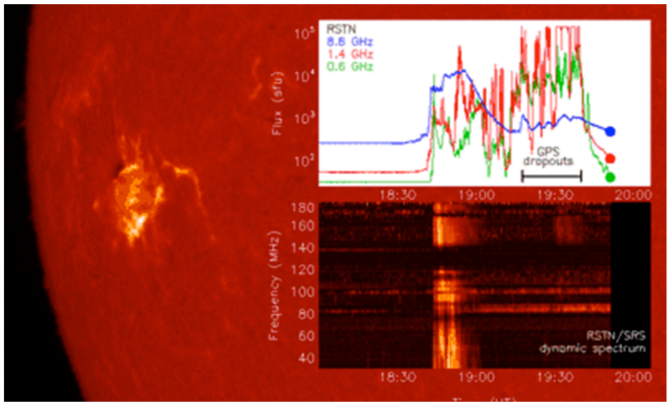


Fig. 5. Radio bursts on Dec 6 2006 and the associated GPS dropouts [6].

- Solar Energetic Particles (SEPs) are protons with energies ~1 GeV that pose a radiation hazard for astronauts and polar flights, can affect satellite electronics, and affect polar cap absorption in the ionosphere. They can come from flares or CMEs, and can arrive within 10 minutes of a flare. vxB forces in the geomagnetic field control the entry of SEPs, and they are more important at earth's magnetic poles than at the equator. The largest events (ground level enhancements, or “GLEs”) are seen by neutron monitors; high-energy protons produce neutrons by nuclear interactions in the atmosphere and can reach detectors on the ground. SEP prediction is similar to flares, but not all large flares produce SEPs.

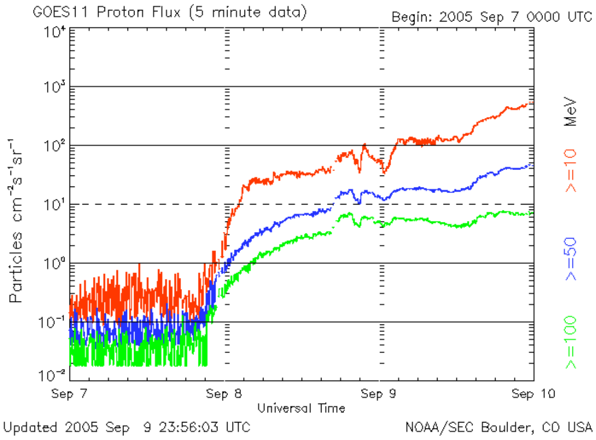


Fig. 6. High energy proton fluxes measured by the NOAA GOES-11 satellite [6].

- Coronal Mass Ejections (CMEs) are large eruptions of mass moving outward from the Sun at ~1000 km/s, generally associated with flares, that take 2-4 days to arrive at Earth and can generate magnetospheric storms. In order to predict the severity of CMEs, one needs to know whether they will strike Earth, and what the magnetic field orientation is. Southerly magnetic fields provide more compression of the Earth’s magnetic field, and compression of the magnetosphere can affect power systems, radiation belts, and ionospheric communication conditions. They may also be progenitors for solar energetic particles.

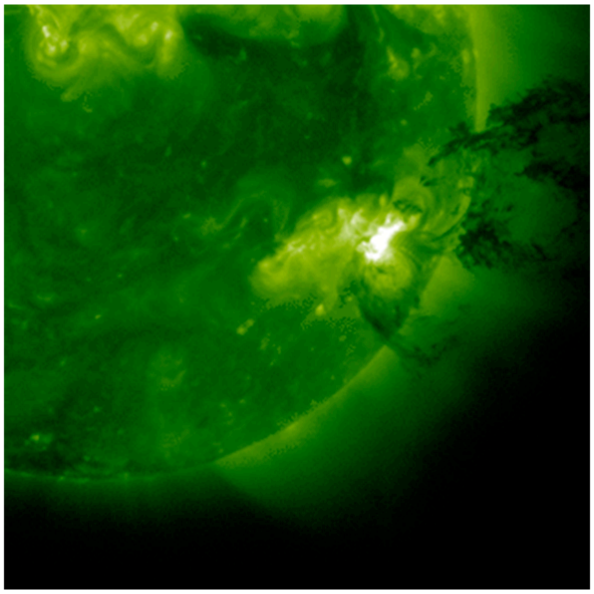


Fig. 7. A CME captured by the Solar Dynamics Observatory (SDO) [6].

- Corotating Interaction Regions (CIRs) arise when fast moving solar wind particles gushing out of a coronal hole (a spot in the sun’s corona where the field lines are not closed) catch a slower flow ahead and the plasma becomes compressed. As the CIRs reach the upper layers of our atmosphere, they can cause high levels of activity in the ionosphere. To date, predictions when CIR events will arrive at Earth have been flawed, in that observations of the features close to the Sun underestimate the speed that they are moving by the time they cross Earth's orbit.

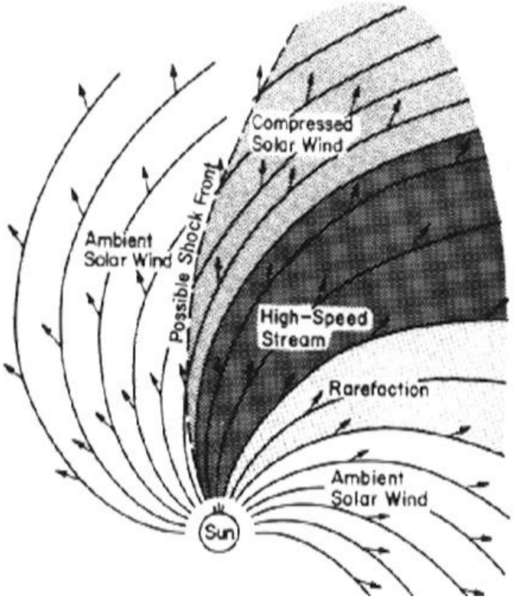


Fig. 8. CIR production in the interplanetary solar wind flow [7].

The effects of Sun-Earth interactions on operations at Earth are many. In the following we group some of them:

- Orbital Drag Predictions for LEO. These depend on the atmospheric neutral density, which depends on the heating experienced by the ionosphere. High heating by high solar activity can lead to errors in satellite orbital predictions. The USAF tries to keep track of all satellites an all detectable orbital debris in order to predict (and mitigate if possible) satellite collisions and to ascribe satellite explosions as due to collisions with other satellites or debris or to hostile acts. Our current model neutral density error is ~15% during geomagnetic quiet times & > 50% during magnetic storms! A data assimilative physical model will reduce orbit prediction error. However, for high accuracy drag models, we must have improved geomagnetic storm formulation and prediction capabilities.
- Scintillation - loss of communication. RF signals are refracted by irregularities in the ionosphere, leading to phase & amplitude variations called scintillation. During quiet times, scintillation will occur mostly at only very high and very low latitudes. However, during magnetic storms, the equatorial ionosphere becomes Rayleigh-Taylor unstable to the formation of plasma bubbles, and scintillation can occur at all latitudes. Scintillation occurs

mainly at night during both quiet and active times, and its intensity depends on F10.7. Its impacts on systems include reducing or eliminating satellite & HF communication options. Real-time targeting depends on "instant" communication, which is compromised when scintillation is severe. Higher bandwidth systems have increased vulnerability. High fluxes of X-rays and SEPS can lead to loss of Communications at high latitudes from polar cap absorption events. And, radio bursts directly interfere with GPS, communications and radar systems.

- Scintillation - Degraded navigation. Ionosphere disturbances degrade GPS systems. This can have severe impacts on DoD systems which rely on a multitude of GPS receivers. Reducing collateral damage depends on accurate precision guided munitions, and this depends on accurate GPS fixes.

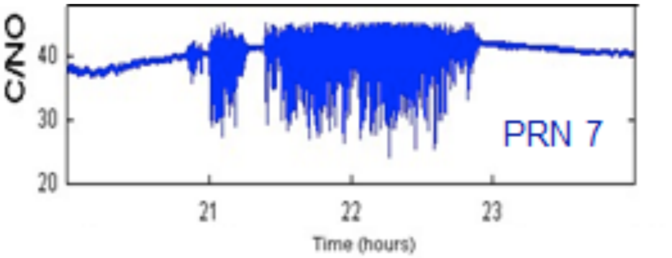


Fig. 9. Scintillation seen in the received signal from C/NOFS, the Communication/Navigation Outage Forecast System satellite [8].

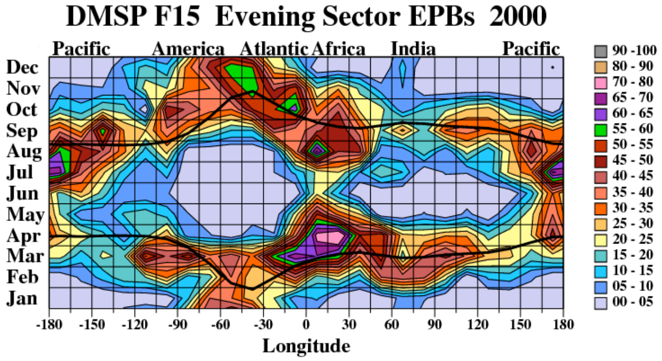


Fig. 10. Scintillation seen using the DMSP satellite as a function of month and longitude during a solar max period. In Spring, severe scintillation was seen on ~75% of nights at longitudes that include Africa and Middle East, hot spots of military operations [9].

In general, geomagnetic storms produce degraded geolocation and a loss of accuracy in Electron Density Profiles and Total Electron Content (TEC). Large gradients in electron density profiles cause geolocation errors. In consequence, surveillance & intelligence applications become difficult. There may be false returns, false targeting, blinding surveillance radars and multiple HF systems. Satellite communications (SATCOM) are also impacted due to signal interference and loss.

- Satellite sensors can be blinded by energetic particle events, and then rapid degradation can set in. For example, Micro Channel Plates (MCPs) can become saturated by MeV and GEV particles that impact them directly. In the real world, Defense Meteorological Satellites (DMSP) which are relied on by military planners and operations personnel have MCP particle detectors which can degrade rapidly from high fluxes and may be degraded or even inoperable after storms. Fig. 11 shows one such event on DMSP-F16.

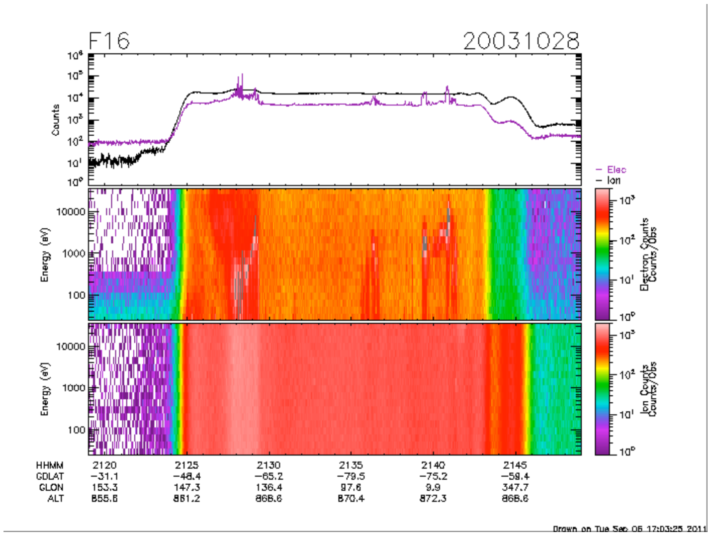


Fig. 11. During an energetic particle event, MCP counts on DSP-F16 were high in both electron and ion channels and the instrument was blinded by high energy particles. There are about 5 such events/solar cycle [8].

- And, finally, arcing can occur on satellites, and has been known to completely debilitate operational satellite systems. The charging of spacecraft, and its role in spacecraft anomalies due to electrostatic discharges, is well known. Charging is caused by energetic particles in the space environment. The main sources of these particles are the Van Allen radiation belts, solar flares and substorms, and galactic cosmic rays. There are two types of charging, surface charging and internal charging, also known as deep dielectric charging.

a) The Nature of Arcing (a Threshold Phenomenon)

In the space environment, satellites are exposed to a constant flux of electrically charged particles. When a charged particle strikes a satellite surface, it can penetrate into the satellite or deposit on the surface. Where it deposits depends on the energy as it hits the surface. Maxwell's equations demand that in steady state the net current to the surface of the satellite be zero. Away from steady state, the charge will quickly build up (redistribute itself) so that the net current drops to zero. As charge accumulates on the surface of a satellite, the potential (electric field) adjusts so that that at each point the net current is zero. If the surface is conductive the current flows along the surface until it becomes an equipotential. If the surface is resistive then it allows an electric field to develop across the surface with differential charge accumulation at different points. All surfaces contain adsorbed material (gases) and if the electric potential across the surface exceeds the breakdown voltage of the surface material or possibly some of the adsorbed material then there will be an abrupt rearrangement of the charge which will be seen as an arc or electrostatic discharge (ESD). Arcs therefore occur when the electric field at a point becomes high enough for charges to be liberated and a cascade of ionization develops. Thus, arcing is a threshold phenomenon in electric field, which translates into a threshold in differential voltages, which is caused by a threshold of charge accumulation being reached.

The sudden flow of electrons across the surface deposits heat and can therefore cause considerable damage. The discharge also is a source of EMI which can lead to spacecraft noise and anomalies. This is surface charging and is caused by low energy electrons of 5-50 keV in GEO, 2-20 keV in PEO, or on high voltage arrays in LEO where low energy electrons may lead to secondary electron emission. These low energy electrons do not penetrate the surface of the material. During the 1970's and 1980's, protection techniques were developed to try to mitigate the surface charging problem. Since anomalies continue to occur on spacecraft, investigation of deep dielectric charging was also required.

b) Surface Arcing vs Deep-Dielectric Discharge

Deep dielectric charging occurs when high energy electrons or ions penetrate the surface of, and deposit charge within, a dielectric material. This is caused by electrons of 200 keV-3 MeV, protons of > 10 MeV, or prompt SEPs or X-rays (which cause internal ionization). If the deposition of incoming charged particles is greater than the charge leakage through the material, a large potential difference can build up in the material and lead to a discharge. The basic problem is that high energy particles from the space environment penetrate the surface of the dielectric material, and lose energy until they stop somewhere within the material. These stopped particles induce an electric field within the material. This electric field causes the particles to move, producing a current in the material. This current in turn influences the electric field. The electric field continues to grow until equilibrium is reached between the flux of incoming particles and the particle flux leaving due to the current. If the electric field exceeds the dielectric strength of the material before equilibrium is reached, a breakdown and subsequent electrostatic discharge occurs.

c) The Case for Arcing as the Source of Satellite Anomalies

Several spacecraft failures have been associated with electrostatic discharges resulting from deep dielectric charging, including the $300 million Telesat Canada communications satellites ANIK E1 and E2, and the ESA spacecraft Olympus. Other spacecraft have experienced switchings or anomalies due to electrostatic discharges resulting from deep dielectric charging, including Intelsat K, ECS-2 and ECS-4, and the Combined Release and Radiation Effects Spacecraft (CRRES). It should also be noted that while some spacecraft have been affected by deep dielectric charging, other spacecraft of similar design and in operation at the same time have not been affected. This may be due to aging of spacecraft materials, differences in environment with longitude or local time in orbit, or to the stochastic nature of arcing itself.

In some cases, spacecraft telemetry of housekeeping data can identify the reason for an anomaly. In other cases, detection of arcing EMI or arc effects can give a positive identification. In the vast majority of cases, however, statistics must be used to identify the source of spacecraft anomalies, as most satellites do not carry arc detectors or environmental diagnostic instruments.

IV. ANALYZING SPACECRAFT ANOMALIES

A. When and Where GEO Satellites Fail

1) Where GEO Satellites Fail Due to Spacecraft Charging

In Fig. 12, a plot of anomalies is shown for four different GEO satellites. The data were obtained from [10]. It is typical for surface charging anomalies to be concentrated mainly in the midnight to morning sector of the orbit (local time, or LT from 0 hrs to 6 hrs). There are several reasons hypothesized for this. One is that geomagnetic substorms start at about the midnight point and proceed counterclockwise around the magnetosphere because of their origin in reconnecting stretched out antisolar field lines. We will see another reason when we discuss the influence of eclipses on satellites. Deep-dielectric charging is not restricted to any specific orbital position, in keeping with the relative transparency of the magnetosphere to high energy electrons and protons at GEO altitudes. Thus, arcs on solar arrays, instruments, or payloads exposed to the space environment will be concentrated to morning LT's and arcs in shielded electronic boxes or underneath spacecraft thermal blankets will not be restricted to any particular LT values.

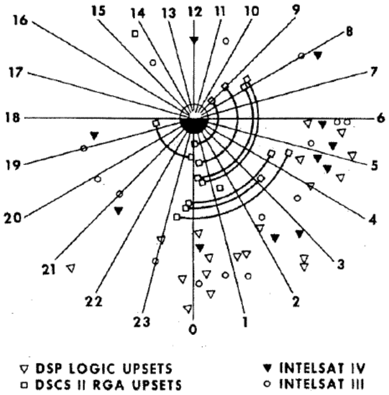


Figure 3. Local time dependence of anomalies observed on geosynchronous satellites.

Fig. 12. Fig. 3 of [10], showing the LT dependence of primarily surface arcing anomalies.

2) When GEO Satellites Fail

a) Number of GEO Satellites – A Normalizing Factor

Fig. 13 shows a plot of the number of operational GEO satellites. If we wish to investigate the solar cycle dependence of satellite anomalies, we must use the number of operational satellites as a normalizing factor, else we'll be misled into believing the frequency of anomalies is increasing.

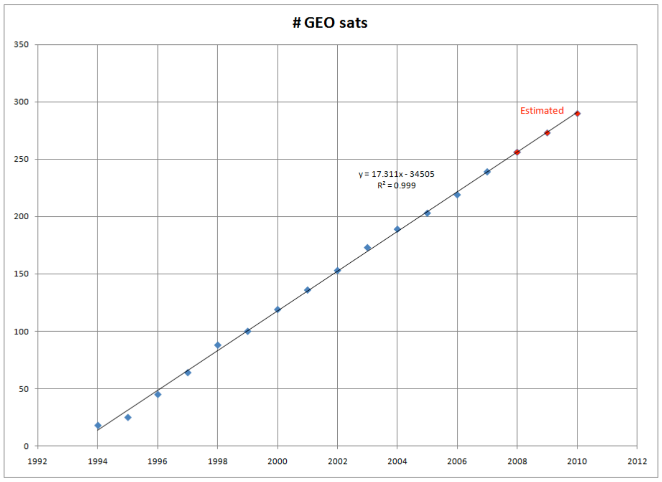


Fig. 13. The normalized number of GEO satellite anomalies versus month of year for 1994-2010. The data were obtained from Satellite News Digest [12].

b) Eclipse Seasons (near the Equinoxes)

Surface arcing anomalies are concentrated toward times near the equinoxes for two reasons. First there is the Russell-McPherron effect [11], a geometrical effect making it easier for the CME and solar wind plasma to enter Earth's magnetosphere at those times of year. Secondly, GEO satellites only go into the Earth's shadow when the sun is near the celestial equator, near the equinoxes. This has two effects. Firstly, the satellites are cold in eclipse, increasing dielectric resistivities, and secondly, the lack of sunlight on spacecraft surfaces prevents photoemission, a key satellite discharging factor, during eclipses. Then, when a satellite comes out of eclipse, its surface dielectrics have higher than normal resistivities (and thus higher electric fields), are charged up a great deal, and then photoemission from sunlit surfaces partially discharges them, producing high differential voltages with surfaces in shade. Such effects can be modeled with modern spacecraft charging codes, such as *Nascap-2k.*

Fig. 13 shows the normalized number of GEO satellite anomalies versus month of year for 1994-2010. The data were obtained from Satellite News Digest [12]. The effect of eclipse seasons is clearly seen in this chart. The anomalies that show this type of behavior are predominantly surface charging anomalies.

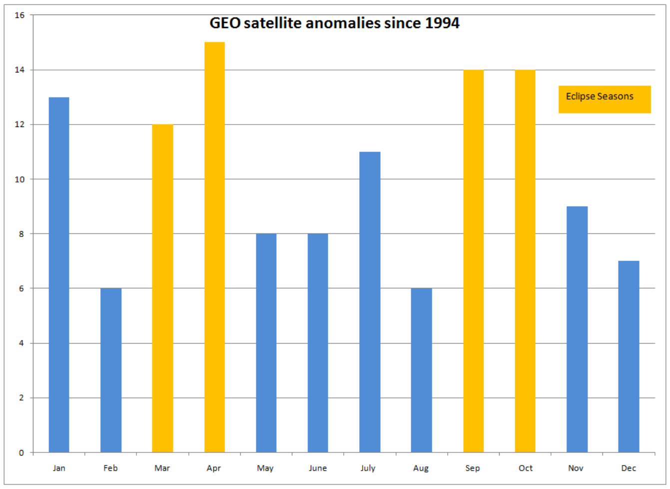


Fig. 13. Non-mechanical GEO satellite anomalies from 1994-2010.

a) Dependence on Type of Anomaly

Although Fig. 13 shows all types of anomalies, the correlation with season is even stronger when anomalies of payload, power, and control processors are plotted, as in Fig. 14. Here, the data are from the SpaceTrak database [14]. Rates of these anomalies during eclipse seasons are 50-90% higher than outside eclipse seasons.

Some space weather-caused anomalies are not due to surface charging and surface ESD. These deep-dielectric discharges typically affect different spacecraft systems than do surface discharges. The types of these anomalies may be primarily those on mechanisms, beam antenna, telemetry, and attitude control. They show no special dependence on season.

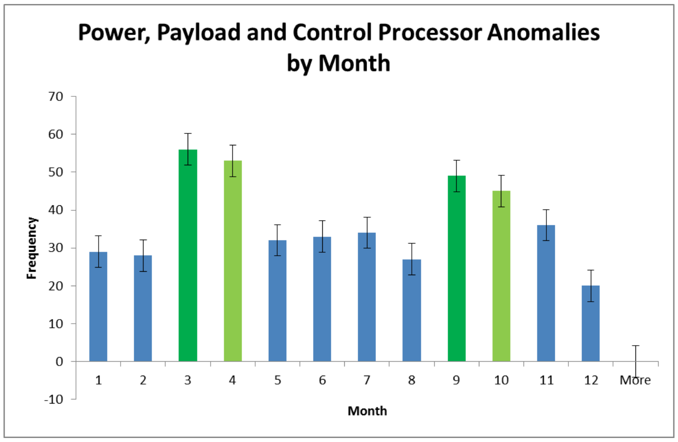


Fig. 14. Power, payload and control processor anomalies on GEO satellites through 2013. Green months are eclipse seasons.

Wong [15] has shown that the seasonality of upsets on GPS satellites does not follow the pattern above, and thus presumably includes a sizable contribution of non-surface charging anomalies.

b) *Solar Cycle*

Just as the Sunspot Number varies throughout the solar cycle, so does the number of spacecraft anomalies. In Fig. 15 is a plot of yearly normalized numbers of spacecraft anomalies, the yearly averaged Sunspot Number, and the yearly number of days of Kp ≥ 6 for 1994-2010. Here it is obvious that satellite anomalies roughly follow the sunspot cycle with pronounced minima at sunspot minima. All types of anomalies are included, because surface charging and dep-dielectric charging are both related to the solar activity.

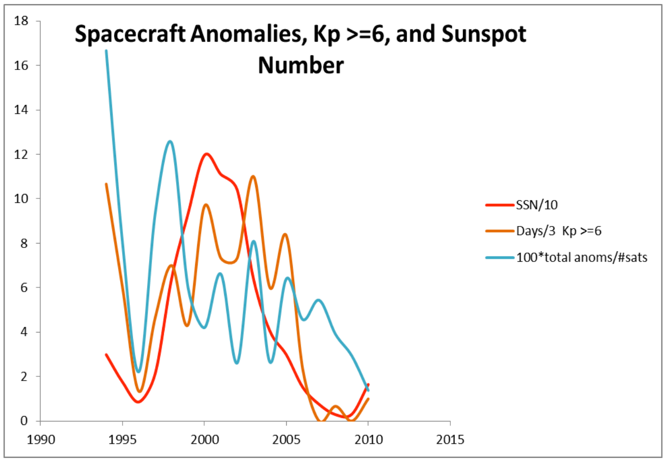


Fig. 15. Yearly normalized numbers of spacecraft anomalies, yearly averaged Sunspot Number, and yearly number of days of Kp ≥ 6 for 1994-2010.

c) *Correlation with Kp ≥ 6*

The normalized yearly number of GEO spacecraft anomalies is significantly correlated with the yearly number of days with moderate geomagnetic storms (Kp ≥ 6), as shown in Fig. 16. This is consistent with the threshold nature of arcing, and implies that spacecraft surface charging may not be sufficient to produce arcing for Kp < 6.

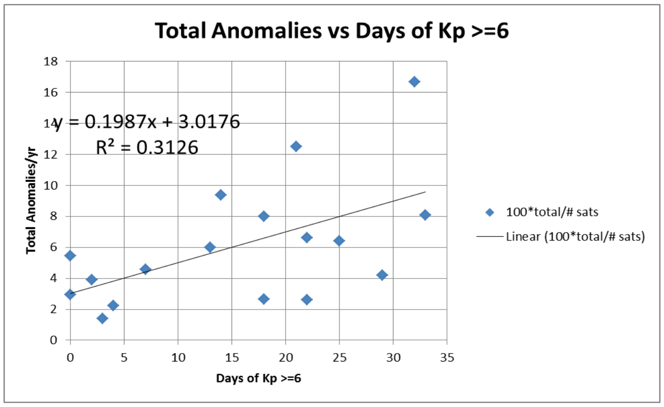


Fig. 16. Normalized yearly GEO satellite anomalies versus the yearly number of days with Kp ≥ 6 (a moderate geomagnetic storm) for 1994-2010.

d) *Correlation with Kp High All Day*

While surface charging and arcing follows electron fluxes closely, deep-dielectric charging for unshielded cabling may depend more closely on fluences over a time period of a day or more. As is shown in Fig. 17, the normalized yearly number of GEO spacecraft anomalies is also significantly correlated with the yearly number of days with the sum of all Kp periods being 35 or more. That is the sum of all eight 3 hour periods in the UT day. This implies an average Kp for the entire day of ~ 4.4 or more may provide enough energetic particle fluence for some interior charging to produce arcing conditions. This is consistent with the recommendations of Garrett and Whittlesey, a 10 hour fluence threshold.

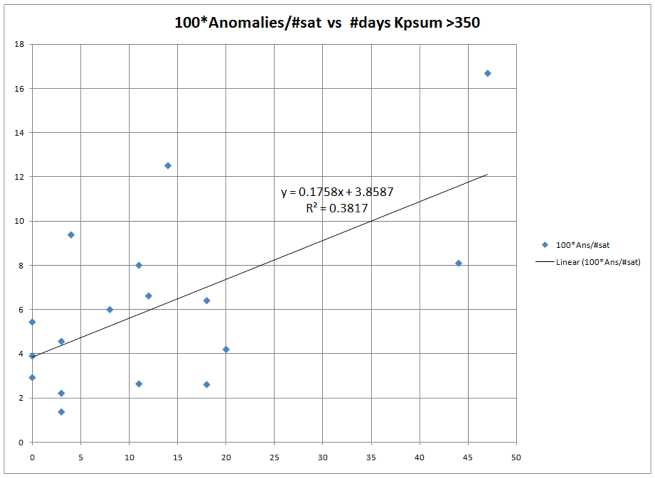


Fig. 17. Yearly normalized numbers of GEO satellite anomalies versus yearly number of days with Kp sum > 35.0 for 1994-2010.

e) *Fluences of "Killer Electrons"*

For some satellite anomalies, such as deep-dielectric discharges inside shielded "Faraday" cages, as recommended in NASA-HDBK-4002a and NASA TP-2361, electrons of > 2 MeV or protons of > 10 MeV are required to penetrate the shielding. J. Allen [16] has termed such highly energetic electrons "killer" electrons. M. Bodeau has [17] published a plot showing that for some of these anomalies, a charge bleedoff time of weeks or months is needed to produce a fluence that causes these anomalies. Fig. 18 is one version of that plot. In other words, charges may build up for days, weeks, or months inside spacecraft interiors and eventually lead to electric fields high enough for breakdown. Ferguson et al [18] have shown that for cold dielectrics, charge may even build up for years and eventually cause discharges.

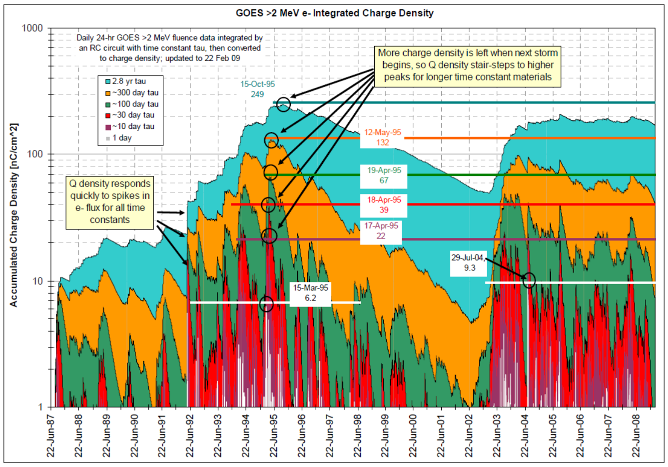


Fig. 18. Spacecraft anomalies with different accumulated charge thresholds and time constants for charge bleedoff.

f) Very Dangerous Periods

- Eclipse Seasons (equinoxes) – satellites charge more in eclipse (no photoemission, cold conditions)
- Equinoxes – Russell-McPherron Effect – Interplanetary Magnetic Field (IMF) couples to magnetosphere better
- Time of Day – anomalies prefer the morning-side after eclipse (differential discharging from photoemission)
- High Max Kp – Days of Kp >~ 6 are most dangerous
- Extended Periods of High Kp – Days of Kp Sum > 35 are most dangerous
- Immediately following X-class flares
- 2-4 days following a CME on the Sun, or when a CIR reaches Earth
- After prolonged periods (months or years) of high energy (> 2 MeV) electron flux spikes

V. CLASSIC EXAMPLE – GALAXY 15 ANOMALY

A much studied recent spacecraft anomaly was that of the Galaxy 15, a commercial GEO satellite using the Star Bus built by Orbital Sciences Corp. and used to relay DirecTV programs. In April, 2010, immediately following impact of a CME with Earth's magnetosphere, Galaxy 15 stopped accepting commands from its controllers and, because station-keeping could not be maintained, started drifting around GEO orbit. Unfortunately, it was still capable of relaying any TV signals it received back to Earth, and it became a source of interference for all other GEO satellites it happened to pass. Also, housekeeping functions were unimpaired, so it maintained power and "operations" until its momentum wheels finally saturated in December, 2010 and it underwent a reset and became operational once more. Although the cause of the anomaly remains officially proprietary, it was clearly caused by the space environment because of the timing of the failure. In what follows, we recount what was known by the authors as of January, 2011 [19].

A. *Generic Spacecraft Nascap-2k Model*

In order to estimate the charging that occurred on Galaxy 15 in a non-proprietary manner, a generic *Nascap-2k* geometrical model was used that incorporates many features of commercial GEO satellites. It is shown in Fig. 18. In the *Nascap-2k* modeling, the uneclipsed sun was allowed to impinge on the solar cells, and in eclipse the sun was "turned off." Materials properties were the default values for *Nascap-2k.* The satellite environment history was kindly furnished by J. Rodriguez as measured by the NOAA GOES-13 and GOES-15 satellites. We assume that Galaxy 15, only about 30 degrees in longitude from the nearest GOES satellite, experienced the same electron and ion environment.

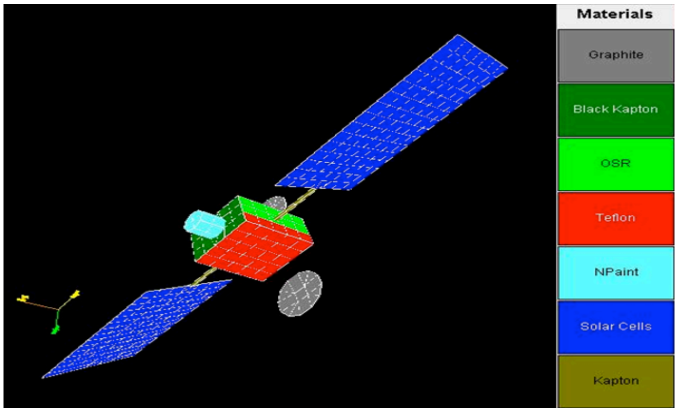
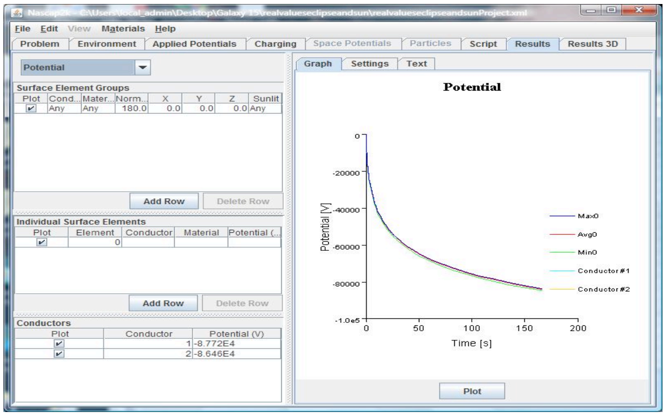


Fig. 18. The generic Nascap-2k geometrical model used to estimate charging on Galaxy 15.

B. *Nascap-2k Model Charging History During Galaxy 15 Eclipse*

In the case of Galaxy 15, the geomagnetic storm impacted the magnetosphere while the satellite was in eclipse. At the height of the storm, the temperature moments calculated from GOES-15 electron flux measurements were the highest on record, a huge 10^9 K (86.4 keV) temperature, but the electron densities were relatively low (< 0.084 cm^{-3}).

Using these parameters, and assuming an initially uncharged, spacecraft, we obtained in Fig. 19 a plot of the history of spacecraft charging for our "generic" Galaxy 15 in eclipse.



Surface Element Groups

Plot	Cond...	Mater...	Norm...	X	Y	Z	Sunlit
☑	Any	Any	180.0	0.0	0.0	0.0	Any

Individual Surface Elements

Plot	Element	Conductor	Material	Potential (...
☑	0			

Conductors

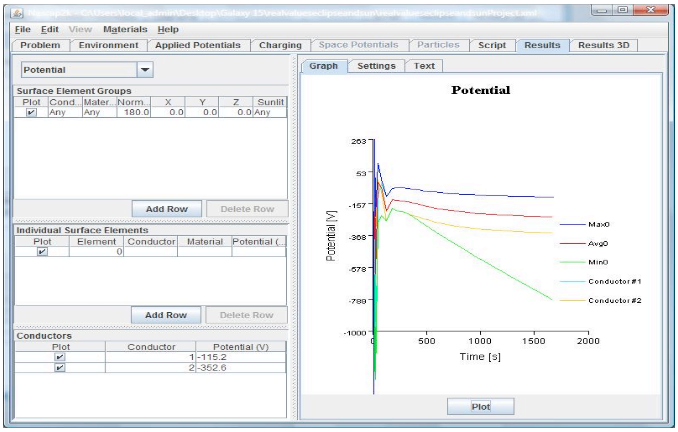
Plot	Conductor	Potential (V)
☑	1	-8.772E4
☑	2	-8.646E4

Fig. 19. Charging history of a "generic" spacecraft in the Galaxy 15 eclipse environment.

After only 200 seconds of charging, the spacecraft would have reached a whopping -87,000 V potential with respect to the surrounding plasma, and would have achieved at least a 1200 V differential potential between its body and solar array wings.

C. *Charging History after Galaxy 15 Eclipse to Time of Anomaly*

Fig. 20 is the time history of charging for the "generic" Galaxy 15 satellite, in sunlight after eclipse, starting from the last eclipse values and continuing for 1800 seconds (1/2 hour), the time after eclipse when the Galaxy 15 event occurred. For this period a constant plasma was assumed with the density and temperatures at the time of the event.



Potential

Surface Element Groups

Plot	Cond...	Mater...	Norm...	X	Y	Z	Sunlit
☑	Any	Any	180.0	0.0	0.0	0.0	Any

Individual Surface Elements

Plot	Element	Conductor	Material	Potential (...
☑	0			

Conductors

Plot	Conductor	Potential (V)
☑	1	-115.2
☑	2	-352.6

Fig. 20. Charging history of a "generic" spacecraft in the Galaxy 15 post-eclipse environment.

Finally, from the potentials on spacecraft surfaces shown in Fig. 20, it can be seen that the maximum differential potential achieved before the event was about 700 V, well within typical arcing range for GEO spacecraft.

D. *The Case for Electrostatic Discharge (ESD) on Galaxy 15*

It is almost a complete certainty that the Galaxy 15 event was due to electrostatic discharge. Among the telling signs are the following:

- The event occurred during and eclipse season,
- A rare strong geomagnetic substorm (Kp > 7) hit while Galaxy 15 was in eclipse,
- A record high electron temperature (> 4 times NASA worst-case) probably led to record high absolute charging levels (*Nascap-2k* modeling),
- The anomaly occurred a short time after eclipse exit, a time of many other spacecraft ESD related anomalies over the years,
- The MLI blanket-penetrating (NIST codes) electron fluence at energies E > 200 keV was above the threshold level (NASA-HDBK-4002a) for deep dielectric discharge, and
- Modeling shows that surface differential potentials were probably above the threshold level for plasma arcing.

VI. A FEW SEVERE SATELLITE ANOMALIES AND THEIR PROBABLE CAUSES

Although catalogs of spacecraft anomalies run into the thousands of events, and untold numbers of anomalies are not severe enough to be reported or operational work-arounds have prevented their reporting, a few notable recent anomalies stand out:

- Anik E-1 and E-2 (1994) – deep dielectric electron charging during severe geomagnetic storm led to communications disruptions lasting for days
- Tempo-2 and PAS-6 (1997) – sustained arcs from geomagnetic substorm ESDs caused complete Loss of Mission (LOM)
- ADEOS-2 (2003) – micrometeoroid strike during auroral charging event caused complete LOM (loss of mission)
- Galaxy 15 (2010) – ESD caused electronics problem coming out of eclipse during severe geomagnetic substorm, recovered after 8 months adrift
- DMSP-15 (2011) – computer upset after large total internal dose from X-class flare X-rays
- Echostar 129 (2011) – temporary (24 hr) pointing/positioning loss after huge peak in GOES > 2 MeV ("killer') electrons
- SkyTerra-1 operated by LightSquared (March 7, 2012) – knocked out for 3 weeks due to SEU caused by energetic protons & CME
- Other March 2012 anomalies – Venus Express, HughesNet-Spaceway 3

VII. SPACE SITUATIONAL AWARENESS

According to the 2010 National Space Policy [20] and the 2011 National Security Space Strategy [21] space situational awareness is a key goal for the US Department of Defense (DoD). The DoD must determine, in real-time if possible, whether anomalies are due to the Space Weather or to hostile actions. Also, operations may be affected by efforts to prevent space weather-related outages, so Space Weather prediction and real-time anomaly resolution very important to US Security.

The military has long relied on long-range communications as have key commercial concerns such as banking. Both the US and German air forces understood the potential impact of space weather on communications during World War II. Indeed, the US Air Force established a Geophysics Directorate soon after it founded its first laboratory, the Air Force Cambridge Research Laboratory, in the late 1940s and then (1952) set up the Sacramento Peak Observatory to study solar effects on the environment relative to Air Force operations. Today these Space Weather research units have evolved into the Air Force Research Laboratory's Battlespace Environment Laboratory (AFRL/BEL) the Solar Optical Observing

Network (SOON) and the National Solar Observatory (NSO). Space weather remains a major concern for all aerospace operations today. But there are several particular aspects of space weather that warrant particular attention now.

As the military faces increased competition for scarce resources it has turned to commercial and private sector assets to supplement, and even replace military capabilities. This is particularly true in communications, whether space-based, ground-based or internet-based. We are now also relying on civil and commercial space services for crucial data such as imagery. However, these commercial assets seldom have the same degree of protection that military systems do. They tend not to be designed to be as effective as military systems against either man-made or natural threats such as space weather. Additionally, the economy upon which US strength is based is increasingly dependent, and vulnerable to space weather effects. It's clear that a major event such as the 1859 Carrington effect would devastate civil and military communications, as well as potentially destroy the global economy. It has been estimated that a Carrington event now could blow out thousands of transformers on the nation's power grid, and it would be months before replacements could be put into place and full electrical power could be restored. And the probability of extreme events is not insignificant. On July 23, 2012, the Sun launched a CME that, had it been directed at Earth, is estimated to have been as severe as the 1859 Carrington event [22].

However, there are potentially devastating problems at much lower levels of space environmental disturbances. A recent paper by Schrijver and Rabanal [23] shows that commercial users believe they could use space weather data to mitigate more routine, but nonetheless serious impacts to routine services such as GPS positioning and even commercial power.

Data now emerging shows that many routine outages on such utilities as the power grid are highly correlated with routine space weather activity. Even the rate of lightning strike during storms has been correlated with space weather activity [24]. This raises an additional concern. Today, routine problems with the internet are often difficult to distinguish as to origin – is it manmade or natural? A significant attack or degradation in critical services could be masked by space weather disturbances. It may take some time, and a deliberate attack could do significant damage before its true nature was discerned. It's thus crucial to much better understand and predict the specific impact of space weather on routine operations, particularly commercial and civil systems we are increasingly dependent upon.

VIII. PREVENTING AND MITIGATING ANOMALIES

A. *How to Design to Prevent Space Weather Charging-Related Anomalies*

There are many ways to design spacecraft to prevent space weather charging-related anomalies. Among them are the following:

- Harden all vital electronics and place in well-shielded Faraday cage (0.5 mm of Al or greater, NASA TP-2361 [25], NASA-HDBK-4002a [26])
- Use grounded conductive surface coatings everywhere (with high secondary electron emission and low photoemission, if possible), even on solar arrays, to prevent differential surface charging (per Shu Lai, 2011, "Spacecraft Charging" [27])
- No ungrounded or unshielded conductors (Galaxy 15 failure mechanism, NASA TP-2361), including for attached payloads
- Use a well validated spacecraft charging code – SPIS (ESA), MUSCAT (JAXA), or *Nascap-2k* (USAF, NASA)
- Design and test arrays to prevent ESDs and sustained arcs (Tempo-2 failure mechanism, NASA-STD-4005 [28], NASA-HDBK-4006 [29], ISO 11221 [30])
- Use accelerated life testing to ensure that end-of-life (EOL) materials properties are the same or better than at the beginning-of-life (BOL), so surface charging may be prevented throughout the spacecraft life
- Design spacecraft to prevent deep dielectric discharges (NASA-HDBK-4002A)
- Stop flying blind. Include small, lightweight internal charge and/or surface charge monitors in spacecraft designs, as was done with some Intelsat satellites, so that hazard warnings can be issued and evaluated in real time, allowing sensitive electronics to be put in safe mode as needed and if possible

B. *Operations to Mitigate Space Weather-Related Satellite Anomalies*

- Upload software that resets after SEUs. This would have mitigated Galaxy 15 and SkyTerra-1.
- Monitor space environments and charging predictions from real-time spacecraft charging models, the Space Weather Prediction Center (SWPC), the Air Force Weather Agency (AFWA), The Space Environmental Anomalies Expert System, Real-Time (SEAESRT) [31], etc.
- When severe Space Weather is predicted, turn off sensitive electronics if possible, such as thrusters, focal-plane arrays, MCPs, electronic latching relay circuits, etc.
- Shunt arrays (or in LEO feather them into the wake) when severe charging is likely and/or when coming out of eclipse.

C. *Techniques to Mitigate Space Weather-Related Earth Problems*

1) Use "Smart-Grids" to route power around problems
2) Have plenty of spare high voltage transformers on-hand
3) Reduce absolute reliance on satellite systems
4) Have backup systems in place for:
    a. Time-keeping (atomic clocks),
    b. Communications (cell phones, microwave towers),
    c. Geolocation (celestial navigation, dead-reckoning),
    d. Power (emergency generators, batteries, hydroelectric, solar, wind)
    e. Currency (cash vs ATM or credit cards)

IX. SPACE WEATHER - SUMMARY

Space Weather is important to our technological civilization. All major societal systems are affected by space weather, on Earth and in space. Space Weather will get worse before it gets better. Solar Max is happening right now, and Satellite Anomalies due to Space Weather are more common after the sunspot peak. Proper designs and suitable operations can mitigate space weather effects on Earth and in space. Eventually, Earth will experience another "Carrington event." We need to get ready now for when more failures and anomalies occur.

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