Recent End User Experience with High Energy GOES Electron Data

THE VALUE OF PERFORMANCE.

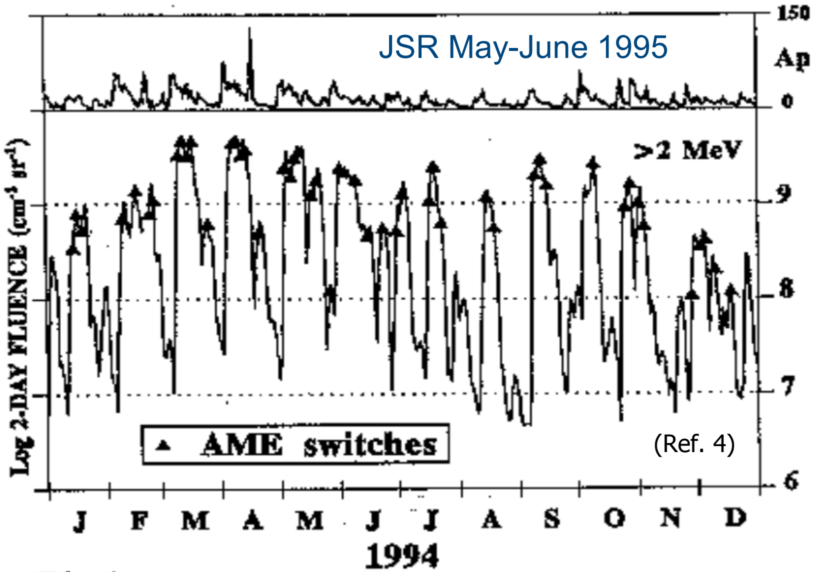
NORTHROP GRUMMAN

Deep Charging Study

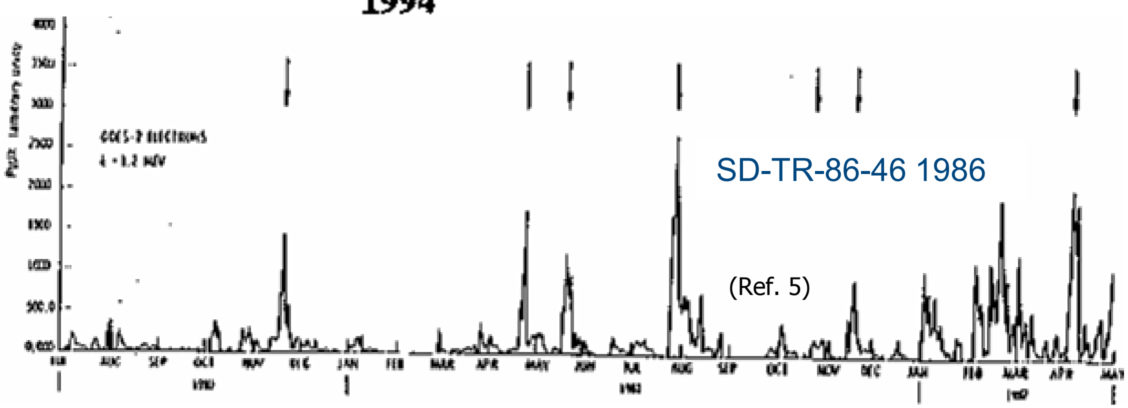
Sept. 5, 2017

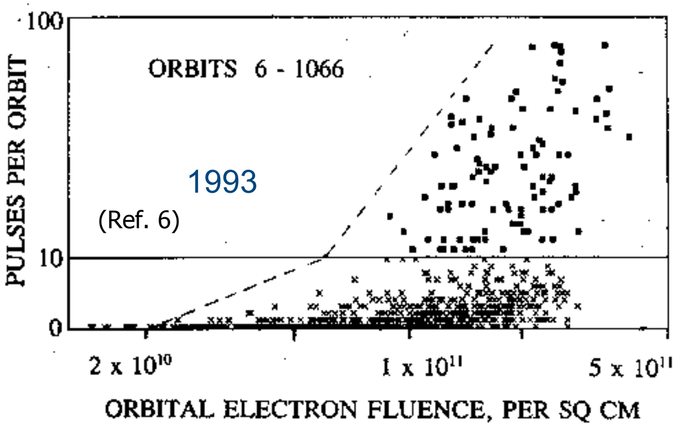
Michael Bodeau
Tech Fellow

Backgound: Anomalies Correlate with Short Term Peak Energetic e- Flux



- Many spacecraft anomalies correlate with peaks in external flux of energetic penetrating electrons
- 10-hr, 24-hr and 48-hr average external fluxes have been used in these correlation studies (internal flux not disclosed)
- NASA HDBK 4002 recommends a "safe" limit to peak internal flux of <100fA/cm^2, and provide a worst-case (several hour averaged) external flux for GEO

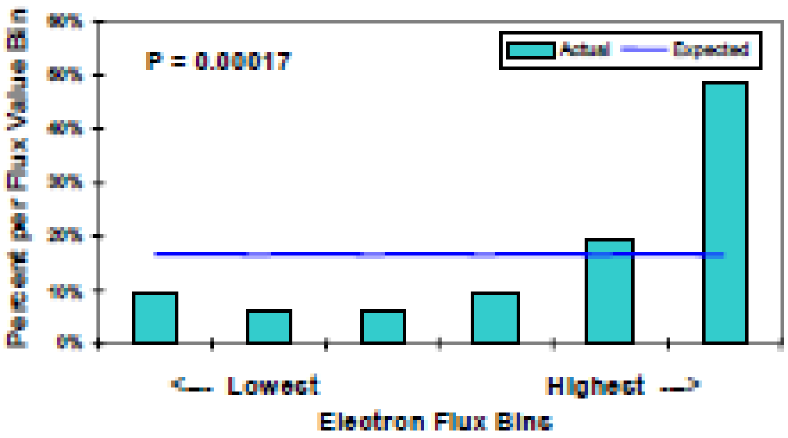


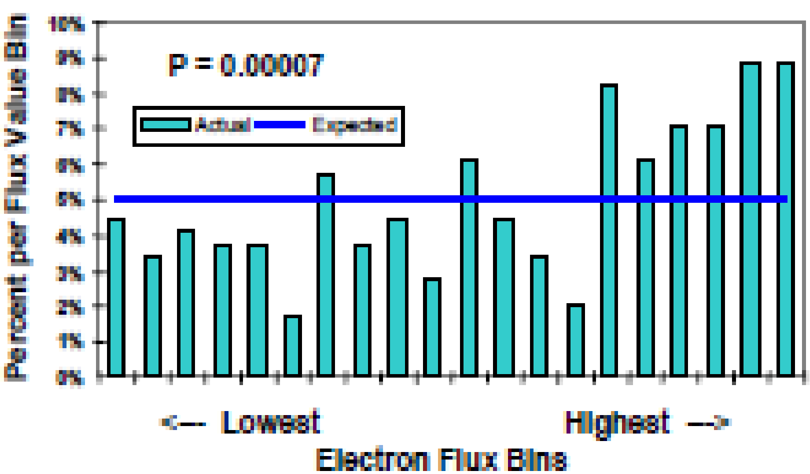


Correlation Is Not Causation & Does Not Support Design

Strong Statistical Evidence Exists That Anomalies Correlate with Energetic e- Flux

NORTHROP GRUMMAN



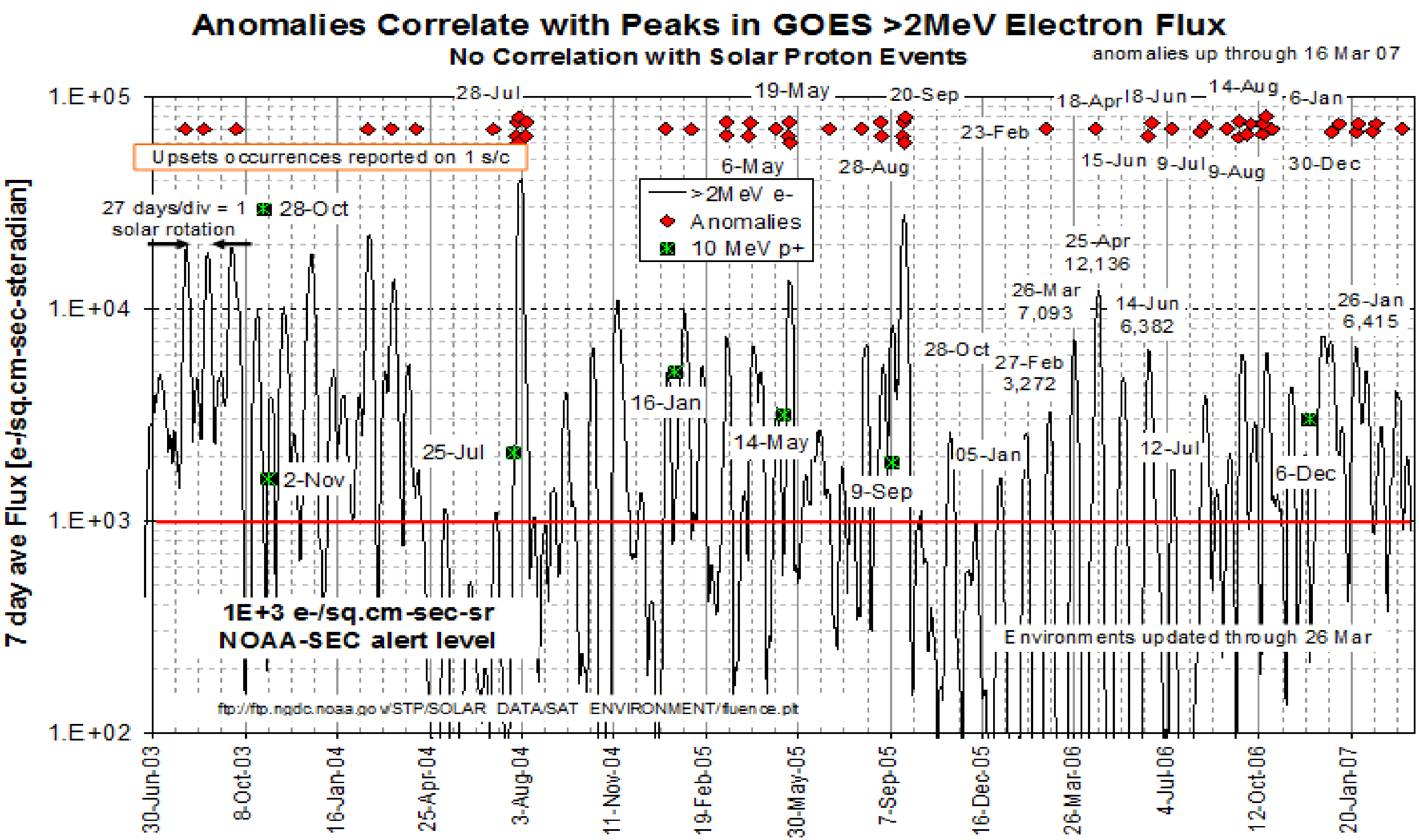


Balcewicz et al., 6th Spacecraft Charging Technology Conference, 4 November 1998

- Rigorous statistical studies showed correlation between high energy electron flux (outside the spacecraft) and anomalies occurring in individual unit types (top graph) and in fleets of similar spacecraft (bottom graph)
- A review published in 2010 (AIAA 2010-1608) documented 17 different studies showing anomaly correlation with *external* energetic electron flux
- None of the studies explained where the charging was occurring and how high the internal flux was, or how the discharges affected the electronics
- Simple guidelines on “safe-flux” levels were issued (NASA 4002), based on CRRES (10hr fluences)

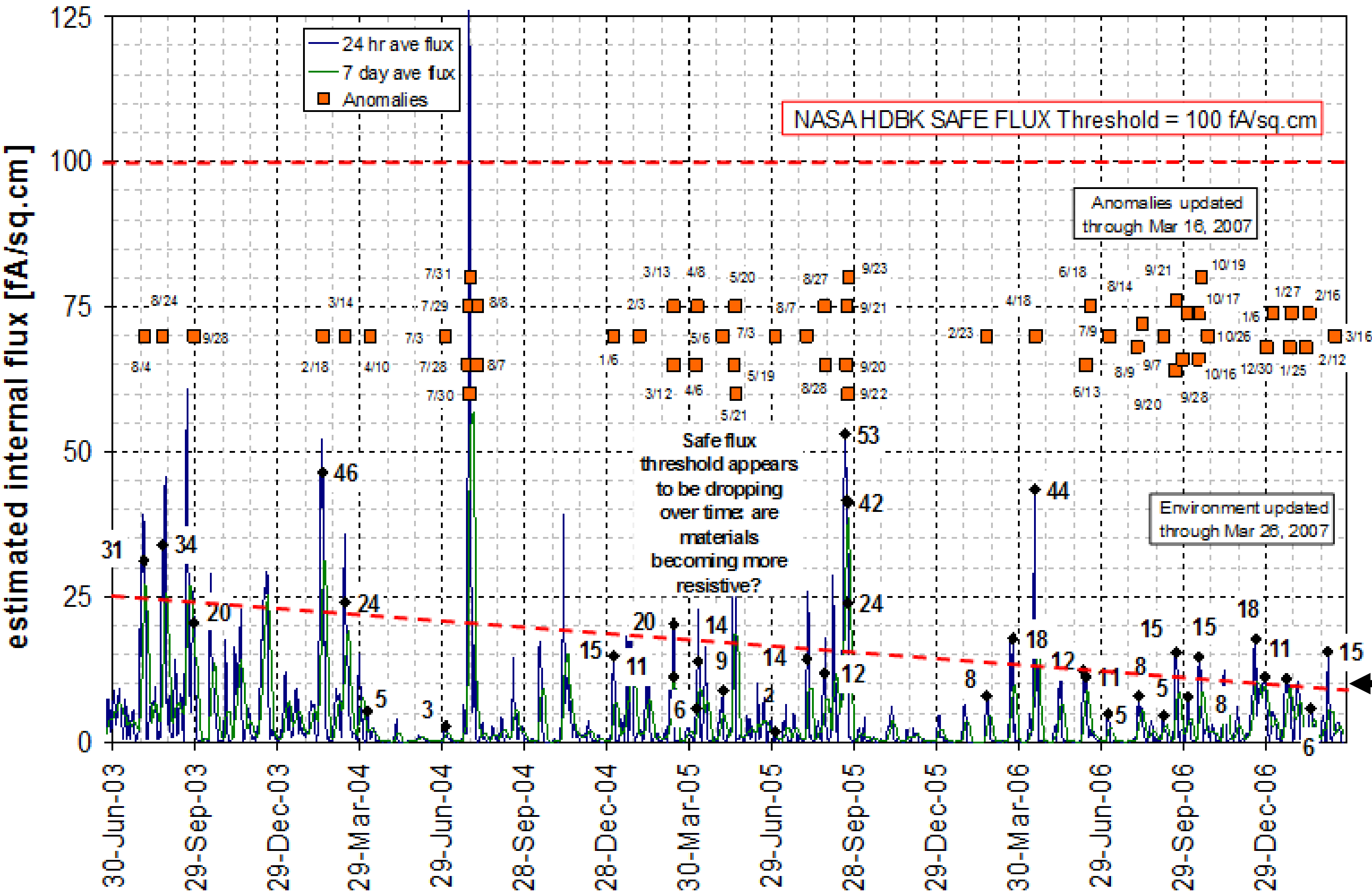
Example of a Strong Correlation between Anomalies and Environment

- Recurring anomalies on 1 spacecraft clearly correlated with external >2MeV energetic electron environment (Satellite Industry Requires Accurate and Timely Space Environmental Data, Space Weather Enterprise Forum (SWEF) Workshop April 2007)



Flux preceding anomalies was far below NASA guidelines-*how could such small flux cause ESD*?

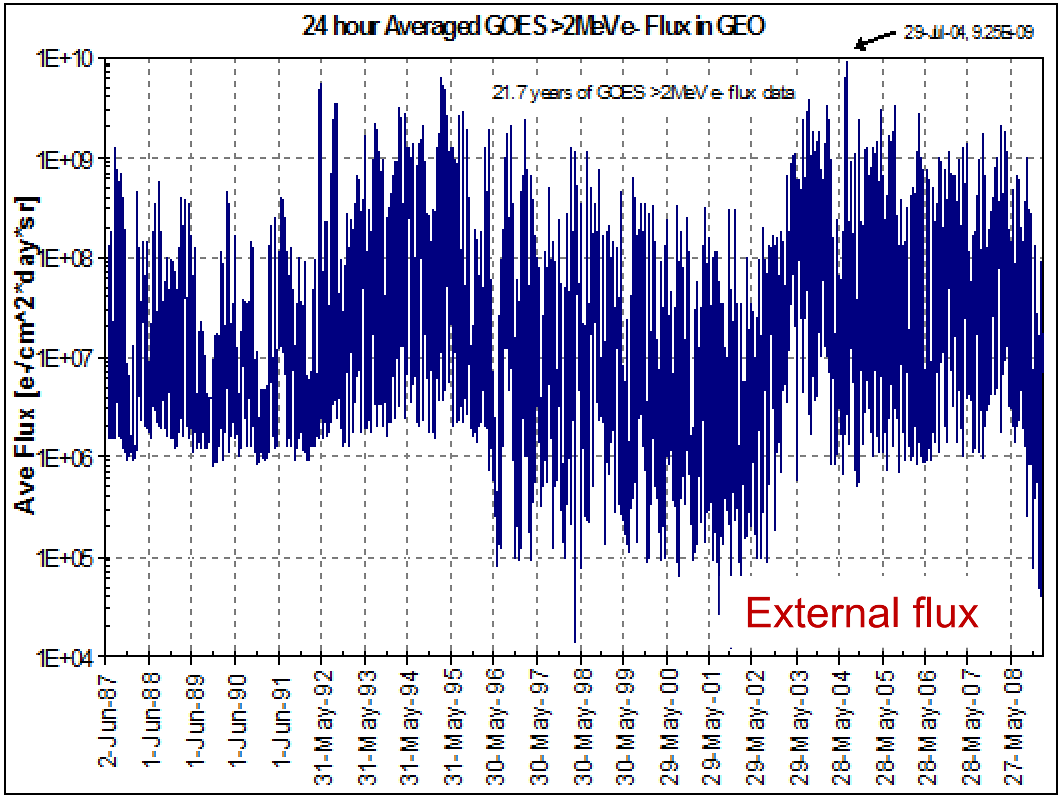
- Internal flux at location of source of discharges (determined by other engineering tests) was far below NASA “Safe-Flux” threshold (SWEF 2007)

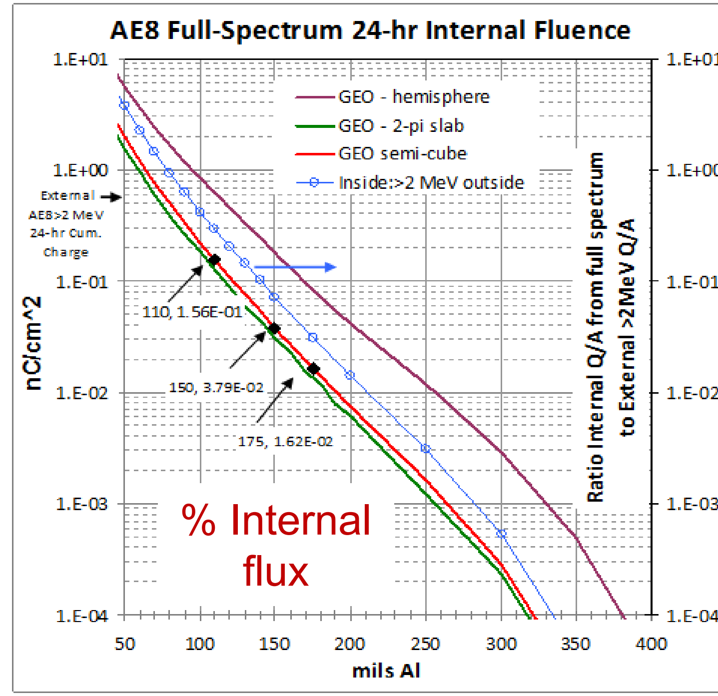


10 fA/sq.cm suggested as safer limit in HDBK 4002A

Engineering Level 1-D Analysis Parametrically Assessed Internal Charging from External Flux

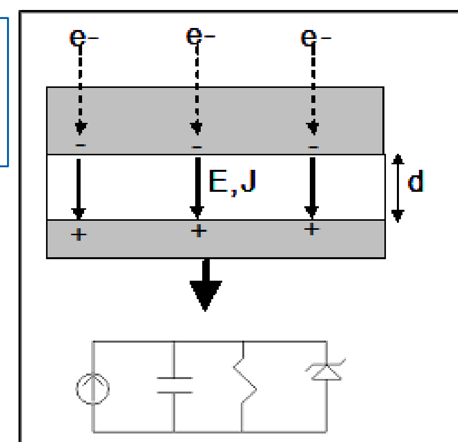
NORTHROP GRUMMAN





$$\tau = \rho\varepsilon = RC$$

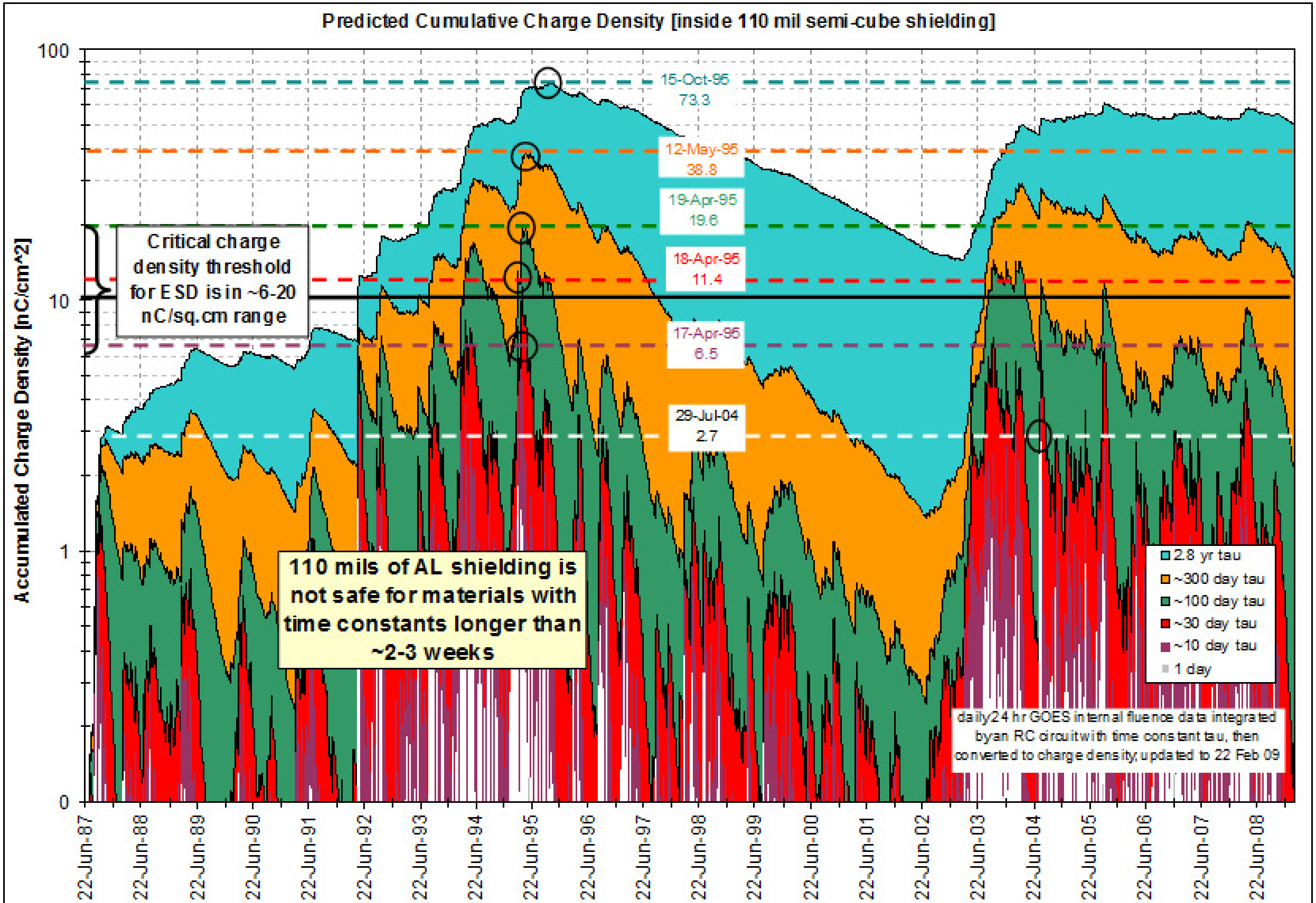
Charging analysis with ρ and τ



The process was described in **AIAA-2010-1608**; 1-D circuit model for deep charging is widely used. See also Appendix E NASA-HDBK-4002, Feb 17, 1999; also Figure 2 of “Internal Charging and Secondary Effects,” Romero and Levy, The Behavior of Systems in the Space Environment, Ed. R. N. DeWitt et al., 1993 Kluwer Academic Publishers, p565ff

Charge Buildup & Decay Depends upon Electrical Time Constant of Insulators (in space)

NORTHROP GRUMMAN



Real Criteria is Fluence Accumulated Inside over 3 Electrical Time Constants

NORTHROP GRUMMAN

- Discharges can occur despite low flux levels inside spacecraft and even inside unit chasses…
  - …If the dielectrics are highly resistive
  - Surprise!, better test methods (than ASTM D-257) confirmed many dielectrics are sufficiently resistive in vacuum
- Accumulated charge “stair-steps” up until breakdown threshold is reached, if energetic electron storms occur frequently enough
  - Breakdown most likely to occur near peak of an individual storm that pushes accumulated Q over the limit (which gives appearance of correlation with peak flux)
  - However, breakdown will not occur during every storm—explains gaps in time history (see slides 4 and 5)

Recent User Experience Investigating if Energetic Electrons Caused a New Anomaly

NORTHROP GRUMMAN

Was the external energetic flux high preceding the event?

- Go get GOES history data prior to the event
- Shoot, the old links don't work
- Found it, but wait, the anomaly occurred before the date on the plot! (Significant lag time usually occurs between an anomaly and the date when environment data is sought)
- Where's the older history data?

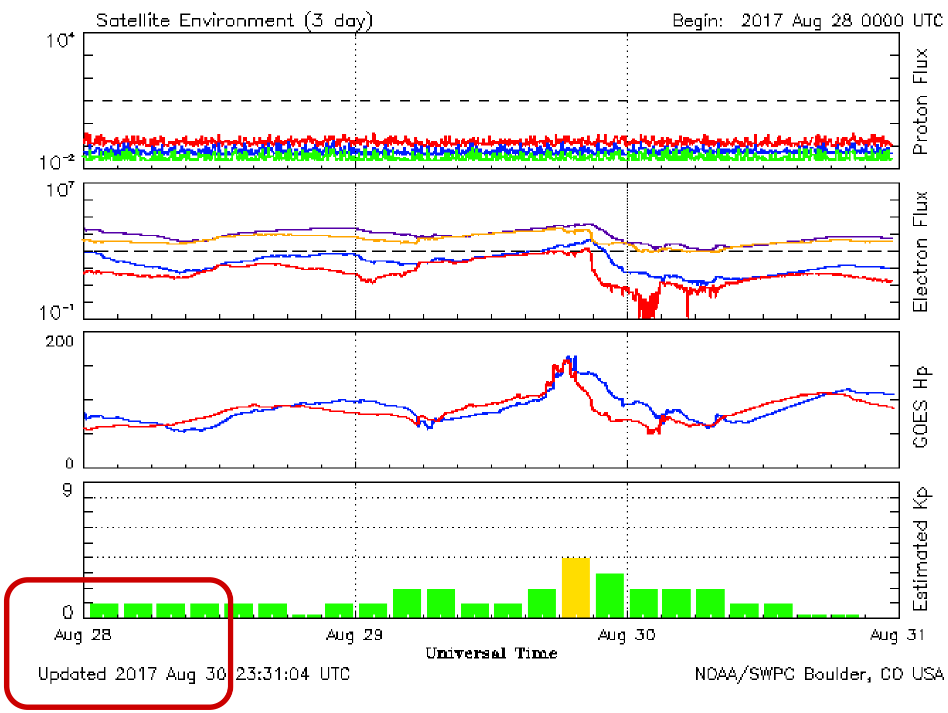
~~http://solar.sec.noaa.gov/rt_plots/elec_3d.cgi~~

~~http://www.swpc.noaa.gov/sources.html#usgov~~

http://www.swpc.noaa.gov/SWN/

http://www.swpc.noaa.gov/communities/satellites

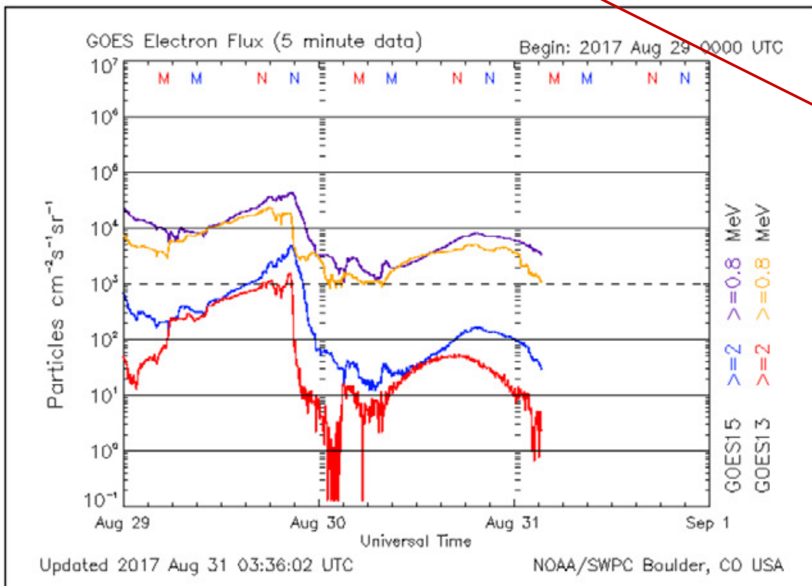
http://www.swpc.noaa.gov/products/goes-electron-flux



Keep Looking

NORTHROP GRUMMAN

- Somewhere in here?
- How about here?



Usage | Impacts | Details | History | Data

The official archive for GOES Energetic Particle data, including electron flux data, can be found at:

http://www.ngdc.noaa.gov/stp/satellite/goes/index.html

A latest version of this plot is available directly from SWPC.

The current report is also available as a text file.

Close, but the data you want is here

HOME

ABOUT SPACE WEATHER

- Impacts
  - Earth's Climate
  - Electric Power Transmission
  - GPS Systems
  - HF Radio Communications
  - Satellite Communications
  - Satellite Drag
- Partners and Stakeholders
  - Commercial Service Providers
  - Federal Agencies
  - International Organizations
  - International Service Providers
  - Space Weather Research
- Phenomena
  - Aurora
  - Coronal Holes
  - Coronal Mass Ejections
  - Earth's Magnetosphere
  - F10.7 cm Radio Emissions
  - Galactic Cosmic Rays
  - Geomagnetic Storms
  - Ionosphere
  - Ionospheric Scintillation
  - Radiation Belts
  - Solar EUV Irradiance
  - Solar Flares (Radio Blackouts)
  - Solar Radiation Storm
  - Solar Wind
  - Sunspots/Solar Cycle
  - Total Electron Content
- Additional Info
  - NOAA Space Weather Scales
  - NOAA's Space Weather Toolkit

PRODUCTS AND DATA

- Forecasts
  - 27-Day Outlook of 10.7 cm Radio Flux and Geomagnetic Indices
  - 3-Day Forecast
  - 3-Day Geomagnetic Forecast
  - Forecast Discussion
  - Predicted Sunspot Numbers and Radio Flux
  - Report and Forecast of Solar and Geophysical Activity
  - Solar Cycle Progression
  - Space Weather Advisory Outlook
  - USAF 45-Day Ap and F10.7cm Flux Forecast
  - Weekly Highlights and 27-Day Forecast
- Reports
  - Forecast Verification
  - Geoalert - Alerts, Analysis and Forecast Codes
  - Geophysical Alert
  - Solar and Geophysical Event Reports
  - USAF Magnetometer Analysis Report
- Models
  - Aurora - 30 Minute Forecast
  - D Region Absorption Predictions (D-RAP)
  - Geospace Geomagnetic Activity Plot
  - Geospace Ground Magnetic Perturbation Maps
  - Geospace Magnetosphere Movies
  - North American (US Region) Total Electron Content
  - North American Total Electron Content
  - Relativistic Electron Forecast Model
  - SEAESRT
  - STORM Time Empirical Ionospheric Correction
  - WSA-Enlil Solar Wind Prediction
  - Wing Kp
- Observations
  - Boulder Magnetometer
  - GOES Electron Flux
  - GOES Magnetometer
  - GOES Proton Flux
  - GOES Solar X-ray Imager
  - GOES X-ray Flux
  - LASCO Coronagraph
  - Planetary K-index
  - Real Time Solar Wind
  - Satellite Environment
  - Solar Synoptic Map
  - Space Weather Overview
  - Station K and A Indices
- Summaries
  - Solar & Geophysical Activity Summary
  - Solar Region Summary
  - Summary of Space Weather Observations

Other likely candidate links send you around in circles

And when you get there, it is intuitively?? obvious which link you want

NORTHROP GRUMMAN

The GOES-NOP satellite era has prompted many changes in the way we deliver GOES SEM data. The "new_" directories below and the data files within them reflect those changes. The biggest impact on users is the new delivery formats: NetCDF and CSV. We are in the process of reformatting the older GOES data into these formats and have generated them back to 1995.

Hint: If you open a CSV files in Excel you really should use this custom format for the first column: yyyymmdd hh:mm:ss.000

In addition to these pregenerated data files we have **Web Services** that some may find convenient for accessing data interactively. Web services have been taken offline indefinitely, see "What's New" page.

There isn't a GOES NOP SEM user's guide, however, new users can familiarize themselves with the GOES NOP satellite series by reading relevant portions of the Data Book. Busy users can make do by just reading the section on the Space Environment Monitor.

GOES_NOP_EUV_readme.pdf describes how to access new EUV products.

View a summary plot of the latest 14 days or 108 days using time-averages or the latest 3 days of full resolution data from GOES-15.

./new_plots					Browse plots in PDF format.
	./yyyy (i.e., ./2010)	./goesxx (i.e., ./goes13)	./qc		Monthly quality control plots.
			./summary		Monthly summary plots
	./latest	./goesxx (i.e., ./goes13)			QC and summary plots of latest 3-days and 14-days.
./new_full	./yyyy (i.e., ./2010)	./mm (i.e., ./04)	./goesxx (goes13)	./csv	Full resolution data in CSV format, daily files.
				./netcdf	Full resolution data in NetCDF format, daily files.
./new_avg	./yyyy (i.e., ./2010)	./mm (i.e., ./04)	./goesxx (i.e., ./goes13)	./csv	Time averaged data in CSV format, monthly files.
./euvs					GOES_NOP_EUV_readme.pdf

Steps to getting your hands on the history data (1 month at a time)

NORTHROP GRUMMAN

Pick a year, a month, source satellite, file type, then data type & cadence and download 1 month of 5min ave data; repeat for each month of history

Name	Last modified	Size
Parent Directory		-
1986/	2014-03-18 15:48	-
1987/	2014-03-18 15:48	-
1988/	2014-03-17 21:48	-
1989/	2014-03-17 21:48	-
1990/	2014-03-17 21:48	-
1991/	2014-03-17 21:48	-
1992/	2014-03-17 22:20	-
1993/	2014-03-17 22:20	-
1994/	2014-03-17 22:20	-
1995/	2011-08-16 11:09	-
1996/	2011-08-16 22:14	-
1997/	2011-08-16 22:31	-
1998/	2011-08-16 22:47	-
1999/	2011-08-17 11:08	-
2000/	2011-08-17 14:20	-
2001/	2011-08-17 14:37	-
2002/	2011-08-17 14:54	-
2003/	2011-08-17 22:01	-
2004/	2011-08-17 22:18	-
2005/	2011-08-17 22:34	-
2006/	2016-09-14 20:09	-
2007/	2016-09-14 20:09	-
2008/	2016-09-14 20:09	-
2009/	2016-09-14 20:09	-
2010/	2016-09-14 20:09	-
2011/	2016-09-14 20:09	-
2012/	2016-09-14 20:10	-
2013/	2016-09-14 20:10	-
2014/	2016-09-14 20:10	-
2015/	2015-12-02 08:18	-
2016/	2016-12-02 10:58	-
2017/	2017-08-02 09:15	-

Name	Last modified	Size
Parent Directory		
01/	2017-01-02 10:57	-
02/	2017-02-02 10:58	-
03/	2017-03-02 10:58	-
04/	2017-04-02 09:15	-
05/	2017-05-02 09:15	-
06/	2017-06-02 09:15	-
07/	2017-07-02 09:15	-
08/	2017-08-17 18:53	-

Name	Last modified	Size
Parent Directory		-
goes13/	2017-01-02 10:57	-
goes15/	2017-01-02 10:57	-

Name	Last modified	Size
Parent Directory		-
csv/	2017-08-16 20:54	-
netcdf/	2017-08-16 20:54	-

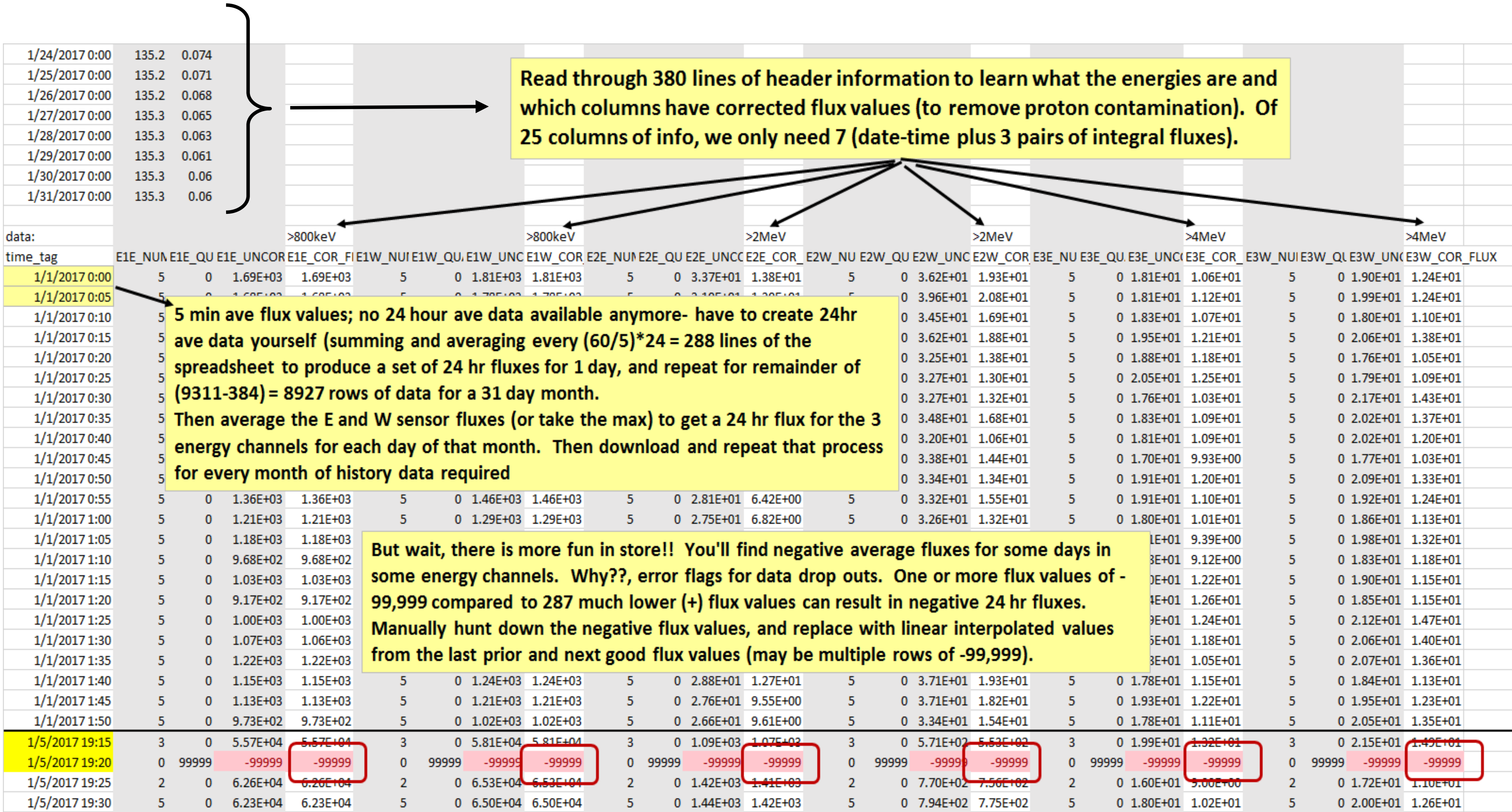
Name	Last modified	Size
Parent Directory		-
g15_epead_a16ew_1m_20170101_20170131.csv	2017-08-16 20:46	8.0M
g15_epead_a16ew_5m_20170101_20170131.csv	2017-08-16 20:46	1.9M
g15_epead_cpflux_5m_20170101_20170131.csv	2017-08-16 20:46	3.1M
g15_epead_e13ew_1m_20170101_20170131.csv	2017-08-16 20:46	5.4M
g15_epead_e13ew_1m_20170101_20170131_science_v1.0.0.csv	2017-02-01 14:15	8.5M
g15_epead_e13ew_5m_20170101_20170131.csv	2017-08-16 20:47	1.7M
g15_epead_orientation_flag_1m_20170101_20170131_v1.0.0.csv	2017-02-01 14:15	1.2M
g15_epead_p17ew_1m_20170101_20170131.csv	2017-08-16 20:47	11M
g15_epead_p17ew_5m_20170101_20170131.csv	2017-08-16 20:47	3.6M
g15_hepad_ap_1m_20170101_20170131.csv	2017-08-16 20:48	5.1M
g15_hepad_ap_5m_20170101_20170131.csv	2017-08-16 20:48	1.1M
g15_hepad_s15_1m_20170101_20170131.csv		
g15_hepad_s15_5m_20170101_20170131.csv		
g15_maged_19me15_1m_20170101_20170131.csv	2017-08-16 20:49	55M
g15_maged_19me15_5m_20170101_20170131.csv	2017-08-16 20:49	6.8M
g15_magneto_1m_20170101_20170131.csv	2017-08-16 20:50	14M
g15_magpd_19mp15_1m_20170101_20170131.csv	2017-08-16 20:51	54M
g15_pitch_angles_1m_20170101_20170131.csv	2017-02-01 14:01	5.6M
g15_xrs_1m_20170101_20170131.csv	2017-08-16 20:51	2.5M

No 24 hr ave flux data files

No 24hr Flux Data Files, So You Have to Create Your Own from the 5min Data CSV Files

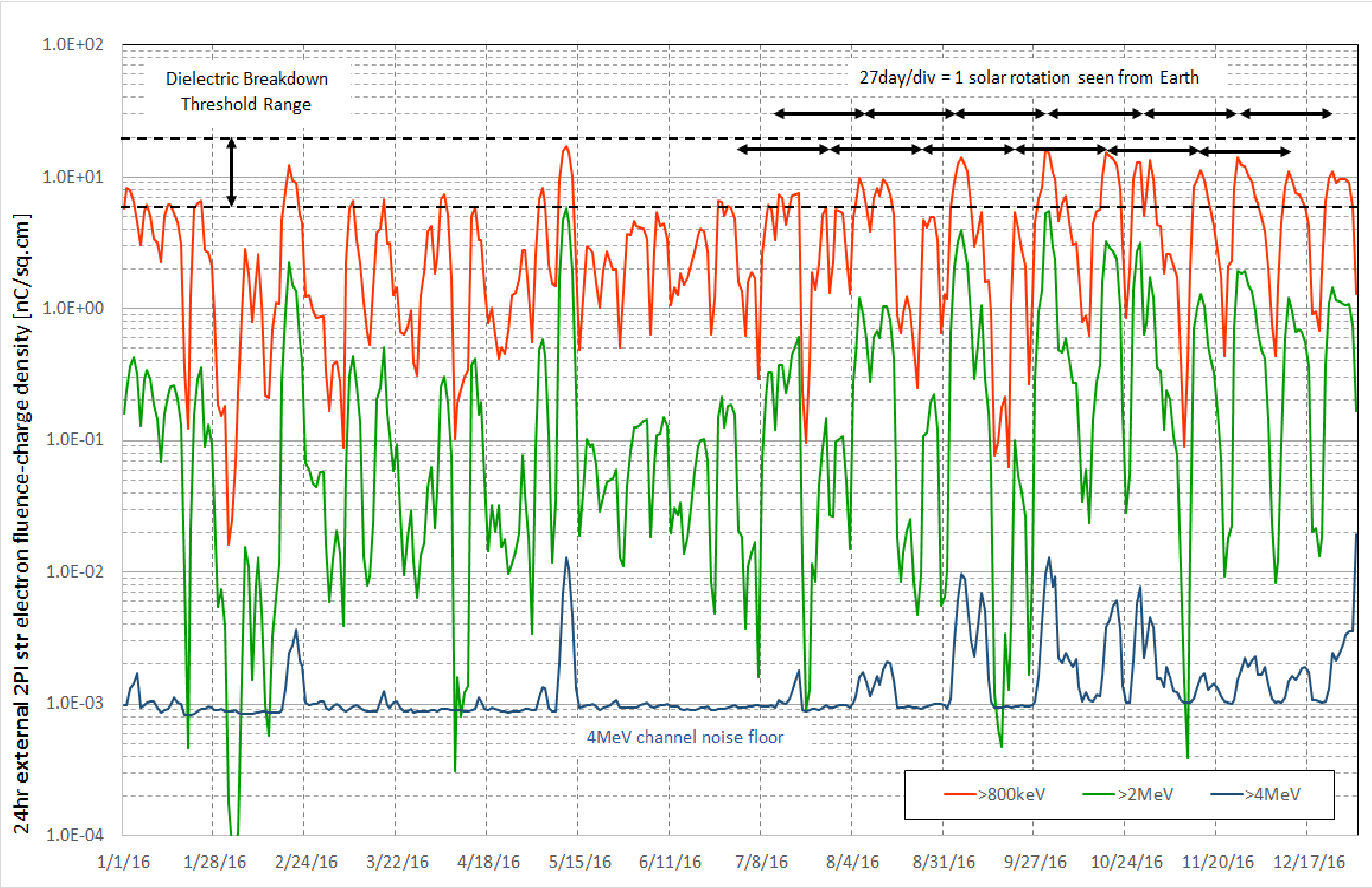
NORTHROP GRUMMAN

Files contain 5min average uncorrected and corrected flux values from each sensor channel and look direction, plus columns of quality check data. We only want date-time, and corrected flux



Repeat 12 Times and You Can Produce 1 Year of External 24 Hr Ave Flux Data History (~132 times for one ~11yr solar cycle)

NORTHROP GRUMMAN



NOAA SWPC has taken 3 steps backwards in end user friendliness for deep charging community

NORTHROP GRUMMAN

- Ready now to go back to slide 6 and begin 1-D charging analysis to see if *internal* flux is high enough & often enough to drive materials to breakdown thresholds
- What changed from prior to recent experience??
  - Manual process that used to takes a few days to assemble years of relevant 24hr charging flux history now takes weeks of tedious manual data manipulation to remove data you don't want (e.g., uncorrected flux) ….
  - …. and fill gaps in data you do want….
  - …. then sum and average 5min fluxes to produce time averaged flux at a cadence that is more suited to deep charging analyses (e.g., 24 hr ave flux)
  - while programs and customers want answers NOW
- *Knowing what we know now, this process should be automated*
- *NO warning to the end user that this is the right way to go*
- *Wasteful to force each end user to develop own SW to regenerate the type of data that had been previously available (e.g., 24hr ave flux)*

Update: the 24 hr data exists!! But you need to know where to look

NORTHROP GRUMMAN

- Thanks to Dr. H. Singer

> - Go to SWPC main page
> - Under Observations heading, just before the link to Dashboards, click on the link "Data Access"
>   - (There are a lot of useful links here that you may want to browse.)
> - Click on the archive "warehouse" link
> - Towards the bottom, click on the year of interest, eg. 2015
> - Click on e.g. 2015_DPD.txt
> - There you will see the daily proton and electron fluence

- Don’t forget to check for data drop outs (they do show up in the 24 hr data, just not as often)

THE VALUE OF PERFORMANCE.

NORTHROP GRUMMAN

Environmental On-Orbit Anomaly Correlation Efforts at Hughes

Presented at the Sixth Spacecraft Charging Technology Conference
4 November 1998

P. T. Balcewicz, J. M. Bodeau, M. A. Frey, P. L. Leung and E. J. Mikkelson
Hughes Space and Communications Co., El Segundo, CA

ABSTRACT: On-orbit spacecraft anomalies are relatively infrequent occurrences on modern satellite systems. However, the severity of these anomalies can vary dramatically, ranging from the corruption of telemetry data to the loss of an entire spacecraft. It is the dire consequences of a major anomaly which focus so much attention on anomalous on-orbit events.

An environmental cause is often suspected for many of the observed anomalies, but it is quite difficult to conclusively demonstrate such a link. Limited data and limited resources complicate the investigation, making it almost impossible to identify a single root cause.

The large Hughes commercial satellite fleet affords a unique opportunity to develop meaningful statistics regarding repeated anomalies. A close examination of the Hughes anomaly database has made it possible to identify certain patterns and trends that would not be discernible with a smaller sample set. A correlation technique has been developed which makes it possible to definitively isolate an environmental relationship for a given class of anomalies. This technique has been utilized to identify those anomalies which are generated by the high energy electron (deep charging) environment, and thus focus product improvement and corrective action efforts in a more constructive manner.

INTRODUCTION

It has long been known that Space Weather phenomena (storms, sub-storms and flares) can greatly affect the anomaly rate of on-station spacecraft. A great deal of work was performed in the 1970s on surface charging and Single Event Effects (SEE), which can lead to anomalous events in satellite systems. The use of conductive films and loading, along with careful grounding of external structures, has helped reduce the surface charging threat to manageable levels in today's generation of satellites. Careful part selection has done the same for SEE. Detailed investigation of bulk charging phenomena did not really begin until the 1980s, with seminal work by many members of the spacecraft charging community [1,2]. Controlling internal electrostatic discharge (ESD) has been a more difficult proposition since internal electrical isolation requirements often conflict directly with grounding concerns.

Therefore, the primary focus of our anomaly correlation efforts has been to determine whether a significant portion of on-orbit anomalies may be attributed to bulk charging phenomena. It is hoped that establishing a direct connection between the internal charging environment and anomalous on-orbit events can help motivate appropriate design changes to mitigate this effect.

Motivating design changes can be an extremely difficult proposition, since many designers consider the current anomaly rates to be quite acceptable. Overall, Hughes anomaly rates are quite good, with very few recorded events per spacecraft per year—ranging from minor annoyances such as telemetry glitches up to the (fortunately much more rare) unit failures. This translates to an approximate unit anomaly rate of once per fifty to a hundred years on many payload units. A rate this low leaves little opportunity or motivation for improvement. Why should designers expend precious time and money in an attempt to further reduce an already insignificant problem?

Our customers on the other hand, with up to eighty transponders per spacecraft and a fleet of 15 satellites, interpret the same data as a temporary channel outage once per month. This frequency of service interruption is far less palatable when an outage can disrupt the transmission of the Super Bowl or World Cup. Hughes must chart a careful course which responds to our customers' concerns, while at the same time minimizing costly redesigns which do not significantly improve our anomaly rate. In order to accomplish this difficult mission, we must be able to accurately determine which anomalies are precipitated by the high energy electron (bulk charging) environment and which are not. This has also been a crucial focus of HSC's correlation effort.

The stakes are quite high. A number of very prominent events and failures have been publicly attributed to bulk charging over the years—most notably the loss of the Anik (LMCo), Telstar (LMCo) and Galaxy (HSC) satellites. Although Hughes has demonstrated that the Galaxy IV failure was almost certainly not due to a deep charging event, the widespread media reaction to this event demonstrates how much attention can be devoted to a major on-orbit anomaly.

THOUGHTS ON ANOMALY RESOLUTION

Space environmental data from NOAA, LANL, USAF and other sources are invaluable in the resolution of on-orbit satellite anomalies. These data help confirm or refute the space environment as the cause of these events. However, other concurrent data must also be available to confirm the space environment as the cause for any on-orbit anomaly. Cooperative sharing of data by the satellite owner/operator, the satellite manufacturer and the various agencies which maintain space and geomagnetic weather data, is generally required to fully resolve on-orbit anomalies.

The satellite owner must provide as a minimum; a record of satellite position and orbit along with the exact GMT of the anomaly, a complete record of all commands sent to the satellite for several days preceding the anomaly, a complete record of on-board stored commands executed over this same time, a full set of all available telemetry from the satellite for the same period in as much detail as possible, and a complete record of pertinent satellite ground station activities for the same period.

The satellite manufacturer can then evaluate the on-orbit anomaly for correlation to a space weather induced cause using knowledge of the spacecraft's physical and electrical design information. Generally, only the manufacturer has sufficient information to make the final determination as to the cause of an anomaly.

EARLY CORRELATION EFFORTS

Fortunately, although the individual satellite anomaly rate is quite low, the large number of satellites which Hughes has orbited over the years offers an excellent statistical sample from which to draw general conclusions about anomaly behavior. Hughes-built satellites comprise a significant fraction (>35%) of commercial spacecraft at geosynchronous orbit and have accumulated more than 1000 spacecraft-years on-orbit. The satellite fleet is large enough to allow the ensemble to be broken into statistically meaningful subsets (e.g., 3 axis vs. spin stabilized). Also, there is enough commonality between successive spacecraft (evolutionary rather than revolutionary changes) to permit fair comparisons.

The goals of this effort were simple; to rigorously determine if bulk charging driven anomalies were occurring on HSC spacecraft, to determine what magnitude of environmental excursion it takes to induce these bulk charging events, and to determine what fraction of HSC anomalies were caused by this phenomenon. We have succeeded in accomplishing these objectives and are now in the process of working on two additional items. Hughes is presently extending this work into multi-energy bands, rather than simply relying on the GOES 2 MeV environment. It is hoped that the correlations will show some type of peak at a particular energy, which when combined with electron range data, will afford us additional clues as to where to concentrate our product improvement efforts. Ultimately, the goal is to make use of this information to implement targeted design modifications to reduce or eliminate bulk charging anomalies.

The initial attempt at an anomaly correlation was fairly crude (Fig. 1). The solid line represents the number of days per month where the 2 MeV environment exceeded 10 times the NOAA alert level. The vertical bars represent anomalies per spacecraft per month. As can be seen, the number of anomalies tended to increase when the high energy electron environment was elevated for an extended period of time and tended to decrease when the GOES electrons were quiet. A pattern was emerging, but the statistical significance of these trends was not yet established. The connection needed to be made more obvious and mathematically sound.

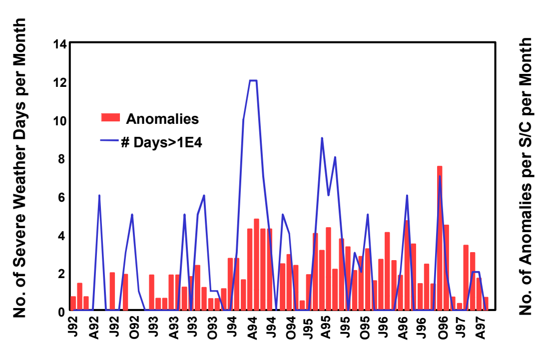


Figure 1: On-orbit Anomaly Rates Tend To Peak Concurrently With The High Energy Electron Environment

The next attempt (Fig. 2) hit closer to the mark. The GOES data was sampled over a long period of time and divided into days where various flux thresholds had been exceeded. At the same time, the anomaly data was examined to identify those days on which events had been reported. It was noted that anomalies tended to cluster on those days where the flux was elevated. For certain electronics units, it was determined that as many as 20% of the anomaly events occurred on the hottest 5% of days and 10% of the anomalies during the top 1% of days.

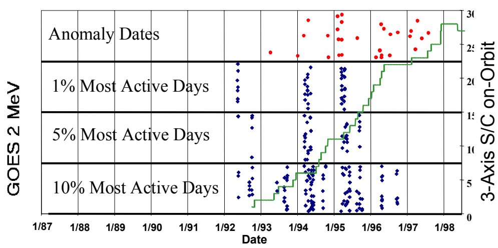


Figure 2: Occurrence Rates Increase With The Severity Of The Environment

STATISTICAL CORRELATION EFFORTS

A statistician (Tony Lin of HSC) was consulted to inject additional rigor into the correlations. The statistician developed a method to quantify this relationship by dividing the days into a number of equally sized bins sorted by the average flux during that day, and counting the number of anomalies in each bin. A non-environmentally driven anomaly should show approximately equal numbers of events in each bin (once it has been properly normalized to the number of spacecraft on-orbit). By performing a chi-squared (χ^2) fit on the data versus the expected flat line, a probability could be derived which measured the likelihood that a certain distribution of events would occur if the events were unrelated to the environment. Conversely, this also yields the probability that the anomalies are indeed related to the environment.

(Incidentally, the correlations presented in the following charts were computed using the seven day GOES flux averages, rather than the one day numbers. The longer averages better reflect the long time constants found in internal bulk charging and were empirically found to optimize the correlations.)

The following bar graph (Fig. 3) demonstrates a marked increase in anomaly incidence during the periods of highest flux. This translates to a probability of 0.017% that such a drastically skewed distribution would occur if the events were randomly distributed without regard to the environment. This corresponds to a 99.983% chance that these anomalies are correlated with the bulk charging ESD environment.

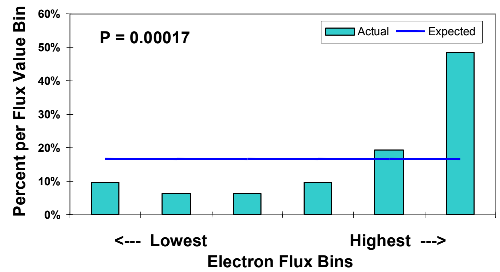


Figure 3: Unit A Anomalies Concentrated On Days Of Most Intense Environment

The next graph shows another set of units where the anomaly rate is even more closely tied to the environment (Fig. 4). The listed probability of 0 is not real. The program used to make the chi-squared (χ^2) correlation truncates the number of decimal places, but nonetheless, it is obvious that this particular anomaly is exceedingly well-correlated with the high energy electron environment.

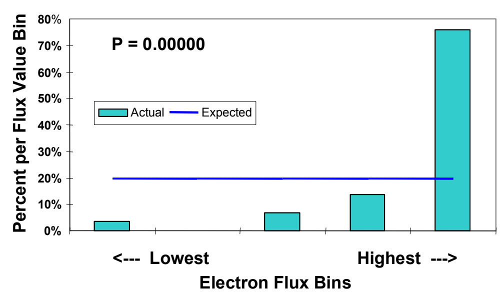


Figure 4: Unit B Anomalies Concentrated On Days Of Most Intense Environment

The next chart (Fig. 5) shows the correlation for the entire Hughes body-stabilized fleet. As you can see, the correlation is less dramatic, but still definitely there. There is a distinct flux threshold where the anomaly rate suddenly increases by about a factor of 2, and the probability of an entirely non-environmental cause producing this skewed a distribution is once again close to 0. The large number of samples in this fleet-wide example gives high confidence in an environmental cause in spite of the less pronounced deviation at high flux levels.

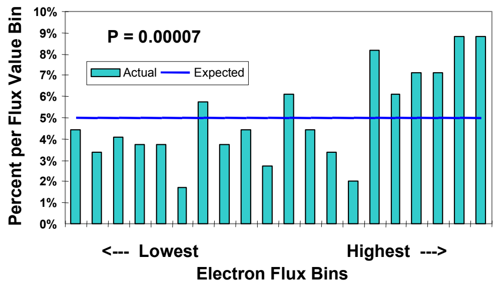


Figure 5: Overall HS601 (Body-Stabilized) Anomalies Also Concentrated On Days Of Most Intense Environment

The last of this sequence of charts (Fig. 6) is for the Hughes spin stabilized spacecraft (spinner) fleet. As can be seen, the increase in anomaly events at high flux is far less dramatic than for the 3-axis stabilized satellites—indicating very little environmental component in spinner anomalies. Yet the chi-squared (χ^2) probability is extremely low. This is due to the bulge in events in the low flux bin. The elevation in rate at the low end indicates that events occur preferentially on days with a very low high-energy electron flux. The reason for this anti-correlation is that the hottest time period for solar electrons is during the approach to solar minimum, which is the opposite point in the cycle from the large proton events at solar maximum. The cluster of events in the low flux bin are identified proton-driven single events on an early spinner system. The relationship becomes obvious when the correlation exercise is repeated with the GOES 10 MeV proton environment instead of the 2MeV electrons as the relevant figure of merit (not shown).

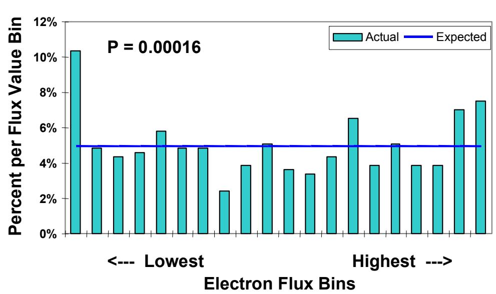


Figure 6: Overall HS376+ (Spin-Stabilized) Anomalies Not Strongly Concentrated On Days Of Most Intense Environment

FOLLOW-UP ANALYSIS

The anomaly data was examined further to confirm that the grouping of anomaly events in the high flux channels was consistent with a bulk charging hypothesis (Fig. 7). The composition of events that make up the highest flux bin (presumably ESD-related) was compared with the events which make up a bin in the middle of the graph (presumbaly unrelated to ESD). For the high flux bin, over three-quarters of the anomalies were from units where bulk charging effects have long been implicated. For the medium flux bin, this number is reduced to one-quarter, and the non-environmental anomalies (such as an out-of-spec temperature or an underperforming thruster) tend to dominate.

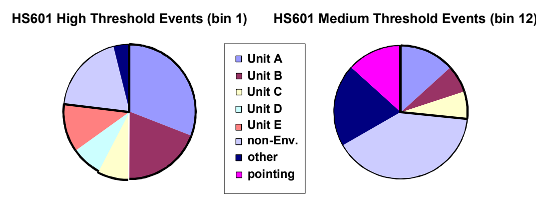


Figure 7: ESD-Related Anomalies Predominate On High Flux Days. Non-ESD Events More Common on Low Flux Days

Thus, consistent with expectations, the anomalies which are attributed to bulk charging tend to occur during an extended period of high average flux, while non-ESD related events are evenly distributed without correlation to the high energy electron environment. Our data indicates that internal ESD events occur while the flux is still elevated above our empirical electron flux threshold of 2×10^3 e's/cm-s-sr—there is no lag or delay time associated with this phenomenon.

CONCLUSIONS

A rigorous correlation between the high energy electron environment and anomalies in the Hughes fleet has been demonstrated. An empirical flux threshold of 2×10^3 e's/cm-s-sr has been established where a marked increase in the incidence of anomalies is observed. It has been determined that approximately 10% of the fleet-wide anomalies at Hughes appear to be attributable to bulk charging (more for the body stabilized and less for the spin stabilized spacecraft). Finally, further investigations are planned with multiple energy band data in order to gain additional insight into internal ESD anomalies and devise effective actions to mitigate this problem.

REFERENCES:

1. A.R. Frederickson, IEEE El. Ins. Vol. 18, Pg. 337 (1983)
2. P.L. Leung, et al, JSR Vol. 23, No. 3, Pg. 323 (1986)

High Energy Electron Climatology that Supports Deep Charging Risk Assessment in GEO

Michael Bodeau, Technical Fellow, Northrop Grumman Aerospace Systems

Abstract

Charging deep within spacecraft has been established as the root cause of anomalies on many satellites. Design guidelines that mitigate the risk of electrostatic discharge (ESD) from deep charging have evolved over the years. A standard reference for these guidelines is "Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects," NASA Handbook 4002.[1] The one guideline from this handbook that has been adopted the most widely throughout industry is the "safe flux" of 100 fA/cm^2 (1fA = 1E-15 amp). Specifically, a design is deemed safe if there is sufficient shielding (mass) to reduce the worst-case electron flux to a level below 100 fA/cm^2 at the internal electrical circuitry. Less well known is that a worst-case external environment is also defined in the handbook.

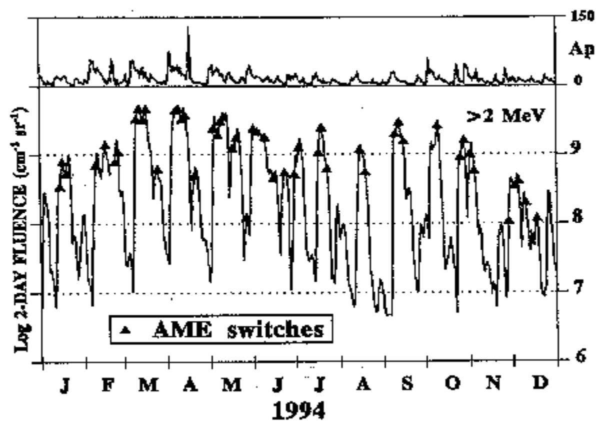
The safe flux criterion is traceable to the Combined Release and Radiation Effects Satellite (CRRES) internal discharge monitor (IDM) flight experiment, which did not experience any ESD events when the total electron fluence accumulated over a 10 hour orbit was below about 2E+10 electrons/cm^2. So the safe flux criterion is literally a safe 10 hour fluence criterion.

A simple one dimensional charging model is used to show how materials with long electrical time constants react to the dynamic electrical flux in geosynchronous orbit (GEO). It shows that the critical parameter is the total fluence or charge density accumulated over several time constants. This leads to a process of exponentially accumulating and averaging the external electron flux to derive a worst-case, time-integrated fluence and equivalent time-averaged flux.

Historical Anomalies Correlate with Deep Charging Flux

There are numerous examples of anomalies that have occurred on satellites that correlate with episodes of high fluxes of energetic electrons. A sampling of literature[2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17] is given in Table 1. Figure 1 shows an example of anomalies that occur when the energetic (>2MeV) electron flux is high. Such a correlation of anomalies with peaks in the external flux naturally leads to a question of how low the flux must be to prevent ESD. Unfortunately, most of these historical examples do not define useful engineering design criteria, such as a threshold internal flux or fluence for ESD and the minimum required shielding levels to reduce the flux to that limit.

Figure 1. Anomalies on DRA-δ correlate with peaks in high energy electron flux [ref 9]

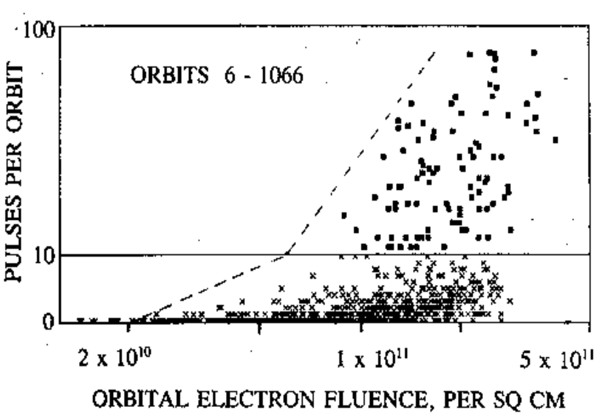


The CRRES satellite, with its IDM experiment package, was flown to investigate the charging of circuit boards and cables in space. The IDM circuit board and cable samples were small, but were constructed from materials used on actual spacecraft. The electron flux to these samples was maximized by limiting the shielding to only 0.2 mm (8 mils) aluminum. A very high flux was deemed necessary to charge the samples to ESD breakdown, based on the resistivity data available at the time. The satellite flew in a modestly inclined geostationary transfer orbit (GTO) that passed through the most intense electron flux regions of the radiation belts twice per 10-hour orbit. A clear relationship between the fluence of electrons and the number of ESD events detected by the IDM experiment over a 10-hour orbit was established (see Figure 2). It appeared that, as long as the 10-hour fluence was below 2E+10 e-/cm^2, ESD would not occur (equivalent to a current density of 90 fA/cm^2, where 1 fA = 1E-15 amps). Figure 2 shows that only a few of the thousand-plus orbits of the CRRES mission saw a fluence that low.

Table 1. Historical Examples of Anomalies Caused by Deep Charging

Satellite	Correlated Environment	External Flux Threshold	External Fluence	External Current Density	Internal Fluence e-/sq.cm	Fluence Duration	Internal Current Density	Shielding for Safe Flux	Author	Reference
Star sensor	1.2 MeV e- from GOES 2	--	--	--						
NTS-2 clock anomaly	High-energy electrons	--	--	--						
Voyager 1 POR	10 MeV electrons	--	--	--	1E+12	Few hrs to 1 day	~ 2 pA/sq.cm	1.5 mm	Vampola	2
Meteosat-1	MeV electrons	--	--	--						
GPS autotrack upset	MeV electrons	--	--	--						
SCATHA	>1.4 MeV e-	1000 e-/sq.cm-sec-str	--	--	--	--	--	--	Koons	3
CRRES ground tests		--	--	--	~1E+12	1-8 hrs	>4.5 pA/sq.cm	--	Coakley	4
FR4 circuit board	Lab environment	--	--	--	~2E+12 to 2E+13	~ 3-day electrical time constant	1-10pA/sq.cm	--	Robinson & Coakley	5
CRRES IDM flight data	>300keV e- flux	--	--	--	2E+10	10-hour orbit period	5.6E+5 e-/sq.cm-sec 89 fA/sq.cm	--	Frederickson Violet	6,7
CRRES S/C anomalies	>300keV e- flux	--	--	--	--	--	--	--	Violet	8
DRA-d AME switches	>2MeV e-	--	3E+8 to 1E+10 e-/sq.cm-str	0.8-29 fA/sq.cm	--	2 days pi steradian exposure	--	--	Wrenn	9,10,11
	>200 keV e-	--	6E+10 to 2E+11 e-/sq.cm-str	180-600 fA/sq.cm	--	2 days pi steradian exposure	--	--		
NOAA SEC anomaly database	>2MeV e-	1000 e-/sq.cm-sec-str	--	--	--	--	--	--	Wilkinson	12,13
Fleets of s/c	2 MeV e-	--	--	--	--	--	--	--	Balcewicz, Baker, Pilipenko, Leach	14,15, 16,17

Figure 2. CRRES discharge rate vs electron fluence (per 10-hr orbit)



Based upon the above discussion, the 100fA/cm^2 safe flux criterion is really a 10-hr safe fluence criterion. Geostationary satellites are in orbit for 10-15 years, and it is not obvious that a fluence that is safe for 10-hour exposures is low enough to assure ESD free operation over mission lifetimes exceeding a decade. However, NASA had collected electrical properties data for many materials commonly used on spacecraft from manufacturers' specifications and material handbooks (Table I in section 6.2 of HDBK 4002). As discussed in section E7 of the handbook, the key properties governing deep charging are bulk or volume resistivity ρ and the related electrical-decay time constant τ, which is given by the product of bulk resistivity ρ and dielectric constant ε. A material being charged by a constant flux will reach 95% of the steady-state charge density and electric field in 3 electrical time constants, and will have lost 95% of the accumulated charge in 3 time constants after the flux ceases. The data collected by NASA for key materials showed electrical time constants that ranged from a few minutes to less than 3 hours, well under the 10-hour duration of the worst-case specified environment. These materials would reach steady state within the duration of the worst-case environment, and would lose all stored charge in a fraction of a day after the charging environment passed. On this basis, a worst-case 10-hour averaged flux appeared appropriate even for long missions.

Appendix E3 of NASA HDBK 4002 discusses using the ASTM D-257-91 method[18] to determine the bulk resistivity of materials, while Appendix E6 discusses an alternate method that charges samples in vacuum with a non-penetrating electron beam and then monitors the surface potential decay with a non-contacting electrostatic probe. HDBK 4002 did not present any material resistivities or time constants specifically derived by the non-contacting probe method.

Testing with the non-contacting probe method was subsequently performed. In particular, CRRES IDM engineering model samples were tested by the non-contacting probe method[19] and shown to have time constants of 21 hours for alumina, 5 days for FR4 boards and 339 days for Teflon (versus HDBK 4002 time constants of 0.8 second, 2.4 hours and 2.1 days respectively). These results revealed that the bulk resistivities of materials in vacuum are orders of magnitude higher than measurable by the ASTM D-257 methods. This increases the electrical time constants and the corresponding exposure durations required to reach steady state by the same orders of magnitude. In this light, a 10-hour or 24-hour worst-case flux and fluence are not bounding or appropriate for a deep charging assessment of long time constant materials.

1-D Charging Model for Deep Charging

Various one-dimensional charging models have been used to investigate the accumulation of volumetric charge and the build up of the internal electric field.[20,21,22,23] For our purposes, we are not interested in the details of the charge and electric field profiles through the dielectric thickness, since the probability of ESD depends upon the peak electric field and critical charge density. The peak field always occurs beyond the charge centroid (shown clearly by Figure 3 and 4) and experiments have shown the discharge initiates at the interface between electrode and dielectric,[24] which is subject to this peak field. So we are only interested in estimating the total fluence captured in the dielectric and the peak electric field it creates at the underlying ground.

Figure 3. Analytical Charge Deposition Profile [21]

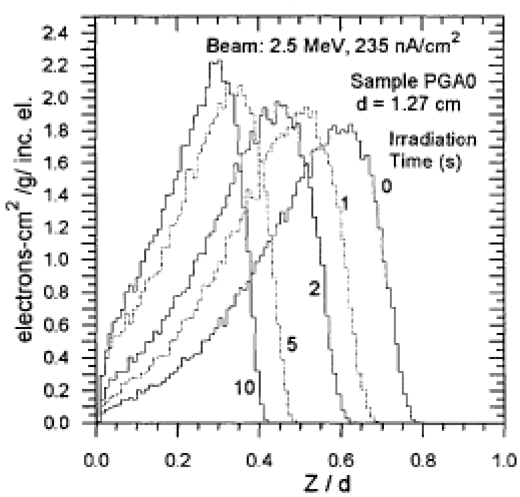


Fig. 3. Time evolution of charge deposition by stopped HE electrons alone. (Stopped conduction charge is not included in this graph.)

Figure 4. Experimental and Analytical Electric Field Profiles [21]

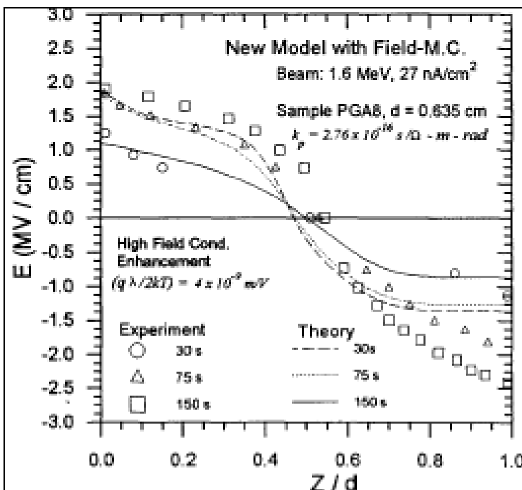
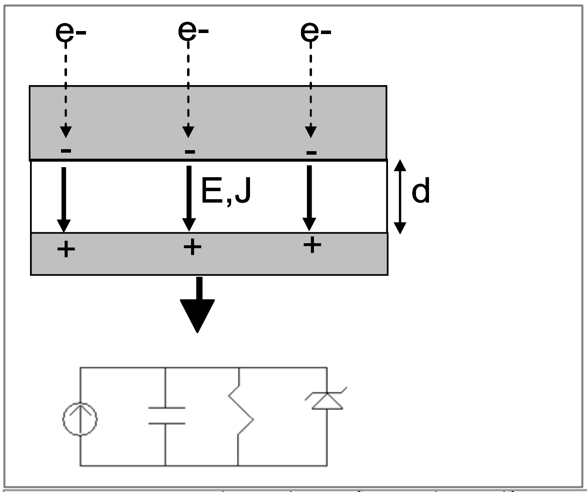


Fig. 8. Electric field vs. distance for sample PGA8. New model with high field conductivity enhancement.

Figure 5 shows the simplified one-dimensional model. A material sample is charged by a uniform electron flux J, incident from the top. Since the flux is uniform, the total current being absorbed is J*A (flux times surface area). Between the depth where the charge stops (upper shaded area) and the underlying conductive ground (lower shaded area) is a non-irradiated region of thickness d. The charge stopped above creates a uniform electric field E within the non-irradiated region that terminates on image charge in the conductive ground. The voltage across the non-irradiated region and ground is V = Q/C, where Q equals the trapped charge and C is the capacitance of the non-irradiated region: $C=\varepsilon_0\varepsilon_r A/d$. Under the influence of the electric field E, the absorbed charge will flow through the non-irradiated region to ground as a conduction current density Jc = ρE, where ρ is the bulk or volume resistivity in the non-irradiated region. This model is a fair representation of the charging of metal (radiation spot shield or heat sink) that traps most of the flux, which is then prevented from flowing to ground by the insulator used to bond the shield to the underlying conductor. It also approximates the behavior of a thick dielectric, where the majority of the incident flux is stopped and trapped in the upper layer.

Figure 5. 1-D Model for Estimating E Field25[25]



$$V(t) = V_c(t=0)\cdot \exp\left(-t/_{RC}\right) + IR\cdot\left[1-\exp\left(-t/_{RC}\right)\right]$$

$$\text{since } R = \rho d/_A,\ C = \varepsilon_r\varepsilon_o A/_d,\ RC = \rho\varepsilon_r\varepsilon_o = \tau$$

$$I = J\cdot A,\ R/_d = \rho/_A,\ IR/_d = \rho J$$

$$E_o = V_o/_d = V_c(t=0)/_d$$

$$E(t) = E_o\cdot\exp\left(-t/_\tau\right) + \rho J\cdot\left[1-\exp\left(-t/_\tau\right)\right]$$

$$Q(t)/_A = Q_0/_A\cdot\exp\left(-t/_\tau\right) + J\tau\cdot\left[1-\exp\left(-t/_\tau\right)\right]$$

$$\text{EARLY TIME SOLUTION : for } t << \tau = \rho\varepsilon_r\varepsilon_o$$

$$\text{Assume no charge at t = 0 : } Q_0 = 0, E_o = 0, V_o = 0$$

$$V(t) \approx It/C = Q(t)/C = \text{total charge w/out leakage}$$

$$\text{q(t) = Q(t)/A} \approx \text{Jt} \rightarrow \text{Charge density = fluence up to time t}$$

$$E(t) \approx Jt/\varepsilon_r\varepsilon_o = \text{fluence divided by dielectric constant}$$

$$\text{LATE TIME STEADY STATE SOLUTION :}$$

$$\text{for } t >> \tau = \rho\varepsilon_r\varepsilon_o,\ \text{assuming no discharge}$$

$$V(t) \approx IR\ \text{ and current absorbed = leakage current out}$$

$$E(t) \approx \rho J, \text{q(t)} \approx \text{J}\tau$$

$$\text{ESD occurs if E field exceeds} \approx \text{100 - 200kV/cm threshold}$$

$$\text{or if q} \sim \text{6 - 20nC/cm}^2$$

The equations in Figure 5 for V(t), E(t) and q(t) describe how charge leakage (first exponential term on the right hand side of the equations) and charge deposition (given by the second term in the same equations) result in a time varying voltage, charge density and electric field.

The simplest case to discuss assumes that the electron flux is constant, begins at time t=0, and that there is no prior stored charge. The charge density, electric field and voltage start from zero and build at a constant rate with time. The sample acts like a pure capacitance for times $t<<\tau = \rho\varepsilon_0\varepsilon_r$. As the voltage and electric field increase, the leakage current increases and the net rate of charge accumulation slows. Eventually, at $t\geq\sim 3\tau$, a steady state condition is reached and the leakage current density just balances the incident flux. Reaching steady state presumes that the electric field does not exceed the dielectric strength of the insulator.

Unlike the constant flux case just discussed, Figure 6 shows that the GOES >2MeV electron flux varies orders of magnitude from day to day. There is also a periodicity in the envelope to the flux peaks associated with the 11-year solar cycle. This GOES 24-hour-averaged flux has been used as the time-varying current source to drive the 1-D charging model, and the daily accumulated charge density has been computed for a range of material time constants. Figure 7 shows that the charge accumulated by a material with a 1-day time constant rises and falls in sync with the 1-day average flux. The worst-case peak accumulated charge occurs on 29 July 2004, the date of the highest 24-hour flux shown in Figure 6. We can conclude that whenever the dielectric's time constant matches the duration over which the flux is averaged, the peak flux and peak accumulated charge density are highly correlated and it makes sense to discuss a maximum safe time-averaged flux in this case. However, Figure 7 shows that the peak accumulated charge density reached during a storm gets higher and higher as the electrical time constant gets longer. So the risk of ESD increases significantly for materials that are more resistive, and doesn't depend solely upon the 24-hour averaged flux environment.

For very long time constant materials (such as 300 days and 1025 days = 2.8 years), we observe in Figure 7 that the accumulated charge barely decays between storms. During the active years of the solar cycles (1992-1996 and 2003-2007), the accumulated charge continues to ratchet upward because additional storms are occurring faster than the charge can decay.

Figure 6. Dynamic High Energy Electron Flux in GEO (data courtesy of NOAA SWPC)

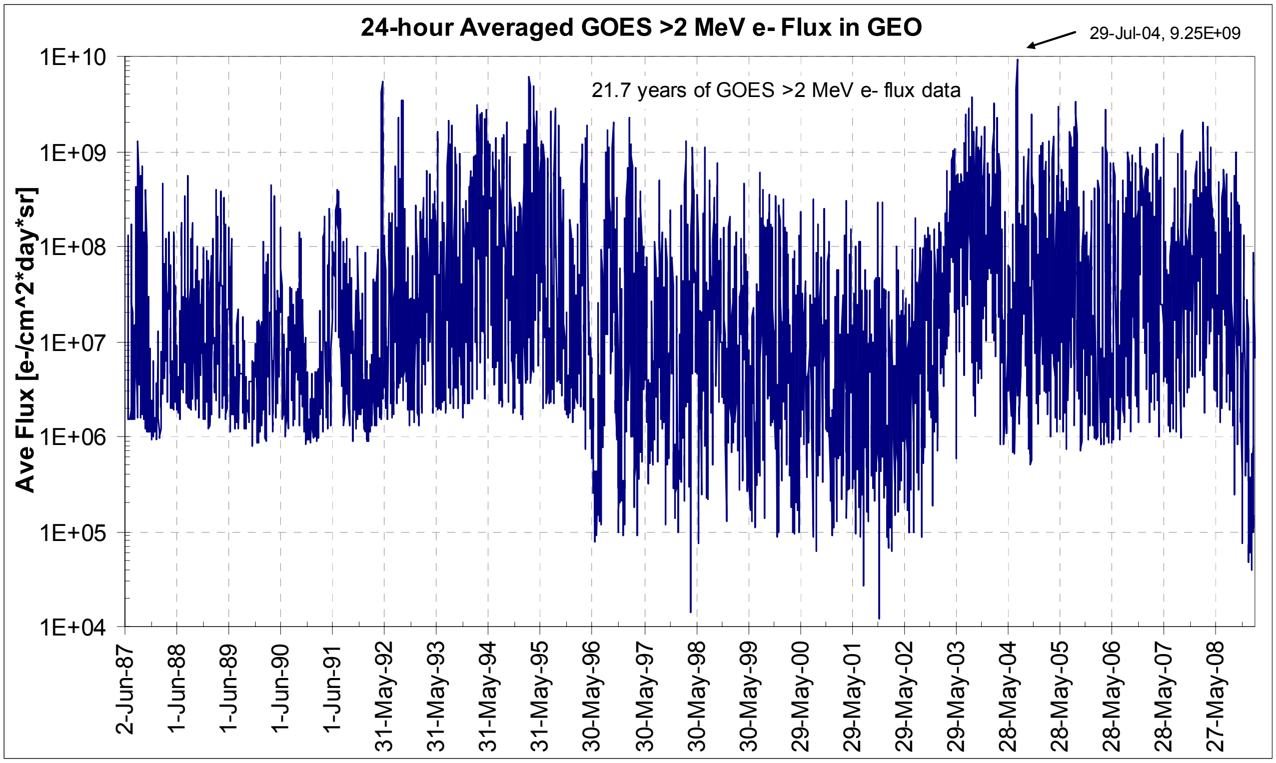


Figure 7. Accumulated Charge Density Vs. Material Time Constant

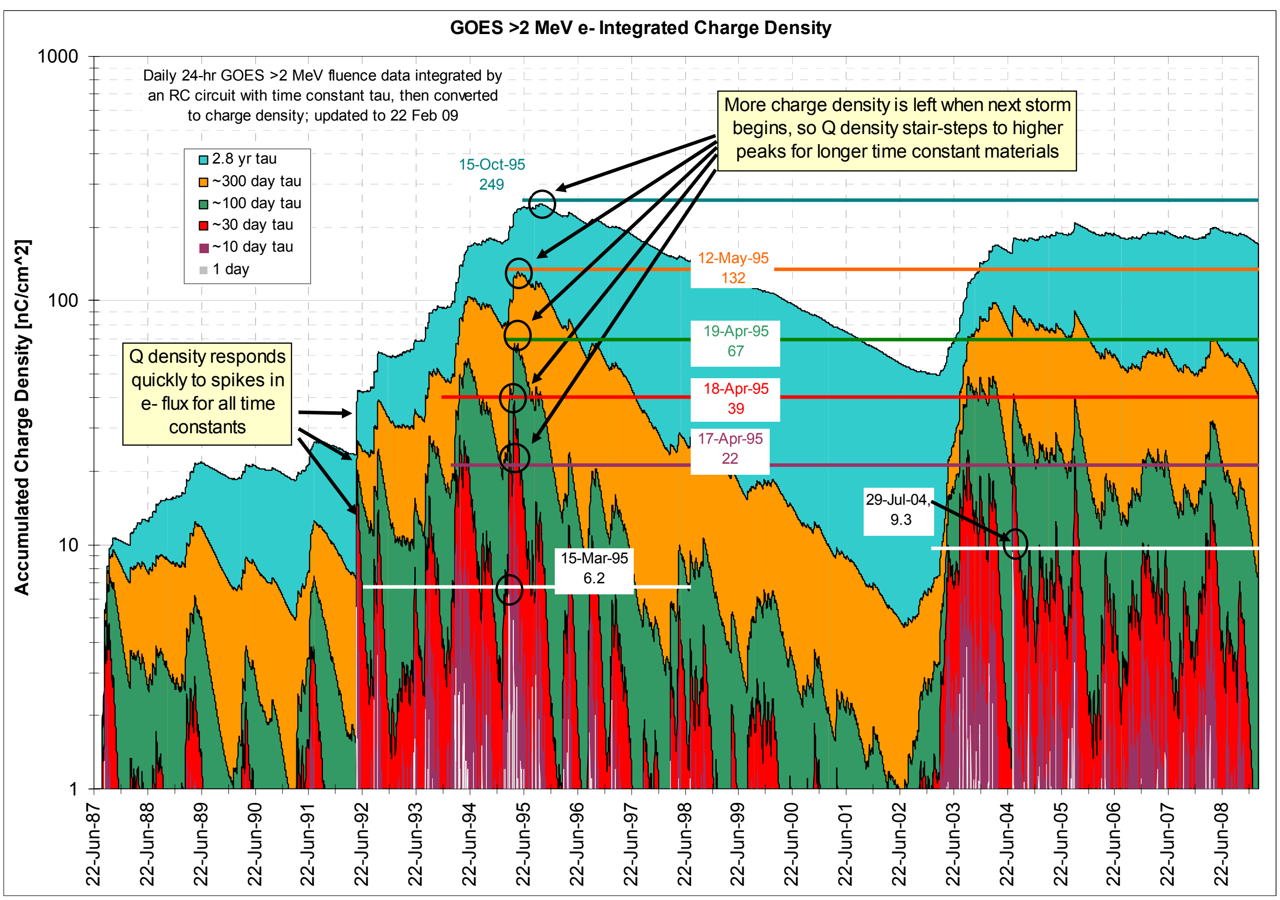


Figure 8. Long time constants increase charge accumulated from recurring storms

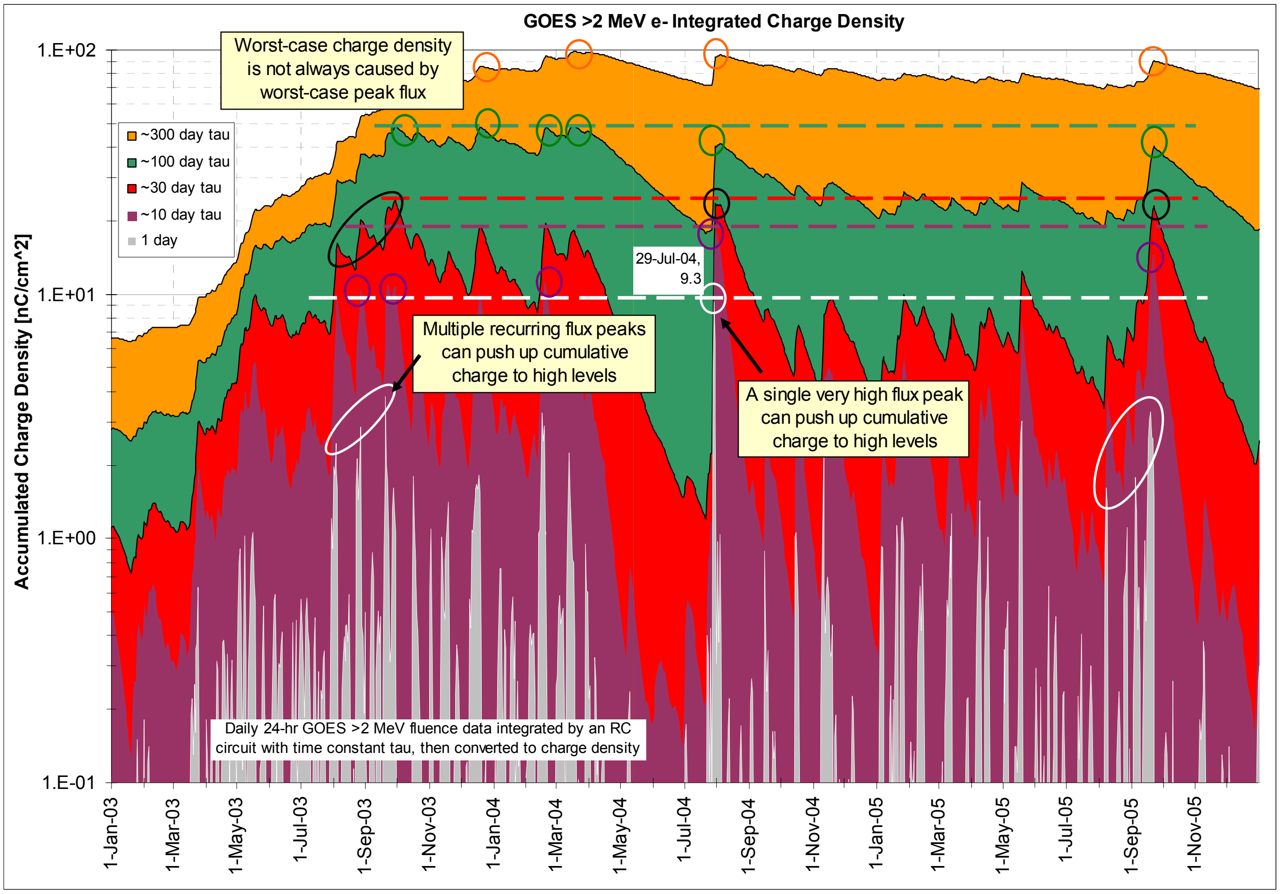
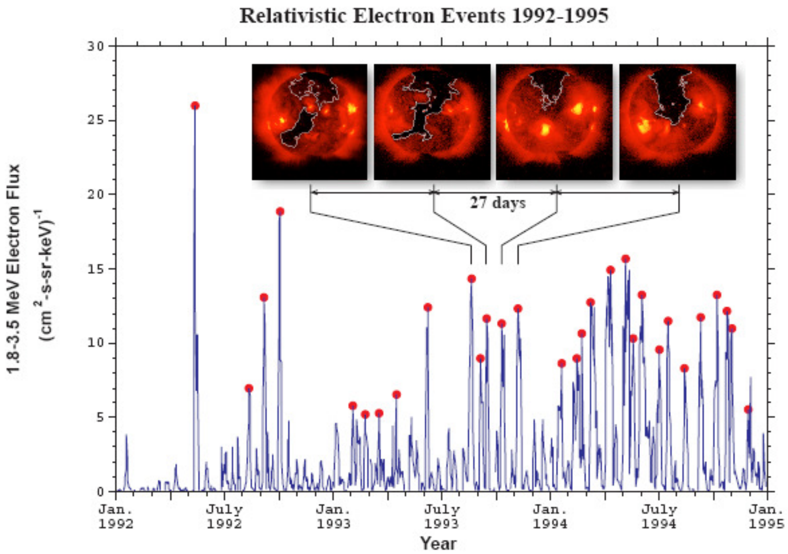


Figure 8 zooms in on 2003-2005. The high 24-hour peak-flux storms that occurred during these years produced rapid increases in the accumulated charge for all cases. But the peak of the accumulated charge (and the electric field it produces) varies by an order of magnitude depending upon the electrical time constant. In addition, note that materials with time constants of 30 days or longer do not see the worst-case accumulated charge during the storm with the highest 24-hour flux. For example, the peak accumulated charge for materials with τ=30 days occurs around 20 Sept. 2003, while the worst-case 24-hour flux occurred 2 months earlier on 29 July 2004. The figure also shows that multiple storms of lesser magnitude that occur in rapid sequence can produce hazardous levels of accumulated charge exceeding the charging produced by the single worst-case storm. Because of the wide variability of time constants and this memory effect, there is no single 24-hour flux level that provides a safe condition for all materials and the peak 24-hour storm flux may not represent the worst-case charging environment.

This pattern of recurring high-energy electron "storms" is a natural phenomenon that occurs during the right "season" in the 11-year solar cycle. During the transition from solar maximum to solar minimum, coronal holes on the sun appear near the solar equator (see the dark regions on the solar disk images in Figure 9). Coronal holes are open magnetic field regions on the sun that emit fast streams of particles into the solar wind[26] and when these holes open near the solar equator, the fast solar wind streams will intersect Earth's orbit. The high-energy electron storms observed by satellites are triggered when these high-energy streams interact with the Earth's magnetosphere.[27,28] (The detailed mechanics of the interaction is a subject of current research in the space science community.) Because coronal holes can persist for several months, they will reappear and trigger new storms about every 27 days, which is the period of a solar rotation (as seen on the Earth). When more than one equatorial coronal hole is active on the sun, multiple high-energy electron storms are generated each month.

Figure 9. Reappearing Coronal Holes Trigger Recurring High-Energy Electron Storms



As a consequence, materials with an electrical time constant longer than a week or two will be unable to completely bleed off charge between storms and will continue to accumulate more and more charge during the active years of the solar cycle (the "monsoon" season). During the quiet years of the solar cycle (1987-1992 and 1996-2003), storms are less frequent. More charge leaks out of the materials between storms than is deposited during the storms, and the accumulated charge and ESD risk trend downward. In summary, ESD risk is high and increasing during the intense years of the solar cycle, and gradually drops during the quiet years. The cycle dependent risk is not captured in a single 24-hour flux specification.

What Is a Safe Design?

ESD occurs when the accumulated charge density and electric field exceed the dielectric breakdown threshold of the material. The dielectric breakdown strength of most insulating materials falls in the few hundred kV/cm range,[29] when tested using the short duration electric field exposures of ASTM D149. A threshold of 100kV/cm is cited in NASA HDBK 4002, while some other authors put the limit at a lower level of about 10kV/cm. A design is deemed safe if the worst-case electric field that builds up due to accumulation of charge remains under this limit over the satellite lifetime. The electric field and accumulated charge are related by a material's electrostatic permittivity (see equations in Figure 5). The permittivity of many dielectrics falls in a narrow range: as low as ~1.2 for Teflon and up to 3 or 5 for Kapton and FR4 respectively. The critical charge density associated with ESD is about 10 nC/cm^2 (1nC = 1E-9 coulombs). This critical charge density corresponds to an E field threshold of 100 kV/cm for an epsilon of 1.2. A breakdown threshold of 6-20 nC/cm^2 has been separately reported in the electret literature[30] for films of 0.1-1 mm (4-40 mil) thickness. Dielectric strength and the corresponding critical charge are consistent and nearly material-independent criteria. Therefore, an ESD safe design is one that provides enough shielding to reduce the worst-case charge accumulated by <u>internal</u> dielectrics (and conductors isolated by those dielectrics) to levels below the ESD critical charge threshold.

Figure 10. Range of electrons versus energy[31]

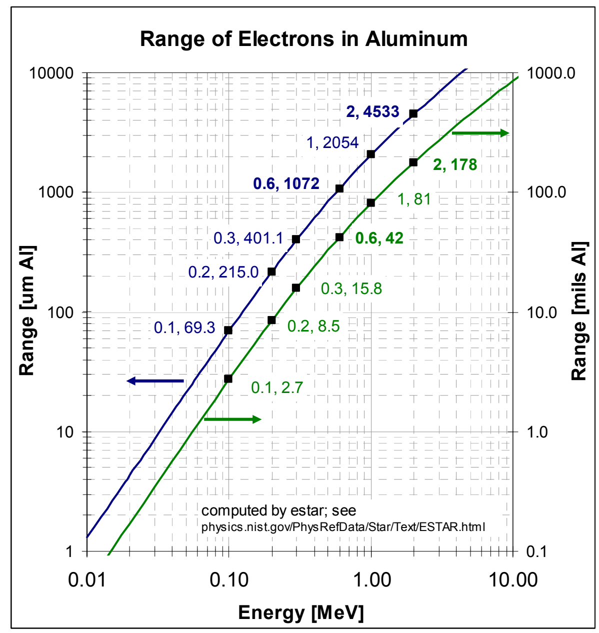
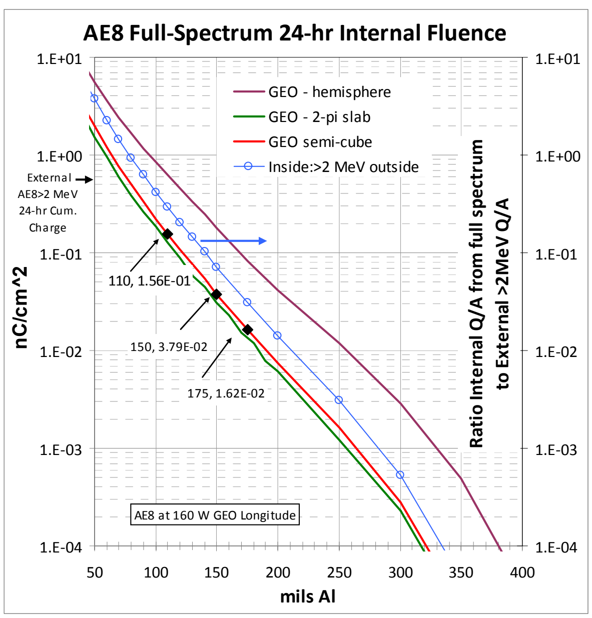


Figure 10 indicates that electrons require about 1 MeV to reach dielectrics and electrically isolated conductors within electronics that are shielded by spacecraft structure and a unit chassis, which together typically provide greater than 80 mils (2 mm) shielding. Consequently, an analysis to define the shielding required for an ESD-free design would require an external flux-energy spectrum defined at energies below 2MeV. GOES satellites have monitored the integral electron flux >600 keV in addition to the >2 MeV flux since 1997. The electron flux data acquired by Los Alamos National Laboratory (LANL) instruments in GEO provides an alternate data set,[32,33] but the > 2MeV high-energy data only goes back to 1996. Figure 6 shows that the worst-case cumulative charging occurred in 1994-1995. So we cannot bound the flux energy spectrum over the last two solar cycles using GOES >600 keV data or LANL data available after 1996.

The AE8 environment model[34] provides a complete electron flux energy spectrum from ~100 keV up to 4.5 MeV (in GEO), which is the basis for most radiation analyses in the satellite industry. However, the spectrum it provides is a long-term "average" suitable for mission total dose calculations, but does not predict any of the dynamics such as that seen in the GOES data.[35]

A hybrid analysis approach is adopted. The full AE8 electron flux-energy spectrum at the worst-case (highest flux) GEO longitude of 160 W was used[36] to define the average external flux. Having established an average external environment, the next analysis step was to transport the external spectrum through the spacecraft and unit chassis shielding to establish the internal flux level, as discussed in NASA HDBK 4002, Appendix D. Appendix A of the handbook identifies several computer codes that can transport the spectrum. One of those tools, NOVICE,[37] was used to transport the AE8 160 W spectrum through simple shield models (slab, semi-cube shell and solid hemisphere) to define the internal fluence vs. shield thickness. The curves shown in Figure 11 show the fluence-depth analogues to the dose-depth curves.

Figure 11. Internal 24-Hour Charge Density from AE8 (at 160 W) Flux-Energy Spectrum



The dynamic *internal* flux is defined by computing the ratio of GOES >2 MeV electron *external* flux to the AE8 >2 MeV electron *external* flux, and using that ratio to scale the *internal* flux from the entire AE8 spectrum. This approach assumes that the electron flux-energy spectrum is constant, regardless of flux intensity. The spectrum does vary over time, but as long as the shielding is thick enough that the threshold energy for penetrating the shielding is in the neighborhood of 2 MeV, this approximation will be reasonably accurate. The approach also simplifies the analysis because only a single electron flux-energy spectrum must be transported with a Monte-Carlo calculation.

NASA Handbook 4002 suggests that 110 mils of aluminum shielding is sufficient protection for GEO (paragraphs 4.9, 5.2.1.2 and 5.2.2.2). We can now evaluate the adequacy of that recommendation for a range of material time constants. The AE8 fluence penetrating a 110-mil aluminum semi-cube shell in 24-hours is 0.156 nC/cm^2, which is equivalent to a 24-hour averaged flux of 1.8 fA/cm^2 (a factor of 56 lower than the NASA limit of 100 fA/cm^2). The large safety factor between the internal AE8 flux and the NASA safe flux level *appears* to support the assertion that 110 mils of shielding should be safe in GEO.

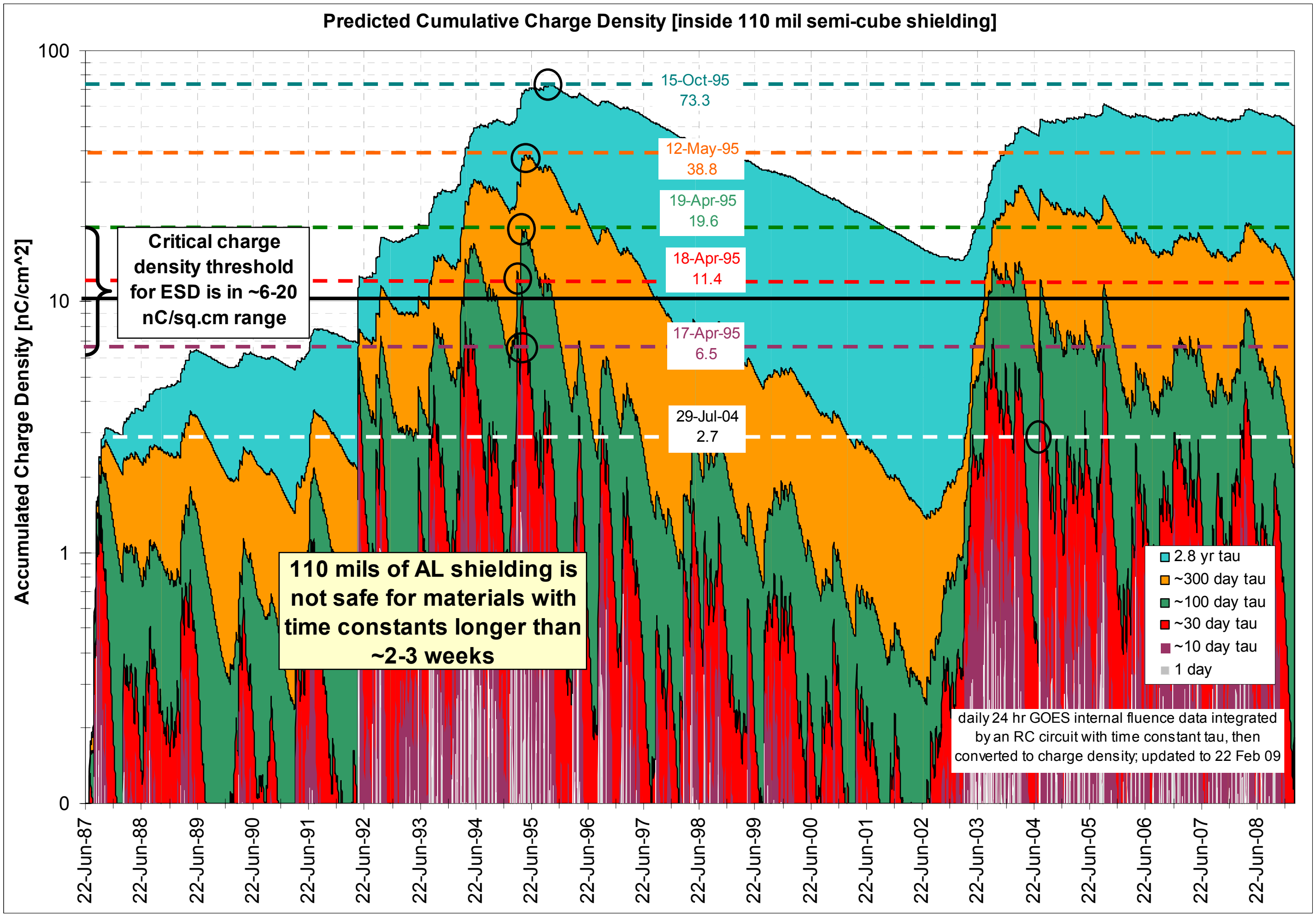
Figure 12 shows that a critical charge density threshold of 10 nC/cm^2 is breeched for materials with an electrical time constant of 30 days or longer, while a decay time constant of 10 days or less provides a margin of 35% or more. So clearly, 110 mils is inadequate to prevent ESD for materials with time constants as long as those observed in the recent NASA-sponsored testing. (Note: data also exists in older literature[38] demonstrating time constants for some materials such as Teflon with time constants exceeding thousands of days, even at elevated temperature, so it is not clear if the recent data is worst-case.)

We also infer from Figure 12 that the number of years within a solar cycle where ESD is a risk increases significantly when the time constant exceeds 30 days. The duration of ESD risk (time above threshold) was longer during the "monsoon season" between 1994 and early 1996 than the equivalent season between mid 2003 and mid 2005 for materials with a time constant of about 100 days. The more recent solar cycle (years following 2003) had an ESD risk duration that was longer than the prior cycle (in the mid to late 90's) for materials with very long time constants like 300 days.

It is also likely that multiple occurrences of ESD can occur for materials with very long time constants, since adequate charge is accumulated from subsequent storms to breech the critical charge threshold multiple times.

Additional shielding is required by long time constant materials to preclude reaching the critical charge threshold. Materials with a 300-day time constant require a reduction in accumulated charge by a factor of 4 (the gap between worst-case value of 38.8 and the 10 nC/cm^2 limit in Figure 12). Achieving that reduction requires adding about 40 mils (1 mm) aluminum shielding (Figure 11). This adds 27 kg of mass for every square meter of circuitry to be protected.

Figure 12. 110-mil Shielding is Unsafe for Materials with Long Decay Time Constant



Is There a Safe Time-Averaged Flux?

The foregoing material suggests that assessing ESD requires a complete historical time series record of flux data be available for a minimum of a solar cycle in a format suitable for numerical integration. This requirement is very different from the requirements being imposed on the development of AE9/AP9, the updated versions of the existing standard radiation belt models AE8/AP8. The guidance document[39] for the updated model notes:

> "Of critical importance is the period of time for which statistical distributions of the average flux over that time are needed. Hereafter these periods will be denoted as "flux-average periods" and are defined in terms of the time scales relevant to specific satellite effects rather than natural variation. For example, in the case of internal spacecraft charging it takes a finite time for charge deposited by energetic electrons to build up to critical levels where dielectric breakdown occurs. The timescale is a complex function of geometry, shielding, component material properties and impinging flux level. A meaningful analysis of breakdown probability and the consequent damage to the satellite requires the knowledge of the flux statistics averaged over a number of different time periods. Specific flux-average periods of 5 min, 1 hour, 1 day, 1 week and the mission duration are the consensus values deemed to be sufficient for design purposes."

The 5-minute to 1-week time periods are a subset of the time periods recommended by the radiation environment model users in industry that attended a NASA sponsored workshop in 2004.[40] The industry panel recommended establishing the worst-case day, week, month, 3 months and 6 months averaged flux for deep charging assessments. The results presented herein suggest even longer duration averages are needed. Fortunately, the forthcoming AE9/AP9 model will generate these longer-term averages.[41]

The question still remains; can a worst-case time averaged flux for an environment give an assessment of ESD risk equivalent to a direct charging analysis using the historical time series data? The answer is yes, if an exponential smoothing method of time averaging is used.

Figure 13 begins with the continuous-time solution for accumulated charge (given earlier in Figure 5) and shows how the discrete time-step solution is derived. Note that unlike a moving average, which uses a summation over a fixed and finite number of terms, the number of terms in the series solution for the accumulated charge density after n time steps, q_n, is unbounded since there is nothing to truncate the series. But at each time step, all prior contributions are reduced by another factor of $\alpha<1$, so older and older terms in the series make proportionally less contribution to the cumulative charge. Therefore, the summation remains finite even if n goes to infinity. For the special case of constant flux, the long-time (n goes to infinity) solutions converge to the steady-state, continuous-time solutions for accumulated charge and electric field at $t>>\tau$.

The worst-case time averaged flux is determined as follows. We start with the RC circuit integration of the 24-hour GOES >2 MeV flux (Figure 6) to determine the cumulative stored charge density every day (Figure 7), and then normalize the charge density by the electrical decay time constant τ used in the integration to derive an exponentially time-averaged flux.

The results of this exponentially time-averaged flux are shown in Figure 15. Note that, just like a simple moving average, the exponentially time-averaged flux gets lower as the time constant used in the integration and averaging gets longer. The worst-case exponentially time-averaged flux over the last two solar cycles is noted in the figure for a range material time constants. These peaks of the exponentially smoothed fluxes multiplied by the corresponding time constant return the worst-case cumulative charge density, which determines the real risk of ESD. (Dividing charge density by the permittivity returns the worst-case electric field.) The worst-case values in Figure 12 and Figure 15 are summarized in Figure 14 for convenience.

Note that these are *external* >2 MeV fluxes, and ESD is determined by the critical charge that accumulates inside. A means of extending the spectrum and transporting it to the interior is still required to complete the ESD risk assessment. An approximate method of first transporting the complete AE8 spectrum and then ratioing the GOES >2 MeV flux to the AE8 >2 MeV flux was used. This is a reasonable method for typical electronic shielding, where the energy required is close to 2 MeV.

Figure 13. Exponentially Smoothed Time Series Data for Constant Flux Converges to Steady-State Solutions

$$q(t) = q(t=0)\cdot e^{-t/\tau} + \tau\cdot J(t)\left[1-e^{-t/\tau}\right]$$

$$t_i - t_{i-1} = \Delta t = 1\,\text{day}$$

$$J_i = \text{24hr ave flux on day i}$$

$$\tau = \rho\varepsilon_r\varepsilon_0 = \text{electrical time constant}$$

$$\beta = \Delta t/\tau \quad \alpha = \exp[-\beta]$$

$$q(t=0) = q_0 = 0$$

$$q(t=\Delta t) = q_1 = \tau(1-\alpha)\cdot J_1$$

$$q(t=2\Delta t) = q_2 = \alpha q_1 + \tau(1-\alpha)\cdot J_2 = \tau(1-\alpha)\cdot[\alpha J_1 + J_2]$$

$$q(t=3\Delta t) = q_3 = \alpha q_2 + \tau(1-\alpha)\cdot J_3 = \tau(1-\alpha)\cdot[\alpha^2 J_1 + \alpha J_2 + J_3]$$

$$q_n = \tau(1-\alpha)\cdot\sum_{m=1}^{n}\alpha^{n-m}J_m$$

$$\text{if flux is constant at } J_0\text{, then } q_n = \tau(1-\alpha^n)\cdot J_0\text{, using}$$

$$S_n = 1 + r + r^2 + \dots r^{n-1} = (1-r^n)/(1-r)$$

$$\text{since } \alpha<1,\ (1-\alpha^n)\xrightarrow[n\to\infty]{} 1 \quad\text{and } q_n \xrightarrow[n\to\infty]{} \tau J_c = \text{the fluence over } t=\tau$$

$$\text{Use } J_{wc} \equiv Max[q_n]/\tau \text{ as the worst-case time averaged flux}$$

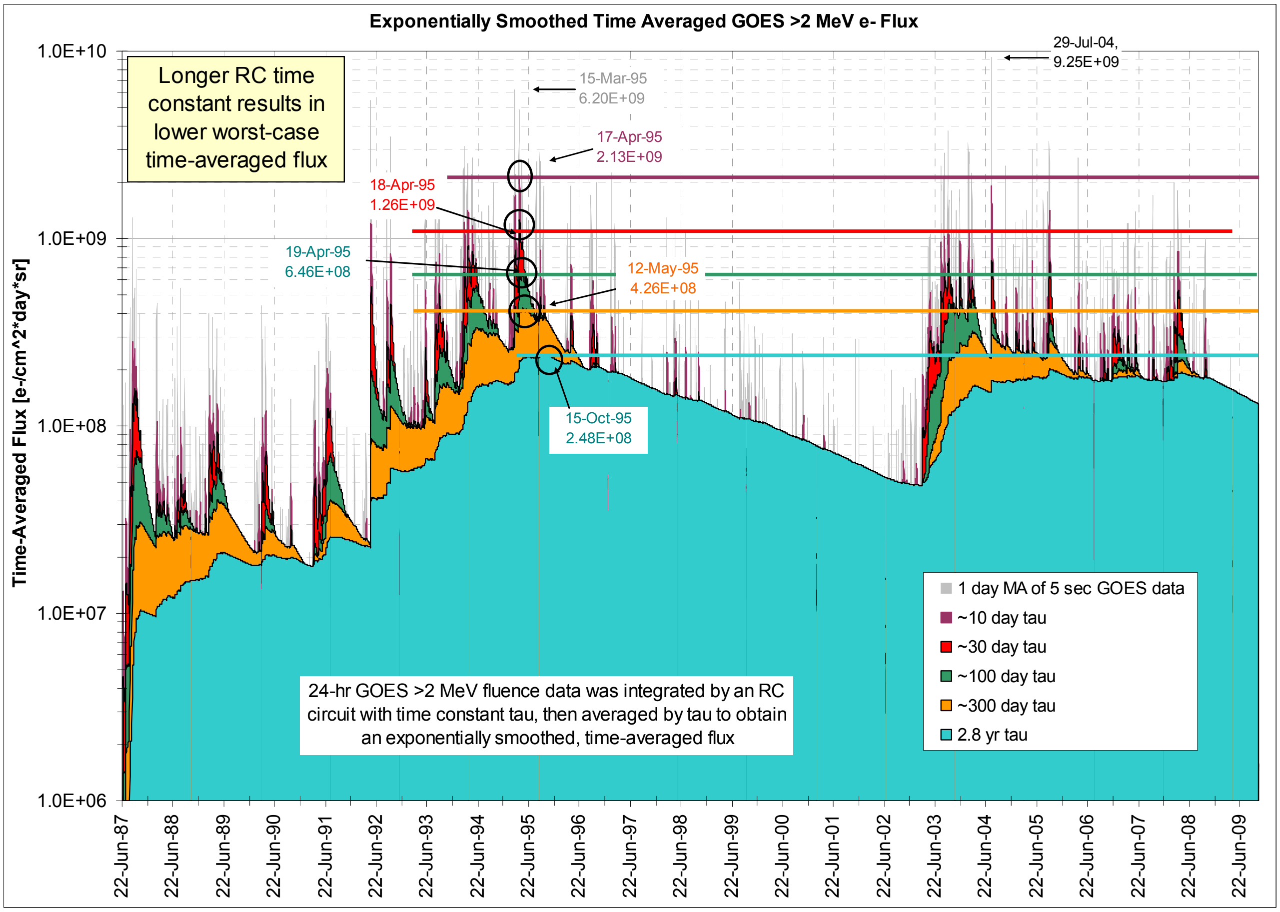
$$\text{The worst-case critical charge density is therefore } q_{wc} = \tau J_{wc}$$

$$E_n = q_n/\varepsilon_r\varepsilon_0 \xrightarrow[n\to\infty]{} \rho J_c = \text{steady-state field, and } E_{wc} = \rho J_{wc}$$

Figure 14. Worst-Case GOES >2 MeV Flux

Approx. Time Constant [days or Yrs]	Rho [Ω-cm]	Tau (εr=1) [days]	W-C Cum. Charge Density [nC/cm²]	W-C Tau Averaged Flux e-/cm²-sr-day
~3	3 E+18	3.07	13.4	4.34 E+09
~10	1 E+19	10.25	22.0	2.13 E+09
~30	3 E+19	30.74	38.8	1.26 E+09
~100	1 E+20	102.5	66.6	6.46 E+08
~300	3 E+20	307.4	132	4.26 E+08
2.8 yrs	1 E+21	1025	249	2.42 E+08
5.6 yrs	2 E+21	2050	342	1.66 E+08

Figure 15. Exponentially Time-Averaged GOES >2 MeV External Flux



Findings and Conclusions

Several key findings and conclusions have been reached:

1. The true failure threshold is related to the accumulated charge density and electric field, not to a short-term averaged flux level. An electric field of about 100-200 kV/cm or equivalently an accumulated charge density of 6-20 nC/cm^2 represent limits that apply to most materials.
2. The greatest accumulated charge did not result from the most severe 24-hour peak flux, but rather occurred following several lesser peak flux storms that occurred in rapid succession over a period of several months. The ultimate critical charge attained depended upon the material electrical time constant. A single short duration (10-hour or 24-hour) worst-case flux limit therefore does not define the risk of charging and ESD for long time constant materials.
3. Analysis supported by two solar cycles worth of GOES data shows the existing NASA Handbook 4002 guidelines of limiting the peak flux to less than 100 fA/cm^2 by providing 110 mils of aluminum shielding is not safe for the long electrical time constants of many materials in use on spacecraft. Achieving a safe design in GEO solely by limiting the internal flux requires substantially more shielding mass than current guidelines recommend.
4. Assessing ESD risks requires a solar cycle of flux history at a minimum. The short-term "space weather" data should be exponentially integrated using the electrical time constant properties of the insulating materials to arrive at an understanding of the worst-case risks of ESD. The long time constant integration makes ESD risk sensitive to solar cycle climatology, rather than to individual space weather storms.
5. Long time constant materials are seen to rapidly increase accumulated charge during a high-flux storm, retain much of their charge in between storms, and rapidly increase cumulative charge during the next storm. This behavior suggests that the critical charge or E field threshold for ESD will likely be breached,

and the consequential anomaly occur, during a short-duration, high-flux storm as opposed to during the long period between storms. This explains why anomalies are correlated with high-flux, short-duration (10-hour or 24-hour duration) storms, and yet do not occur during every storm of similar magnitude.

6. Worst-case exponentially smoothed fluxes have been established for a range of material electrical time constants. The worst-case fluxes return the proper estimates of worst-case cumulative charge density and electric field when multiplied by the electrical time constant and resistivity of the material, respectively.
7. Proposed upgrades to AE8 and AP8 to generate statistics or worst-case limits for flux exponentially integrated and averaged using time constants up to a few years. Short duration averages (hours to one week) will not provide the bounding environments needed for highly resistive materials.

Acknowledgements

The GOES >2 MeV electron data is provided by NOAA-SWPC. Dr. Howard Spitzer, Northrop Grumman Aerospace Systems, performed the radiation transport analysis that defined the internal flux from the AE8 external flux versus shielding.

---

1 "Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects," NASA-HDBK-4002, Feb 17, 1999.

2 "Thick Dielectric Charging on High Altitude Spacecraft," Vampola, J. Electrostatics, 20 (1987) 21-30. This paper is essentially identical to a previous publication: "Thick Dielectric Charging on High Altitude Spacecraft," Vampola, Report SD-TR-86-46, July 25, 1986 (DTIC access number AD-A171 078, approved for public release, unlimited distribution).

3 "A Summary of the Engineering Results from the Aerospace Corporation Experiments on the SCATHA Spacecraft," Koons, et al., 6th Spacecraft Charging Technology Conference, AFRL-VS-TR-20001578, 1 September 2000

4 "Low Flux Laboratory Test of the Internal Discharge Monitor (IDM) Experiment Intended for CRRES," Coakley, et al., IEEE Transactions on Nuclear Science, Vol NS-32, No. 6, December 1985, pp. 4066-4072.

5 "Spacecraft Charging: Progress in the Study of Dielectrics and Plasmas," Robinson and Coakley, IEEE Transactions on Electrical Insulation, Vol. 27 No. 5, Oct 1992, pp. 944-960.

6 "Characteristics of Spontaneous Electrical Discharging of Various Insulators in Space Radiations," Fredrickson et al., IEEE Transactions on Nuclear Science, Vol. 39, No. 6, December 1992, pp. 1773-1782.

7 "Method for Estimating Spontaneous Pulse Rate by Insulators Inside Spacecraft," Fredrickson, IEEE Transactions on Nuclear Science, Vol. 43, 1996, pp. 2778-2782.

8 "Spacecraft Anomalies on the CRRES Satellite Correlated With the Environment and Insulator Samples," Violet and Fredrickson, IEEE Transactions on Nuclear Science, Vol. 40, No. 6, December 1993, pp.1512-1520.

9 "Conclusive Evidence for Internal Dielectric Charging Anomalies on Geosynchronous Communications Spacecraft," Wrenn, Journal of Spacecraft and Rockets, Vol. 32, No. 3, May-June 1995, pp.514-520.

10 "Probability Factors Governing ESD Effects in Geosynchronous Orbit," Wrenn and Smith, IEEE Transactions on Nuclear Science, Vol 43, No. 6, December 1996, pp. 2783-2789.

11 "A Solar Cycle of Spacecraft Anomalies due to Internal Charging," Wrenn, et al., Annales Geophysicae (2002) 20:953-56.

12 "NOAA's Spacecraft Anomaly Data Base," Wilkinson, AIAA-90-0173, 28th Aerospace Sciences Meeting, Jan 1990.

13 "Trends in Spacecraft Anomalies," D.C. Wilkinson, Proceedings of the Spacecraft Charging Technology Conference, 1989, ed. R.C. Olsen, PL_TR_93-2027.

14 "Environmental On-Orbit Anomaly Correlation Efforts at Hughes," Balcewicz, et al., 6th Spacecraft Charging Technology Conference, AFRL-VS-TR-20001578, 1 September 2000.

15 "The Occurrence of Operational Anomalies in Spacecraft and Their Relationship to Space Weather," D. N. Baker, IEEE Trans. Plasma Science, Vol. 28, No. 6, December 2000.

16 "Statistical Relationships between Satellite Anomalies at Geostationary Orbit and High-Energy Particles," Pilipenko, et al., Advances in Space Research 37 (2006), 1192-1205.

17 "Failures and Anomalies Attributed to Spacecraft Charging," Leach and Alexander, NASA RP-1375, August 1995.

18 "Standard Test Methods for DC Resistance or Conductance of Insulating Materials," ASTM D257-07, is the updated version of D257-91 referenced in the NASA HDBK 4002.

19 "Charge Storage Measurements of Resistivity for Dielectric Samples from the CRRES Internal Discharge Monitor," Green, Frederickson and Dennison, 9th Spacecraft Charging Technology Conference, Tsukuba, Japan, April 2005.

20 "Radiation Induced Dielectric Charging," Frederickson, A.R., Space Systems and Their

Interactions with Earth's Space Environment, H.B. Garrett and C.P. Pike, eds., Vol. 71 of Progress in Astronautics and Aeronautics, AIAA, 1980

[21] Frederickson, et al., "Model for Space Charge Evolution and Dose in Irradiated Insulators of High Electric Fields," IEEE Tx NS, Vol. 40, No. 6, Dec 1993, p1393.

[22] Stevens, N.J. and M. R. Jones, "GEOCAT Engineering Code-Methodology and Calibration," AIAA-1994-423, 32nd Aerospace Sciences Meeting, Reno Nevada, Jan 1994.

[23] Sorenson, J. et al., "ESA's Tools for Internal Charging," IEEE Tx NS Vol. 47, No. 3 June 2000.

[24] "On the Mechanism of Dielectric Breakdown of solids," P. Budenstein, IEEE Tx-EI, Vol. EI-15, No. 3, June 1980.

[25] This circuit can be found in Figure 2 of "Internal Charging and Secondary Effects," Romero and Levy, The Behavior of Systems in the Space Environment, Ed. R. N. DeWitt et al., 1993, Kluwer Academic Publishers, p565ff. This R-C decay circuit can also be found in Appendix E of NASA HDBK 4002.

[26] Introduction to Space Physics, Kivelson and Russel, Cambridge University Press, 1995.

[27] "Relativistic Electrons and Magnetic Storms: 1992-1995," G. D. Reeves, GRL, 25, 1817, 1998.

[28] "Flux enhancement of radiation belt electrons during geomagnetic storms driven by coronal mass ejections and co-rotating interaction regions," Kataoka and Miyoshi, Space Weather, Vol. 4, S09004, doi:10.1029/2005SW000211, 2006.

[29] "Dielectric Strength, Short Time, ASTM D149," Appendix 3 of Electrical Properties of Polymers: Chemical Principles, Ku and Liepins, Hanser Publishers, Munich, 1987.

[30] Figure 2.3 of "Physical Principles of Electrets," Sessler, Chapter 2 of Electrets: Topics in Applied Physics, 2nd edition, Volume 33, Springer Verlag, 1987, and references therein.

[31] Electron range computed using ESTAR: physics.nist.gov/PhysRefData/Star/Text/**ESTAR**.html.

[32] "A Model for the Geostationary Electron Environment: POLE, 30 keV to 5.2MeV," Sicard-Priet, et al., IEEE Tx NS, Vol. 53, No. 4, Aug 2006.

[33] "A new international geostationary electron model: IGE-2006, from 1 keV to 5.2 MeV," Space Weather, VOL. 6, S07003, doi:10.1029/2007SW000368, 2008.

[34] "The AE-8 trapped electron model environment," J. Vette, NASA report NSSDC 91-24, NASA/GSFC. Greenbelt, MD, 1991.

[35] See for example "Dynamic Physical Modeling of Trapped Particles for Satellite Survey," Boudarie, et al., and "Recent Developments in the NASA Trapped Radiation Models," S.F. Fung, both in Radiation Belts: Models and Standards, AGU Geophysical Monograph 97, edited by Lemaire, Heynderickx and Baker, 1996.

[36] "The Space Radiation Environment for Electronics," E.G. Stassinopoulos and J. P. Raymond, Proceedings of the IEEE, Vol. 76, No. 11, Nov 1988.

[37] NOVICE. A charged-particle radiation transport code. It uses an adjoint Monte-Carlo technique to model particle fluxes inside a user-specified 3-D shield geometry. T. Jordan, Experimental and Mathematical Physics Consultants, PO Box 3191, Gaithersburg, MD 20885.

[38] Figure 2.27 and Figure 2.28 of "Physical Principles of Electrets," Sessler, Chapter 2 of Electrets: Topics in Applied Physics, 2nd edition, Volume 33, Springer Verlag, 1987, and references therein.

[39] "AE-9/AP-9 Trapped Radiation and Plasma Models Requirements Specification," 14 Jan 2009, G. P. Ginet, Air Force Research Laboratory and T. P. O'Brien, The Aerospace Corporation.

[40] See in particular slide 6 of "Industry Users Group, Model Requirements Update: The Oracle has Spoken," *Working Group Meeting on New Standard Radiation Belt and Space Plasma Models for Spacecraft Engineering,* Oct 2004, College Park, MD, available at http://lwsscience.gsfc.nasa.gov/RB_meeting1004.htm , 2004. [Note: this presentation is identified on this web site as *Model Requirements Update*, paper number 4 in the Introduction section.]

[41] Personal communication with T.P. O'Brien, Aerospace Corporation.