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GEOSYNCHRONOUS SATELLITE OPERATING ANOMALIES CAUSED BY INTERACTION WITH THE LOCAL SPACECRAFT ENVIRONMENT*

Michael A. Grajek
Hiram College

Donald A. McPherson
Science Applications, Inc.

ABSTRACT

It is now apparent that a significant number of satellite operating anomalies are due to differential charging of spacecraft surfaces and resultant discharges. Recent satellite anomaly investigations generally support this conclusion. However, these investigations provide only limited information about the nature of charging/discharging mechanisms and, collectively, they support conflicting opinions on the importance of some environmental effects. This is due in part to limitations of the available data and in part to non-analytical visual inspection procedures that are frequently used to scrutinize and interpret the data. Examples illustrate how such procedures might lead to faulty conclusions. Further examples demonstrate quantitative statistical analysis procedures that can be used to strengthen the data handling, especially attempts to correlate spacecraft anomalies with geophysical parameters. As data from the SCATHA mission becomes available, it should be possible to carry out a very detailed statistical analysis of satellite operating anomalies because of certain key features of the SCATHA Data Analysis Plan.

STATE-OF-THE-ART ANOMALY INVESTIGATIONS

As table I illustrates, hundreds of geosynchronous satellite operating anomalies have been observed, recorded and subjected to analysis (ref. 1 through ref. 7). Most of these events have had little impact on the spacecraft mission, but they have been as serious as total failure of the power system. An examination of these investigations reveals the following general characteristics:

- A relation between actual anomalous behavior and spacecraft charging has been established. The most substantial evidence for this seems to be the highly significant statistical correlation between implied surface discharges and faulty

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responses and circuit resets (ref. 6).

- Conclusions have usually been based on a "pattern recognition" approach. The calculation of meaningful statistical correlations has been severely hampered by a lack of high time resolution data regarding the spacecraft local environment. Nearly all studies have called for routine inclusion of monitoring devices on board future flights.

- Various "correlations" of anomalous behavior with environmental and other effects have been observed. These include

    -local time dependence
    -seasonal dependence
    -geomagnetic activity dependence
    -day-of-the-week dependence
    -long-term decrease

Not all of these dependences are reported in every study, and the statistical basis for the dependences that appear to exist varies greatly. Moreover, there are some discrepancies between studies in the ways that certain correlations are supported:

- local time dependence: this is reported in about half of the flights. The transient events reported in reference 6 show a skewed distribution favoring local midnight to dawn that is statistically highly significant. On the other hand, the anomalous switching events reported in reference 4 are distributed more uniformly. This has led to the proposal of charge storage theories or theories involving discharges occurring at varying thresholds.

- geomagnetic activity dependence: this is said to be apparent in about half of the studies. However, this discrepancy is not considered important because of the limited information contained in the various ground-based geomagnetic activity indices used in the investigation.

- day-of-the-week dependence: this is noted in reference 1. The anomalous events appear to significantly favor the weekend. A similar trend can be found in the reference 6 data, but here the favored days are Friday and Tuesday. A further discussion of this peculiarity will follow.

- a seasonal dependence: an increased likelihood of anomalous behavior during eclipse seasons--and a long term decrease in the rate of anomaly occurrences are noted in most investigations. The latter trend has been theorized to be due to materials degradation effects.

In reference 8, a more detailed discussion of state-of-the-art anomaly investigations, through early 1978, is included.

NEED FOR QUANTITATIVE ANALYSIS

Reliable information regarding the previously outlined interactions of a satellite with its local environment is needed in the following efforts:

- Development of the Spacecraft Charging Standard
- Design Guidelines Update
- Validation and Development of various models including predictive equations for satellite behavior

(These projects are discussed in detail in other papers in these conference proceedings.) The following examples illustrate potential pitfalls of not using proper statistical procedures in these efforts.

Example: Misleading Data Patterns

Table II presents hypothetical data for the local time of sixty observed satellite upsets. In figure 1, this data is depicted in the usual manner in a polar representation with time as the angular coordinate and frequency as the radial coordinate. The data *appears* to support a theory suggesting that upsets are most likely to occur in the midnight to dawn quadrant. Rather than stop at a visual inspection, the *strength* of the support can be quantified by calculating the chi-square (χ^2) statistic using

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

This statistic measures the deviations of observed frequencies (O_i) in each data subdivision from what they would be expected to be (E_i) if the phenomenon producing the data is purely random. Then chi-square tables can be used to associate a probability value with the calculated chi-square value. (See reference 9, pp.274-278, for a detailed explanation.)

In the example, there are four data subdivisions (time quadrants) and since there are sixty data points altogether, each E_i is 15. The calculated chi-square value is 4.13 and the associated probability value is .7522 (ref. 9, table E). The interpretation is that a purely random phenomenon would produce data as unevenly distributed in the four time quadrants as ours with a probability of .2478; in other words, there is nearly a twenty-five percent chance that we would be mistaken if we claimed that the data was *not* due to random phenomenon. Thus, in spite of the visual appeal, it would seem risky to use this data to support a theory suggesting that upsets favor the midnight to dawn quadrant.

Example: Which Hypothesis to Choose?

Similar to figure 1, figure 2 illustrates hypothetical data for satellite upsets. The total number is one hundred. The data appears skewed, but it supports various theories of non-randomness with quite different strengths.

Theory A: upsets favor certain one-hour time periods over others. In this case, 24 data subdivisions are used, and we obtain

$$\chi^2 = 28.14$$

probability = .7893

Theory A has only minimal support.

Theory B: upsets favor the midnight-dawn quadrant. Here there are four data subdivisions yielding

$$\chi^2 = 5.28$$

Probability = .8476

Thus, theory B receives mild support.

Theory C: upsets favor the 0300-0600 and 0600-0900 sectors. This time there are eight data subdivisions and we obtain

$$\chi^2 = 17.12$$

Probability = .9834

Theory C seems well-supported by this data.

Obviously, there should be good reasons for choosing theory C (for example, the possible existence of a "charge buildup" mechanism) aside from its statistical superiority. It is an extremely important principle of inferential statistics that hypotheses should be formulated before data is examined. Nearly all data will support, at least weakly, *some* theory of non-randomness. The problem of examining complicated data sets in search of patterns or clusters is discussed at length in reference 10.

STATISTICAL VERIFICATION OF SPACECRAFT ANOMALY-ENVIRONMENT RELATIONSHIPS

In the anomaly investigations discussed in the first section, and in other studies, correlation analysis frequently consists of plotting the anomaly data versus the appropriate geophysical parameter and attempting to judge the degree of correlation by visual inspection. Unfortunately, this does not generate quantitative, probabilistic statements about the strength of the relationship; as noted in the previous section, it can be misleading, and furthermore, such a non-analytical approach can overlook subtle or weak correlations that may be real and identified with a high degree of confidence provided that a large amount of data are available.

The most common correlation measure is the (Pearson) product-moment correlation coefficient. It is calculated by dividing the covariance of two sets of data by the product of the standard deviations of each set (ref.9, ch. 12). Unity correlation coefficient corresponds to perfect correlation whereas 0 and -1 correspond to no correlation and perfect anticorrelation respectively. The square of the correlation coefficient may be interpreted as that proportion of the variation of one variable that can be explained by variation of the other variable. Thus, if the coefficient is $r = .9$, then only nineteen percent of the variation of one variable cannot be explained by its relationship to the other variable.

If the correlation between two variables is zero (no relationship) and the correlation obtained from the data is r, then the variable

$$t = r[(n-2)/(1-r^2)]^{\frac{1}{2}}$$

has a probability function given by

$$f(t) = \frac{\Gamma\left(\frac{\nu + 1}{2}\right)}{\sqrt{\pi\nu}\ \Gamma\left(\frac{\nu}{2}\right)} \left(1 + \frac{t^2}{\nu}\right)^{-(\nu+1)/2}$$

where the number of degrees of freedom, ν, is given by n-2 with n being the number of data points (ref.11, ch.10 and ch. 17). Then this function can be integrated from negative infinity to t and the result subtracted from 1 to obtain P, which can be interpreted as the probability of error in reporting a relationship if there is none. The analysis can be continued (ref.11, ch.17) to obtain a confidence interval, centered at r, for the true correlation between the variables. Thus r is a measure of the potential strength of the relationship between two variables while P and the confidence interval together give a measure of the reliability of the suggested relationship.

P and the confidence interval depend on r as well as the number of data points. For $r = .50$, table III shows values of P for various data-base sizes. Note that P decreases, and therefore reliability increases, as the number of data points increases.

In the examples that follow, the correlation coefficient r, the chi-square statistic, and the Kolmogorov-Smirnov test will be illustrated as methods for quantifying the relationship between two variables. Of course, many other statistical correlation techniques exist. Reference 12, appendix A contains a brief overview. Excellent in-depth presentations can be found in references 9, 10, and 11.

Example: Large Data Base Correlation

Nanevicz, Adamo, and Shaw (ref.13) show that a certain optical sensor exhibits an increase in temperature at a rate dependent upon geomagnetic activity. Visual examination of the data in Figure 9 of their report does not show any obvious relationship, but a statistical analysis yields a weak correlation with a high degree of confidence ($P < .001$) because there are so many data points available.

Example: Correlation of Anomalies with Geomagnetic Activity

Table IV presents data for anomaly occurrences versus geomagnetic activity for a satellite discussed in references 3 and 13.

The geomagnetic activity is expressed in terms of the index D_{ST} that is designed to measure the equatorial magnetic disturbance produced by magnetic storms, with diurnal and local-time effects removed. Increasing negative D_{ST} implies a more active field. The basis for comparison is the relative cumulative frequency of occurrence of the two variables. Note that about half of the time, the geomagnetic activity corresponds to a $D_{ST} > -15$. Therefore on the average, the anomalies occur during times when the field is more active than normal. One possible statistical test would be to test the hypothesis that the means of two distributions in Table IV are the same. But to do this requires that the theoretical distribution functions for the two variables be known (ref. 11, ch. 10).

It is recommended instead that a distribution-free test be used to test whether the distribution of anomalies is the same as the distribution of D_{ST}. If the two distributions were the same, then there would be no reason to believe that the anomalies depend upon geomagnetic activity. The Kolmogorov-Smirnov test will be used since fewer than 30 data points are available (ref. 9, pp.281-283). Otherwise a chi-square test would be appropriate.

To perform the test, the largest difference between the relative cumulative frequencies (Table IV, middle column) is noted. This value, .44, is compared to tabled values of the Kolmogorov-Smirnov statistic for its significance. The result is that a value this great would be obtained by chance with probability less than .00003.

Conclusion: with 99.997% confidence, occurrence of the anomalies is dependent upon geomagnetic activity as measured by D_{ST}.

Example: Correlation of Anomalies with Local Time

As was noted in the first section of this paper, a common practice for testing correlation of anomalies or events with local time is to plot the time of occurrence on a polar representation of local time. If the data are grouped at any particular time period then the data are judged to be "correlated". If the data are distributed over all local times, then quite often it is concluded that there is no correlation.

More properly, the distribution of the anomaly data should be tested relative to a uniform distribution over local time. If the number of points is less than 30, then the Kolmogorov-Smirnov approach can be used. Otherwise use a chi-square test.

A test has been made of the hypothesis that the Transient Events Counter data in reference 6 are uniformly distributed (occur randomly) in local time. For the three-month period February through April 1976, there were 21 events and the Kolmogorov-Smirnov distribution was used to perform the test. The probability of obtaining a distribution with greater variance, than measured, from uniform was 15%. The conclusion, based on this limited data, is that the events could be uniform in local time. However, as more events are added in for the next nine months, a chi-square test shows that random phenomena would produce such a skewed local time distribution only 0.037% of the time.

Conclusion: with 99.963% confidence, the events are not distributed uniformly in local time.

Example: Correlation of Charging Voltages between Two Satellites

Bartlett, DeForest, and Goldstein (ref.14) have given measurements of charging voltages on two spacecraft when the vehicles were eclipsed simultaneously. For the data presented in Table V, the two satellites were separated by 11 degrees in longitude (over 8000 Km).

The correlation coefficient of these two sets of data is r = 0.84. The corresponding value of P is .0003.

Conclusion: with 99.97% confidence, there is a relationship between the charging voltages on the two spacecraft during eclipse. (Note that we do not suggest a dependency; the existence of a significant correlation does not imply a causal relationship.)

Example: Correlation of Anomalies with Day-of-the-Week

In the first section of this paper it was noted that the spacecraft anomalies of reference 1 appear to significantly favor the weekend. A day-of-the-week dependence is also suggested by the data in reference 6, but here the favored days are Friday and Tuesday. However, in both of these studies, if second and subsequent events on multiple event days are ignored, the day-of-the-week correlation disappears. Moreover, the distribution of multiple event days does not deviate from randomness in a statistically significant manner [for the reference 1 data, χ^2 = 8.62, Probability = .8039].

Conclusion: It would seem that a day-of-the-week dependence is not supported.

STATISTICAL ANALYSIS OF THE SCATHA MISSION DATA

The data ambiguity of the last example of the previous section might not have occurred if it had been possible to accurately measure the magnitude, as well as merely count, discharge events. Then several relatively small discharges occurring over a short time interval would not receive the same status as several larger events spread out over several days. Magnitude is one example of what is called a blocking variable: a variable that defines a category within which the experimenter can restrict the observation of other variables. The reliability and sophistication of a statistical analysis is directly proportional to the number of blocking variables included in the collection of experimental data.

In the preparation of the P78-2 Data Analysis Plan (reference 12) the importance of proper selection of blocking variables was noted in the design of one of the key features of the Plan: the Mission Data Time Line. This concept begins with an enumeration of important spacecraft operating condition categories:

SPACE PLASMA ENVIRONMENT
- Quiet
- Mild Substorm
- Moderate Substorm
- Severe Substorm
- Transient Period (specify kind)

ECLIPSE
- yes
- no

MAGNETOSHEATH CROSSING
- Region 1
- Region 2
- Transient Crossing Period

CONTROLLED EXPERIMENTS/OPERATIONS
- None on
- SC4 Guns on (specify kind)
- Thruster Operations

Then the Mission Data Time Line consists of a chart indicating which of the 90 (5x2x3x3) mathematically possible unique categories the spacecraft is in at any time.

The information contained in the Time Line will be used in two major ways. First, it will be, itself, an important contribution to an understanding of the local environment of a geosynchronous satellite. Second, it will provide important additional blocking variables to be used in the statistical analysis of the various on-board experiments. Thus, for example, internal transient count rates may be compared across different levels of substorm activity; or, it may be possible to develop a regression equation (ref.11, ch.17) that will provide a good, in the sense of statistical significance, formula for the active control of charging effects with gun operations under various spacecraft operating conditions.

CONCLUDING REMARKS

In conclusion, the dependence of a spacecraft anomaly or event upon geophysical parameters should be established on the basis of statistical analysis and the results should be expressed numerically. Examples have been provided for establishing relationships between events and parameters such as geomagnetic activity, local time, and events on other spacecraft. Other examples have illustrated the potential dangers of not using quantitative statistical techniques. As was noted in the last section, the data collection planning and statistical analysis planning should be done together.

It may be noted that most of the examples given demonstrate a high correlation between the events and the geophysical parameter being investigated. These examples have been drawn from data which may have been published because of the highly visible correlation that exists. It is likely that there are data sets that have not been published because the correlation with geophysical parameters is not obvious, but it may well exist if analyzed properly.

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Table I. Summary of State-of-the-Art Anomaly Investigations

REFERENCE	NATURE OF ANOMALY	DATA BASE SIZE	ANALYSIS PROCEDURES	COMMENTS
1	Six types, primarily logic upsets and switching events	101	Distribution of anomalies presented in various histograms and graphs. No statistical correlation calculations reported.	33 months of data on two flights. Reported day-of-the week correlation probably artificial.
3	Faulty detector responses; uncommanded circuit resets surface discharges	41	41 actual anomalies correlated with detected surface discharges. Probability calculations.	Correlations are claimed between time of anomaly occurrence and both substorm activity and spacecraft surface discharges. Presents the most substantial evidence of relation between actual anomalous behavior and sheath environment.
4	Anomalous telemetry events	300+	Distribution of anomalies presented in several histograms. No statistical correlation calculations reported.	No local time correlation report Two years of data; Precautions t to insure data reliability; Vehic contains unusually large number of switching devices. Reports anomalies correlate well with eclipse season and geomagnetic activity.
6	Transients in wiring harnesses	215	Distribution of anomalies presented in various histograms and scatter diagrams. No reported correlation calculations.	1 year of data. Rough correlation with eclipse season noted. Discussion relates transient events to charging and discharging models and lab experiments.
2 & 5	Various performance abberations	200+	Distribution of anomalies presented in various graphs and histograms. Some probability claculations.	Group anomaly data from seven different flights. Correlations reported do not always apply to individual flights.
7	Switching Events	13	K and A_f index readings at times of events compared to the overall distribution of K and A_f. Results of 8 events would occur by chance less than 20% of the time.	Small data base. Exact time of events unknown; some of time estimates could be off by over 24 hours. Interesting probability approach.

Table II. Number of Upsets Occurring in Local Time Segments (Hypothetical Data)

Mid-0100	3	0900-Noon	5
0100-0200	3	Noon-1500	7
0200-0300	4	1500-1800	5
0300-0400	4	1800-2100	6
0400-0500	3	2100-Mid	5
0500-0600	4		
0600-0700	4	N=60	
0700-0800	4		
0800-0900	3		

TABLE III. Effect of Data Base Size on the Reliability of the Correlation Coefficient (r = .50)

N	P
5	.196
10	.071
15	.029
20	.012
25	.005
30	.002

Table IV. Spacecraft Anomaly Occurrence Versus Geomagnetic Activity

D_{ST}	Relative Cumulative Frequency of D_{ST} or greater value	Difference (col.4-col.2)	Relative Cumulative Frequency of Anomaly Occurrences	Number of Anomaly Occurrences
-65	.02	.07	.09	2
-55	.04	.14	.18	2
-45	.08	.24	.32	3
-35	.18	.37	.55	5
-25	.29	.44	.73	4
-15	.48	.38	.86	3
-5	.73	.22	.95	2
+5	.93	.07	1.00	1
+15	.97	.03	1.00	0
+25	.99	.01	1.00	0
+35	1.00	.0	1.00	0

Table V. Charging Voltages on Two Spacecraft When Eclipsed

Vehicle 1	Vehicle 2
0	0
-4000	-3000
0	0
0	0
-1500	-1400
-9000	-11000
-1000	-1400
-6000	-800
-6000	-6000
-1000	-1000
-1600	-3200
-1100	-800

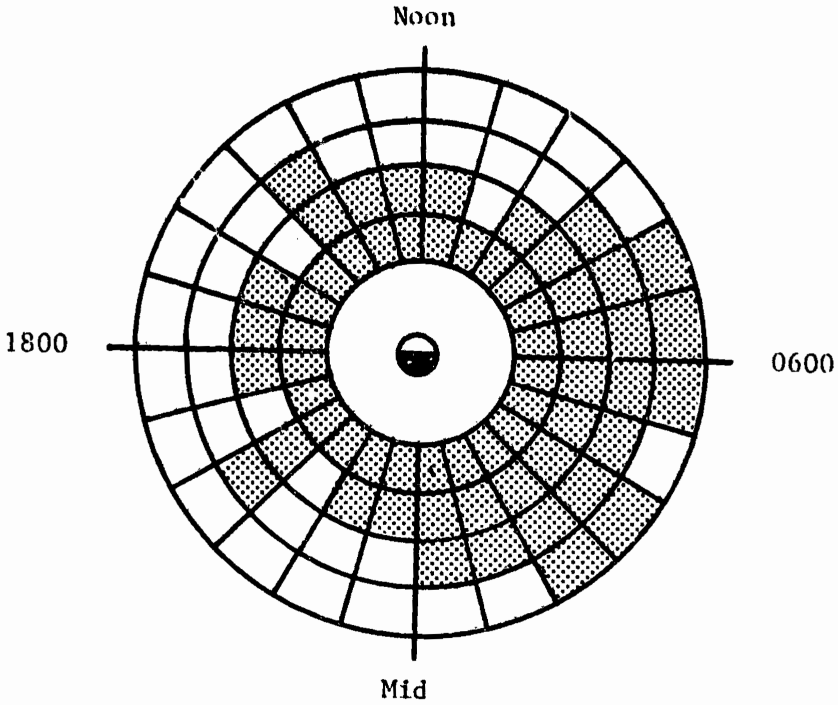

Figure 1. Polar Representation of Local Time of Sixty Upsets (Hypothetical Data).

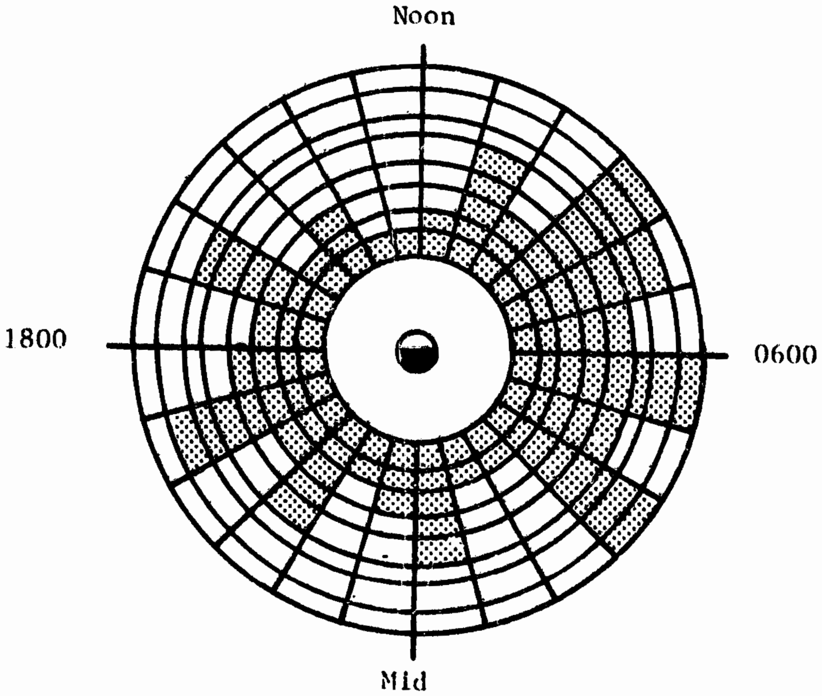

Figure 2. Polar Representation of Local Time of One Hundred Upsets (Hypothetical Data).