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.

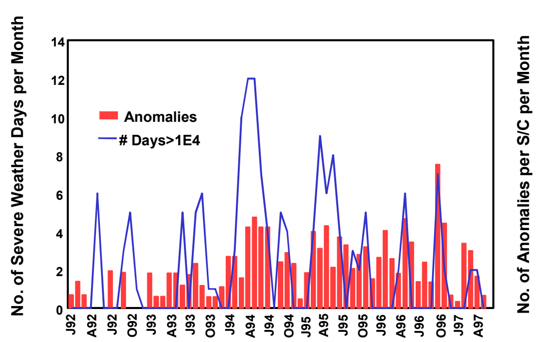

Figure 1: On-orbit Anomaly Rates Tend To Peak Concurrently With The High Energy Electron Environment

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.

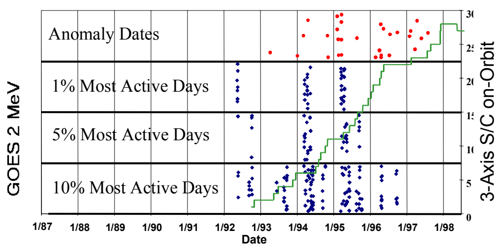

Figure 2: Occurrence Rates Increase With The Severity Of The Environment

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.

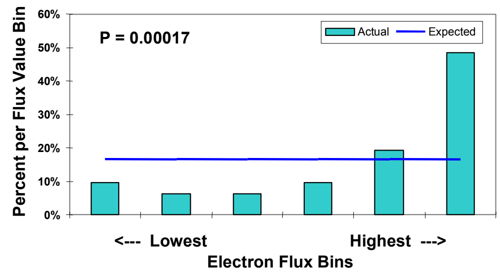

Figure 3: Unit A Anomalies Concentrated On Days Of Most Intense Environment

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.

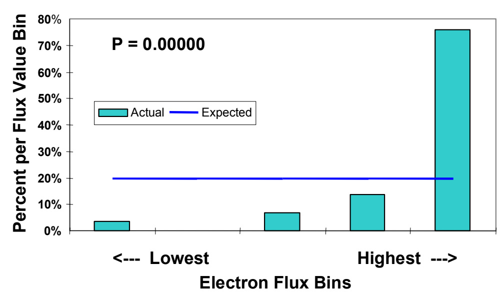

Figure 4: Unit B Anomalies Concentrated On Days Of Most Intense Environment

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.

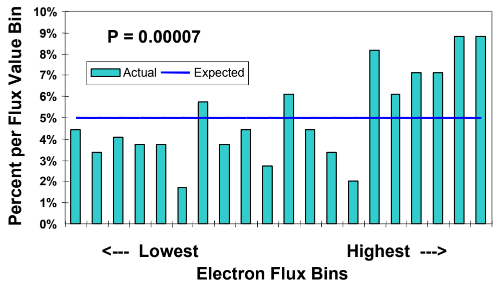

Figure 5: Overall HS601 (Body-Stabilized) Anomalies Also Concentrated On Days Of Most Intense Environment

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).

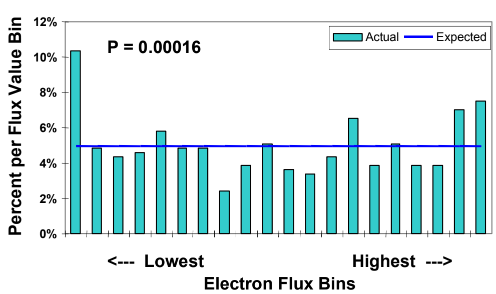

Figure 6: Overall HS376+ (Spin-Stabilized) Anomalies Not Strongly Concentrated On Days Of Most Intense Environment

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.

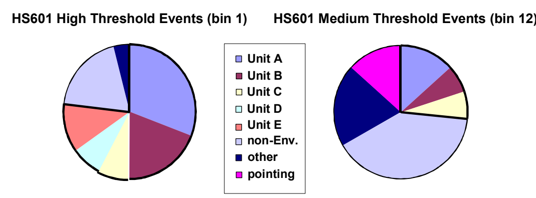

Figure 7: ESD-Related Anomalies Predominate On High Flux Days. Non-ESD Events More Common on Low Flux Days

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