OOPS! WE HAVE A PROBLEM! SPACECRAFT CHARGING-RELATED ANOMALIES FROM DSCS-II TO GPS

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ABSTRACT

Since the early 1970's, spacecraft have experienced on-orbit spacecraft charging-related anomalies. Despite various major design changes, such anomalies persist to the present day. In this paper, I discuss my personal experiences with anomaly investigations at NASA and AFRL, give a brief discussion of the types of anomalies and the physics involved, how anomaly investigations should properly proceed, discuss lessons learned and how they have been and continue to be expressed in Standards, Guidelines, and Handbooks, and try to show the way forward for spacecraft design and operations.

1. SOME SATELLITE ANOMALIES (1974-PRESENT):

- ❖ DSCS-II (1974) - surface discharges on eclipse exit seen as commands for spin-despin rate control.
- ❖ Marecs-A (1981) - surface discharges caused switching errors on attitude control.
- ❖ Anik E-1 and E-2 (1994) – deep dielectric electron charging during severe geomagnetic storm led to communications disruptions lasting for days.
- ❖ TSS-1R (1996) - sustained arc in LEO from vxB voltage on 20 km tether.
- ❖ 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.
- ❖ Recent SSPA failures (1996-2012) – power amp failures from 14 day fluences of >2 MeV (“killer”) electrons.
- ❖ Recent MUX failures (2010-present) – telemetry failures from 3 day fluences of >2 MeV (“killer”) electrons.
- ❖ GPS power degradation (1979-present) - contamination from solar array arcing?

2. SPACE WEATHER IMPACTS ON SATELLITES

Why are satellite disruptions (“anomalies”) important? 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?

- Power (solar arrays and batteries)
- Housekeeping (temperatures, battery status, etc)
- Telemetry and high-power communications
- Position and Attitude Control
- Propulsion
- Payloads

3. SPACECRAFT CHARGING RELATED ANOMALIES

Sources:

- ☐ **Spacecraft Surface Charging**
  May cause electrostatic discharges (ESDs) and arcing on solar arrays, power cables. Caused by electrons of 9-50 keV in GEO, 2-20 keV in PEO, or high voltage arrays in LEO. Threshold in electric field from differential charging.
- ☐ **Deep Dielectric Charging**
  May cause arcing internally to spacecraft. Caused by total dose of electrons of 200 keV-3 MeV, protons of > 10 MeV, or prompt SEPs or X-rays. Threshold in electric field from internal charging. Single Event Upsets (SEUs) caused by ionization trail of single high energy particles in sensitive electronics.

Types:

☐ **Transient effects** (bit flips in electronics, EMI, causing spurious commands or software upsets).

☐ **Permanent damage** (arcs, ESDs, and MCP saturation, may damage electronics, contaminate solar arrays and/or cause power cabling or solar array failure).

4. SPACECRAFT SURFACE CHARGING-RELATED ANOMALIES – SURFACE, TRANSIENT

☐ DSCS-II (1974) - surface discharges on eclipse exit seen as commands for spin-despin rate control.

☐ Marecs-A (1981) - surface discharges caused switching errors on attitude control.

☐ Galaxy 15 (2010) – ESD caused electronics problem coming out of eclipse during severe geomagnetic substorm, recovered after 8 months adrift.

5. SPACECRAFT SURFACE CHARGING-RELATED ANOMALIES – SURFACE, PERMANENT

☐ TSS-1R (1996) - sustained arc in LEO from vxB voltage on 20 km tether.

☐ 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 led to sustained arcing and caused complete LOM.

☐ GPS power degradation (1979-present) - contamination from solar array arcing?

6. SPACECRAFT CHARGING-RELATED ANOMALIES – ALL TYPES

☐ Maximum Differential Charge = Maximum Electric Field ≠ Max Flux.

☐ Differential Charge builds due to electron incident flux (especially flux at E > 9 keV).

☐ Differential Charge bleeds off due to material conductivity.

$$\tau = \varepsilon_0 \kappa \rho,$$

where τ is the 1/e time constant, ε_0 is the permittivity of free space, and ρ is the bulk resistivity.

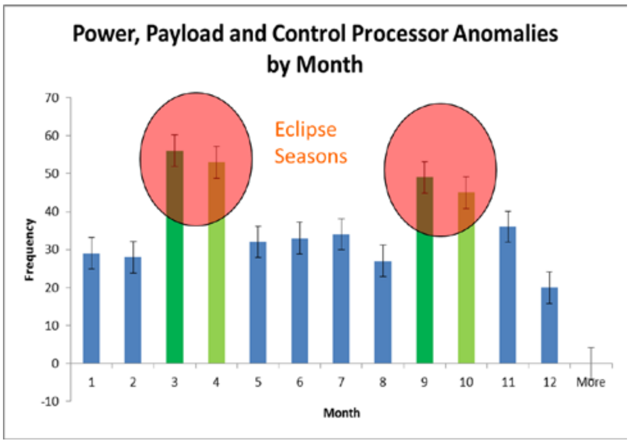
☐ Coverglass resistivities give timescales of hours or days, ceramics give timescales of days, and Teflon and FR4 (circuit-board material) give timescales of months.

☐ Thus, the peak charging comes some time after the peak fluxes.

- True both for surface charging and deep dielectric charging.

☐ For surface charging in GEO, peak electron fluxes come shortly after midnight, but coverglass peak charging comes a few hours later.

7. WHEN GEO SATELLITES FAIL – ECLIPSE SEASONS (NEAR EQUINOXES)



8. SPACECRAFT SURFACE CHARGING-RELATED ANOMALIES – DEEP, TRANSIENT

☐ Anik E-1 and E-2 (1994) – deep dielectric electron charging during severe geomagnetic storm led to communications disruptions lasting for days.

☐ 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.

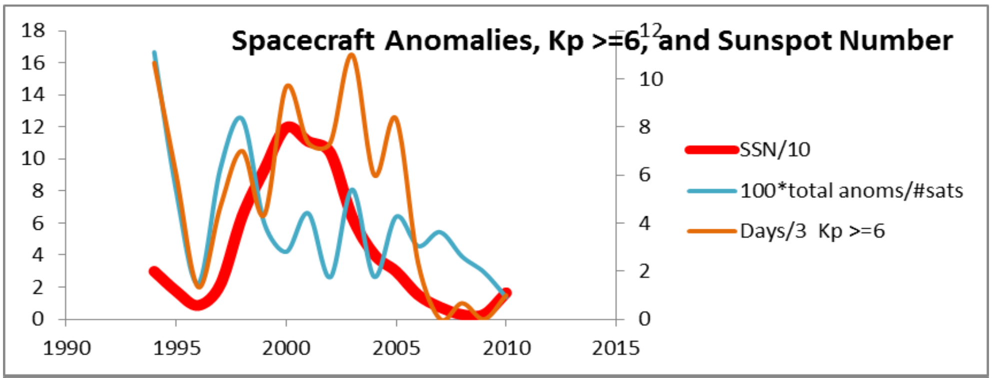
☐ SkyTerra-1 operated by LightSquared (March 7, 2012) – knocked out for 3 weeks due to SEU caused by energetic protons & CME.

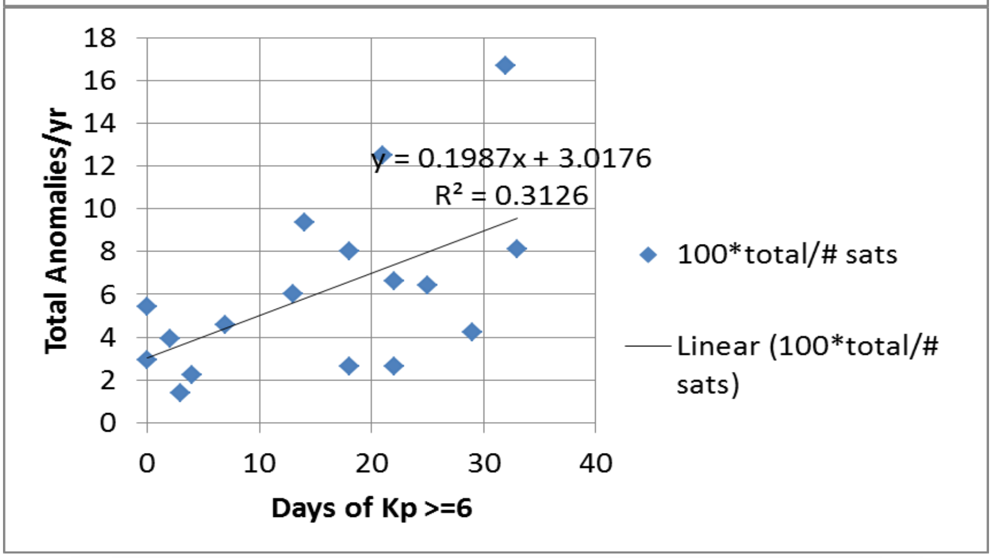
9. SPACECRAFT SURFACE CHARGING-RELATED ANOMALIES – DEEP, PERMANENT

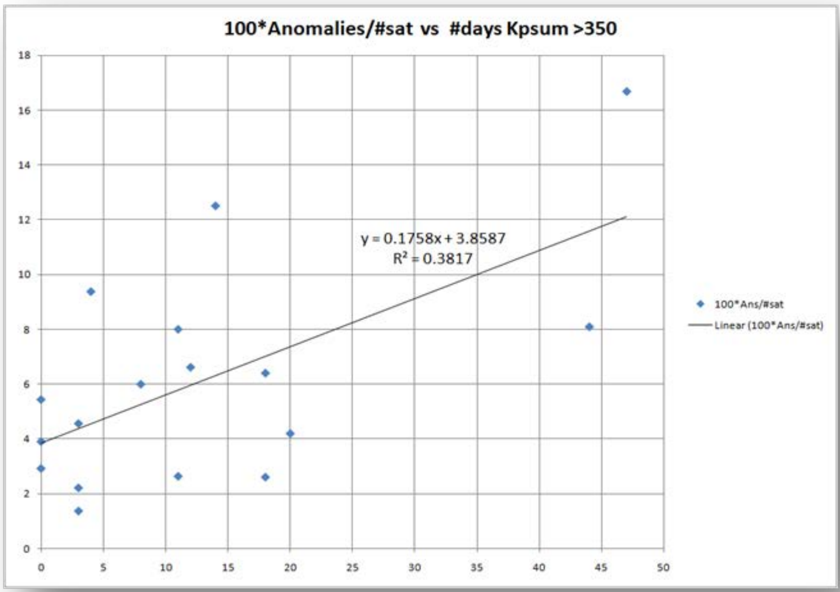
☐ Recent SSPA failures (1996-2012) – power amp failures from 14 day fluences of >2 MeV (“killer”) electrons.

☐ Recent MUX failures (2010-present) – telemetry failures from 3 day fluences of >2 MeV electrons.

10. WHEN GEO SATELLITES FAIL - CORRELATIONS W/ SUNSPOT CYCLE, KP ≥ 6 AND KP HIGH ALL DAY







11. WHEN GEO SATELLITES FAIL – VERY DANGEROUS PERIODS

☐ Eclipse Seasons (equinoxes) – satellites charge more in eclipse (no photoemission), Russell-McPherron Effect – IMF couples to magnetosphere better
☐ Time of Day – anomalies prefer the morning-side after eclipse (differential discharging from photoemission, high density plasma)
☐ High Max Kp – Days of Kp >~ 6 are most dangerous
☐ Extended Periods of High Kp – Days of Kp Sum > 35 are most dangerous
☐ 2-5 days following a CME on the Sun, or when a CIR reaches Earth
☐ After prolonged periods (days, weeks, months or years) of high energy (> 2 MeV) electron flux spikes

12. SATELLITE ANOMALIES – SUMMARY

☐ Recent satellite anomalies are more commonly deep-dielectric charging than surface charging
☐ Many transients are commonly filtered out of sensitive circuits
☐ Good thing – upsets are more infrequent
☐ Bad thing – no evidence of frequency of occurrence of transients
☐ Mitigation strategies exist against all types of environmentally related anomalies
☐ If using conductive coatings or bleed-paths, must make sure they are permanently grounded by continuity testing after vibration testing
☐ Perfect insulators are perfectly awful!
☐ Key tradeoff for deep dielectric charging – mass of shielding versus probability of discharge disrupting sensitive electronics
☐ Standards, standards, standards – read and use them!