THE IMPACT OF THE SPACE ENVIRONMENT ON SPACE SYSTEMS

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Abstract. We have undertaken a study to determine the impact of the space environment on space systems. Known impacts include mission outages, mission degradation and mission failure, launch delays, redesign and retest, anomaly analyses, and the ultimate cost for each of the preceding. We are attempting to quantify these impacts whenever possible. This task is made difficult because impacts are rarely formally documented. We reviewed a variety of sources for anomaly impact information. These sources include anomaly reports from the archives of the Space Sciences Department of The Aerospace Corporation and other organizations, written and oral information from other staff members of The Aerospace Corporation, and contractor reports and published documents relating to spacecraft anomalies. The study provides a good indication of the quality and quantity of the data available. It will also determine the degree to which it is possible to obtain impact information for historical anomalies. In this paper we summarize the results of the study. We emphasize those causes for which it may be possible to provide predictive information such as surface charging, internal charging and the single event upsets that accompany solar proton events.

1. Introduction

We have undertaken a study to determine the impact of the space environment on space systems. We have included all types of spacecraft for which we have been able to find data. These include commercial, scientific, and military – both US domestic as well as foreign.

Known impacts include service outages, mission degradation and mission failure, data loss, sensor degradation, subsystem failure, launch delays, redesign and retest, anomaly analyses, and the ultimate cost for each of the preceding. We have attempted to quantify these impacts whenever possible. This task is made difficult because impacts are rarely formally documented.

2. Sources of Data

A variety of databases were used to determine those spacecraft anomalies that have been attributed to the space environment. The following comprehensive databases were utilized:

(1) Spacecraft Anomaly Manager (SAM). This database is maintained by NOAA/NGDC in Boulder, Colorado. This database primarily contains anomalies that are believed to have been caused by the space environment.

(2) NASA Anomaly Reports [*Bedingfield et al.,* 1996; *Leach and Alexander,* 1997].

(3) The anomaly database maintained by the US Air Force 55th Space Weather Squadron.

(4) Individual Program Offices databases.

The are a number of serious difficulties with these existing anomaly databases. For the most part the databases were designed to determine the extent of spacecraft problems from the standpoint of the spacecraft designer. One of their main uses has been to identify unreliable parts across a variety of different spacecraft and manufacturers. Although in some cases they identify the environment as the cause of an anomaly, the spacecraft generally lack sensors to determine the state of the environment at the location of the spacecraft at the time of an anomaly. Since the appropriate environmental data were not available at the spacecraft, it was often difficult to make a diagnosis with high confidence that an anomaly was caused by the space environment. The assessments that have been incorporated into the data records have been made by a large number of people some of whom are experts in environmental anomaly diagnosis and some of whom have little knowledge or training in this area. Thus, there is a great deal of variability in the quality of the assessments that have been made.

The databases are also poorly maintained. There is no formal mechanism for collecting or submitting data to the organizations that maintain the databases. Often after an anomaly is understood it is no longer considered an anomaly and may no longer be recorded in the database. Thus there is no way to accurately count or even estimate the number of occurrences of a given type of anomaly on even a single spacecraft from the existing databases.

The databases were found to be generally inadequate to perform this study because they contain virtually no information on the impact of the anomalies in the sense that we are studying them.

For both technical and insurance reasons the problems and impacts associated with anomalies are often closely held by the responsible organizations and are not normally released to the public.

3. Approach Used for this Study

We have augmented the databases above with a number of other sources for this study. We have reviewed the anomaly reports from the archives of the Space Sciences Department of The Aerospace Corporation to summarize the anomaly investigations that have been undertaken by the members of the department. In some cases the original source material mentions the impacts the anomalies have had, especially if they have led to a redesign of a spacecraft subsystem. We have also contacted people we have worked with on anomaly analyses to obtain written and oral information regarding those studies. Contractor reports, published journal articles, newspaper articles, and memos have also been reviewed to identify anomaly investigations and impacts. We also visited NOAA/NGDC and reviewed their anomaly files for anomaly impacts.

We have summarized the data collected for this study in a set of Space Environment Impact Forms. Each form contains the information for one class of anomalies for one vehicle. An anomaly class is a set of anomalies with essentially similar observables. This data collection can not and should not be used as an anomaly database for counting the individual occurrences of anomalies because each anomaly is not documented in a unique record. One form may document one anomaly or, in the extreme case, 617 anomalies for the main-bus under-voltage phantom commands caused by surface electrostatic discharges on the MARECS-A spacecraft. The Space Environment Impact Forms contain a description of the anomaly class, the diagnosis (i.e. the environmental cause), an indication as to whether or not the diagnosis was supported by the material in the references, a description of the impact, any relevant comments from the references or the compiler, and a list of the references from which the information was obtained. The data from the forms have been entered into an Microsoft Access database to facilitate gathering statistics for this paper.

4. Results

326 Space Environment Impact Forms were completed for this study. The number of forms by spacecraft affiliation is given in Table 1. The total count in that figure is greater than 326 because some of the spacecraft fall under more than one affiliation such as foreign commercial communication satellites. 299 of the forms contain anomalies that have the cause diagnosed as the space environment. Of these 299 only 155 have impacts obtained from the referenced documents.

Virtually none of the impacts is quantified in terms of the cost. Nor are their descriptions of the effects on the ultimate user of the space system. This is understandable because none of the information was provided by the ultimate user. Most of the information in the available sources was provided by the operators and the vehicle manufacturers. Hence it tends to be related to operator impacts such as time required to restore the vehicle to normal operation or to technical impacts such as the testing and redesign required to “fix” the next generation of vehicles.

Table 1. Distribution of Space Environment Impact Forms by Affiliation.

Affiliation	Number of Forms
DoD	87
Foreign	63
NASA, NOAA	58
Scientific	57
Classified/Other	52
Commercial	51

4.1 Anomaly Diagnosis

The distribution of forms by anomaly diagnosis is given in Table 2. The first group is electrostatic discharges (ESD) and charging. The ESD anomalies group contains the largest number of forms: 162. Virtually all of the anomalies in this area result from discharges. Only one was caused by the voltage changes on the surface of the vehicle. The uncategorized ESD anomalies refer to those which were not identified as either internal discharges or surface discharges in the references.

The second largest number of forms, 85, falls in the Single Event Upsets (SEU) group also shown in Table 2. It contains less than half the number of forms as the ESD group. The uncategorized SEU anomalies refer to those which were not related to cosmic rays, solar proton events, or the South Atlantic Anomaly in the references. Of these the largest class is probably due to cosmic rays and the smallest to solar proton events.

Table 2. Distribution of Forms by Anomaly Diagnosis.

Diagnosis	Number of Forms
ESD - Internal Charging	74
ESD - Surface Charging	59
ESD - Uncategorized	28
Surface Charging	1
Total ESD & Charging	162
SEU - Cosmic Ray	15
SEU - Solar Particle Event	9
SEU - South Atlantic Anomaly	20
SEU - Uncategorized	41
Total SEU	85
Solar Array - Solar Proton Event	9
Total Radiation Dose	3
Materials Damage	3
South Atlantic Anomaly	1
Total Radiation Damage	16
Micrometeorid/Debris Impact	10
Solar Proton Event - Uncategorized	9
Magnetic Field Variability	5
Plasma Effects	4
Atomic Oxygen Erosion	1
Atmospheric Drag	1
Sunlight	1
IR background	1
Ionospheric Scintillation	1
Energetic Electrons	1
Other	2
Total Miscellaneous	36

A distant third with 16 forms is the radiation damage group. The largest member of this group is unusually large solar-array degradation which is only reported as a anomaly when it occurs during a large solar proton event. Total radiation dose anomalies are surprisingly infrequent, representing only 1% of the forms. This probably reflects the conservative limits defined in the radiation models and the conservative approach applied by designers when specifying shielding limits for electronic components.

Twelve other miscellaneous causes amounted to only 36 forms.

4.2 Impacts

Table 3. Distribution of Forms by Impact Duration

Duration of Impact	Number of Forms
Minimal	13
Less than 10 min	8
10 min to 1 hr	14
1 hr to 1 day	54
1 day to 1 wk	7
More than 1 wk	68
Mission loss	9
Unknown	153

The only impact that could be readily quantified is the time required for the operators to recover from an anomaly. This may be taken as the duration of the impact on the user. This impact usually represented complete loss of data or service for the duration. The durations shown in Table 3 are the length of time that was required to restore service to the users. It is interesting to note that it is tri-modal with peaks at *Minimal*, *One Hour to One Day*, and *More Than One Week*.

A *Minimal* duration anomaly has essentially no impact on the users. Some anomalies caused by SEUs are in this category because many spacecraft are designed to detect such anomalies and perform an automatic recovery. Anomalies in housekeeping functions such as temperature sensors are also in this category because they have no impact on the user.

One hour to One day represents the time it takes to recover, for example, when a vehicle suffers an attitude-control anomaly or enters a safe-hold condition. *More Than One Week* includes permanent damage and failures.

Table 4 lists other identifiable impacts that have happened on a number of systems. The largest number of forms is 70 for *Phantom Commands*. The most serious is the *System or Part Failure* category which occurs in 53 or 16% of the cases.

Solar Array Degradation refers to the loss of solar array power capability primarily due to radiation damage of the solar arrays during a solar proton event. In most cases the impact given in the source material was the potential loss of mission lifetime. However, there was no follow up to determine if this shortening of the mission actually occurred. Thus it was not possible to determine if this impact was ultimately real or only predicted.

4.3 Mission Loss

Table 5 lists those missions that were listed as mission losses in the source material and for which the diagnosis was environmental. Because of the impossibility of making a definitive diagnosis

Table 4. Other Impacts

Impact	Number of Forms
Phantom Command	70
Degraded Performance	55
System or Part Failure	53
Upsets	47
Other or Unknown	47
Spurious Signal	24
Solar array Degradation	14

Table 5 Missions Lost or Terminated Due to the Space Environment

Vehicle	Date	Diagnosis
DSCS II (9431)	Jun 73	Surface ESD
GOES 4	Nov 82	Surface ESD
Feng Yun 1	Jun 88	ESD
MARECS A	Mar 91	Surface ESD
MSTI	Jan 93	Single Event Effect
Hipparcos*	Aug 93	Total Radiation Dose
Olympus	Aug 93	Micrometeoroid Impact
SEDS 2*	Mar 94	Micrometeoroid Impact
MSTI 2	Sep 94	Micrometeoroid Impact
IRON 9906	1997	Single Event Effect
INSAT 2D	Oct 97	Surface ESD

* Mission had been completed prior to termination

remotely and the serious repercussions of a mission loss there is usually considerable controversy surrounding the cause of each mission loss. For the most part the diagnoses listed have been identified as probable causes by experts on space environmental anomalies who have been involved in the analyses of anomalies on those vehicles.

The largest cause of mission failures related to the space environment is Surface ESD. In all cases those vehicles were in geosynchronous orbit.

5. Space Weather Forecasting

Spacecraft charging ESD has caused by far the most environmentally related anomalies on spacecraft and surface charging has caused the most serious anomalies, i.e. those that have resulted in the loss of the mission. Unfortunately it is much more difficult to forecast the location and seriousness of spacecraft surface charging than it is to forecast the location and seriousness of internal charging.

Internal charging occurs one to a several days after a major magnetic storm. Hence, the storm itself is a warning that high levels of energetic electrons may be present in the radiation belts in the near future. Since these electrons primarily diffuse inward after the storm their progress could be monitored and flux levels reasonably well predicted one to two days in advance. Efforts to do this have been undertaken using linear prediction filters and neural networks [*Nagai,* 1988; *Baker et al.,* 1990; *Koons and Gorney,* 1991; 1993].

Surface charging is much more difficult to predict. It not only requires a prediction of a magnetic storm or substorm but also the electron distribution function as a function of location in the magnetosphere. Surface charging is not necessarily related to the absolute intensity of the flux of hot electrons around the spacecraft but rather to the details of the electron distribution function. For example, the worst-case surface-charging event on the SCATHA spacecraft on 22 September 1982 occurred at a time when the electron distribution function at low energies (< 1 keV) was below average, at middle energies (1 to 10 keV) was near the top of its average range, and at high energies (20 to 100 keV) was above its average range [*Koons et al.,* 1988; *Roeder,* 1994]. It is likely that the combination of high fluxes in the higher-energy range combined with a reduction in the secondary electrons from primaries in the low-energy range caused the extreme surface charging conditions on that day. Since surface charging occurs on a much faster time scale than internal charging only an imminent forecast is probably possible and it is unlikely that the location can be accurately identified without a significant number of sensors located across the tail of the magnetosphere.

Only the SEUs related to solar proton events can be forecast and only an imminent solar proton event can be expected to be forecast in the foreseeable future. Since these SEUs represent only about 10% of the SEU Space Environment Impact Forms, forecasts of solar proton events will not have a significant effect on impacts caused by SEUs.

Similarly, solar array degradation due to radiation damage of the arrays during a solar proton event will not have a significant effect on environmental impacts. This effect is further reduced because the time remaining in the mission is not necessarily related to this degradation but is more often caused by some other failure on the vehicle.

Other causes make up a small portion of the environmentally related anomalies and many, such as total radiation dose, atomic oxygen erosion, micrometeoroid impact and debris impact, although predictable in the long term, are inherently not forecastable in the short term..

6. Recommendations

We recommend that significant efforts be made to better specify the electron distribution functions responsible for surface charging and internal charging. It is especially important to obtain the worst case environments in the spirit of the 100-year storm used by civil engineers to design dams and flood control systems. With such specifications and with studies of the interactions of these environments with candidate spacecraft materials, the spacecraft designer will be better able to design spacecraft that are immune to the environment.

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References

Baker, D. N., McPherron, R. L., Cayton, T. E., and Klebesadel, R., “Linear Prediction Filter Analysis of Relativistic Electron Properties at 6.6 R_E,” J. Geophys. Res., 95, 15133-15140, 1990.,

Bedingfield, K. L., Leach, Richard D., and Alexander, M. B., “Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment,” NASA Reference Publication 1390, Marshall Space Flight Center, August, 1996.

Koons, H. C., Mizera, P. F., Roeder, J. L., and Fennell, J. F., “Severe Spacecraft-Charging Event on SCATHA in September 1982,” J. Spacecraft and Rockets, 25, 239-243, 1988.

Koons, H. C., and Gorney, D. J., “A Neural Network Model of the Relativistic Electron Flux at Geosynchronous Orbit,” J. Geophys. Res., 96, 5549-5556, 1991.

Koons, H. C., and Gorney, D. J., “Forecasting the Relativistic Electron Flux at Geosynchronous Orbit,” in Solar-Terrestrial Predictions - IV, Proceedings of the Workshop at Ottawa, Canada, May 18-22, 1992. Edited by J. Hruska, M. A. Shea, D. F. smart, and G. Heckman, Vol. 2., pp. 580-586, NOAA Environmental Research Laboratories, Boulder, CO, Sept. 1993.

Leach, Richard D., and Alexander, M. B., “Failures and Anomalies Attributed to Spacecraft Charging,” NASA Reference Publication 1375, Marshall Space Flight Center, August, 1995.

Nagai, Tsugunobu, “Space Weather Forecast: Prediction of Relativistic Electron Intensity at Synchronous Orbit,” Geophys. Res. Letters, 15, 425-428-1988.

Roeder, J. L., Specification of the Plasma Environment at Geosynchronous Orbit in the Energy Range 87 eV to 288 keV, Aerospace Report No. TR-94(4940)-6, The Aerospace Corporation, El Segundo, California, 15 August 1994.