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DOD Space Research and Development

Environmental Sensitivities of the Combined Release and Radiation Effects Satellite (CRRES)

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Abstract

CRRES on-orbit experiments frequently required reconfiguration to meet test objectives. Our analysis of the environmental conditions, during the time of these satellite anomalies, indicated a probable environmental cause. We examined possible contributing factors; such as geomagnetic storms, proton enhancements, and transient, high-energy electron fluxes; to develop experiment reconfiguration thresholds. This paper specifies each threshold's accuracy as an alert or warning criteria and indicates the time-dependence of satellite vulnerability, particularly after the major solar flare of 22 March 1991. We further suggest implications for other similarly radiation hardened satellites or satellite subsystems.

1. INTRODUCTION

The Combined Release and Radiation Effects Satellite (CRRES) endured 223 anomalies between 25 July 1990,the launch date, and 26 August 1991, the last day of the database for this study. Those anomalies ranged from reconfiguring the experiments (thus regaining the ability to obtain serviceable data) to a battery failure, correctable only by switching batteries. The first occurred 3 days after launch. However, most anomalies occurred after an X9/3B major solar flare, on 22 March 1991.

This study examined the available anomaly database to determine if an environmental signature existed and thresholds for alert or warning criteria.

Lt Mike Violet, Air Force Geophysics Laboratory, Hanscom AFB, is working on a more definitive study using the complete database, including clock-jump data and more specific anomaly times, unavailable for this study.

A previous study by Dr Harry Koons, Aerospace Corporation, Los Angeles, showed CRRES had a sensitivity to energetic electrons, 5,000 or more particles per cm^2-sec-sr with energies greater than 5 MeV. (Proton and electron flux used throughout this report is a 5-minute-average integral with units of particles per cm^2-sec-sr.)

Several organizations, including Air Force Geophysics Laboratory (AFGL now Phillips Laboratory/GP), Office of Naval Research (ONR), Air Force Aero Propulsion Laboratory (AFAPL) and the Naval Research Laboratory sponsored instruments on-board CRRES. It's mission was to:

1) Study the effects of the natural radiation environment on microelectronic components and to map this environment,

2) Conduct low altitude satellite studies of ionospheric irregularities, and

3) Conduct a series of chemical releases, at low-and high-altitude, to study the effects of these releases on the ionosphere and magnetosphere.

CRRES's geostationary transfer orbit experiences the environmental hazards of both low altitude and geostationary spacecraft. Such hazards include surface or deep-dielectric spacecraft charging, radiation effects from transient energetic particles, particles trapped in the Van Allen radiation belts and cosmic rays.

2. STUDY METHODOLOGY

2.1 Raw Databases

This study used two separate databases as input. They were the satellite anomaly database and the environmental database. Neither database included any proprietary data unique to the experiments.

John Laning, Consolidated Space Test Center (CSTC) collected 223 anomalies comprising the satellite anomaly database. This database included the time-range during which the anomaly occurred (the previous remote tracking site contact to the contact the anomaly was discovered), the times of perigee or apogee, satellite altitude, and whether or not experiments needed reconfiguring. This database also included nine anomalies designated as spacecraft anomalies. It did not include clock-jump data nor attitude adjustments.

The environmental database included geomagnetic indices, proton and electron data. The proton and electron levels were from the weekly geosynchronous satellite environment summary charts in the Preliminary Report and Forecast of Solar Geophysical Data booklet, published weekly by the joint NOAA-USAF Space Environment Services Center (SESC). We maintain the geomagnetic database locally, including the 3-hour geomagnetic values used in this study. Plots from Air Force Global Weather Center (AFGWC) filled in missing data.

Interpreting the charts added a large degree of inaccuracy (on the order of 20 to 50 percent). Fortunately, this study did not require a high degree of accuracy in reading the proton and electron fluxes to gain valid results. Whether the actual value was 1,000 versus 1,300, or even 1,500, was not as important as the fact that the flux was at least 1,000--an easy threshold to read on the charts.

2.2 Procedures

I analyzed the two raw databases to determine 1) environmental conditions during the anomaly, and 2) an estimate of the usefulness of an environmental threshold as an alert or warning criteria. Since each anomaly took place over a time span from 1 to 8 hours, I took the highest or the most severe value of the environmental hazard. For each of the three types of hazards tested (geomagnetic storms, proton enhancements or increased electron fluxes), I checked three thresholds. The geomagnetic thresholds used were minor, major and severe. Proton enhancement thresholds used were 1 particle with energy at least 10 MeV, 1 particle with energy at least 50 MeV, and 10 particles with energies of at least 50 MeV. Electron flux thresholds used were 1,000, 10,000, and 100,000 with energies of at least 2 MeV.

Two event-time duration categories used in the results were the one-half to full day and less than one-half day. To count as a one-half to full day, the environmental condition must exist for at least 12 hours. For the less than one-half day category, the condition must cover more than 3 hours but less than 12 hours. A 3-hour geomagnetic storm would not count-neither would a quick spike of either electrons or protons crossing the threshold then quickly dropping back below the threshold.

Geomagnetic storms, proton enhancements and electron fluxes above the thresholds listed above were not mutually exclusive events. The three hazards often occurred simultaneously, particularly in March, April, June and July of 1991. No attempt was made to separate the effects of each type of hazard because differences were expected to show up in each threshold's accuracy as alert or warning criteria.

3 RESULTS AND DISCUSSION

3.1 Environmental Signature

Table 3.1 Environmental Signature of the Anomalies

	Number of	Geomagnetic Days			Electron Days`			Proton Days`~		
Time	Anomalies	Minor	Major	Severe	1K	10K	100K	1(10)	1(50)	10(50)^
Jul-Aug 90	5	11	6	1	1	0	0	3	2	0
Sep 90	5	2	0	0	1	0	0	0	0	0
Oct 90	8	3	1	0	4	0	0	0	0	0
Nov 90	3	1	1	0	0	0	0	0	0	0
Dec 90	7	0	0	0	0	0	0	0	0	0
Jan 91	5	0	0	0	1	0	0	1	1	0
Feb 91	1	1	0	0	0	0	0	1	0	0
Mar 91	26	7	3	3	9	5	3	8	7	5
Apr 91	22	8	2	0	6	0	0	3	2	0
May 91	16	8	1	0	7	0	0	2	1	1
Jun 91	49	16	11	3	17	4	0	19	18	11
Jul 91	49	11	5	2	17	2	0	8	6	0
Aug 91*	27	13	7	1	5	0	0	1	0	0

Note: Total Days derived from adding half the less than one-half days to the number of one-half to full days
` five minute average integrated flux /(cm2-sec-sr)
~ #(#) Number of protons (MeV Energy Level)
^ Proton Event
* Database ends on 26 Aug 91.

Table 3.1 displays the number of anomalies and the general level of activity in the space environment each month. This table clearly shows the possibility of the environment causing many of the anomalies. Notice the drastic upturn in the number of anomalies, the geomagnetic-storm days, the electron-event days and the proton-enhancement days in March 1991 and another increase in June 1991. Charts 3-1, 3-2 and 3-3 presents these trends more clearly .

Chart 3-1 Environmental Signature (Geomagnetic)

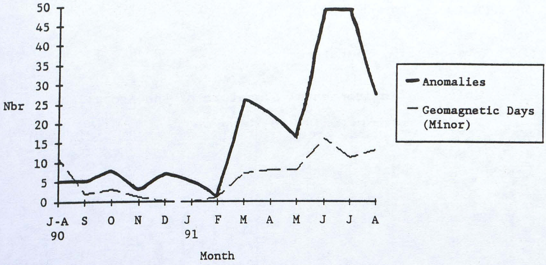

Chart 3-2 Environmental Signature (Electrons)

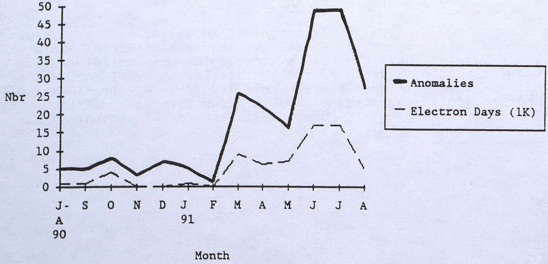

Chart 3-3 Environmental Signature (Protons)

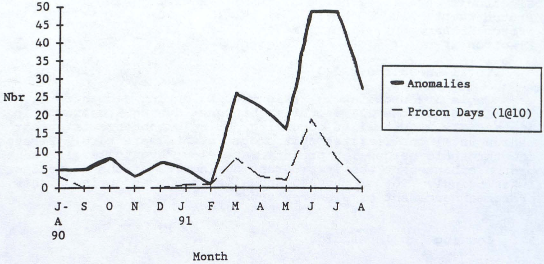

Table 3.1 also reveals a background level of nearly three anomalies per month having no apparent cause--see December 1990. There are two possible explanations for the environment causing these anomalies. First, CRRES's orbit traverses the radiation belts. Trapped particles in these belts can cause an anomaly on any spacecraft transit, regardless of the space environmental activity. Secondly, the random nature of high-energy cosmic rays can cause an anomaly anywhere in the orbit.

There's no way of telling with 100 percent confidence what caused CRRES's anomalies. However, the types of anomalies suffered resemble single event upsets caused by radiation effects or by discharge from deep charging. The best we can do is correlate the occurrence of the anomaly with the environmental condition and test each threshold as to whether any anomalies occurred when the threshold was crossed. Table 3.1 and Charts 3-1, 3-2 and 3-3 show the environmental cause was possible but did not prove it.

3.2 Anomalies and the environment

Table 3.2 Hazard Occurring When an Anomaly Occurred

Hazard	Number of Anomalies
Geomagnetic Storm (Minor)	66
Electron Event (1 @2 MeV)	122
Proton Event (10 @50 MeV)	20
Proton Enhancement (1 @ 10 MeV)	122
Electron Event or Proton Enhancement	166

Total Anomalies: 223

Table 3.2 shows anomalies occurring during each hazard. For example, 66 of the 223 anomalies happened during a geomagnetic storm. The 20 anomalies occurring during proton events appear benign until one realizes that proton events were rare. Perhaps the threshold needed for protons was below "event" level. A proton enhancement was in progress during 122 of the anomalies. Interestingly, 166 of the 223 anomalies occurred during either a proton enhancement or electron event.

3.3 Testing the Thresholds

Testing each threshold was necessary to validate any as alert or warning criteria. What percent of the time did an anomaly occur during each threshold? Geomagnetic storms are the main source of spacecraft charging and a good environmental disturbance indicator.

Table 3.3 Anomaly Occurrence Given Geomagnetic Storms

	Threshold Occurred	
Geomagnetic Threshold	1/2-Full Day	≤1/2 Day
Minor Storm	23/57 40%	12/37 32%
Major Storm	10/23 43%	10/23 43%
Severe Storm	2/5 40%	3/10 30%

Note: #/# number of times with at least one anomaly/number of threshold occurrences

Observe CRRES had a 40 percent chance of experiencing at least one anomaly during a geomagnetic storm. Also, the more intense (major or severe) storms caused no higher anomaly rates. This combined with the fact that only 66 of the 223 anomalies occurred during a geomagnetic storm indicate it's only a partial contributing factor and not the best alert or warning criteria.

Table 3.4 Anomaly Occurrence Given Proton Enhancements

Enhancement Threshold	Threshold Occurred 1/2-Full Day	<1/2 Day
1 @ 10 MeV	22/43 51%	1/5 20%
1 @ 50MeV	19/35 54%	1/2 50%
10 @ 50MeV	9/15 60%	0/2 00%

Note: #/# number of times with at least one anomaly/number of threshold occurrences

CRRES's anomaly risk during proton enhancements was certainly higher, especially if the enhancement lasted at least 12 hours. Protons were usable as alert or warning criteria, but not as good as electron events. See Table 3.5

Table 3.5 Anomaly Occurrence Given Electron Events

Event Threshold	Threshold Occurred 1/2-Full Day	<1/2 Day
1000 @ 2 MeV	37/54 69%	9/25 36%
10000 @ 2MeV	4/4 100%	4/7 57%
100000 @ 2MeV	2/2 100%	0/2 00%

Note: #/# number of times with at least one anomaly/number of threshold occurrences

Clearly electrons were the best alert or warning criteria of three hazards. Notice, in Table 3.5, the increase in the likelihood of suffering an anomaly when the threshold was maintained for the longer time period (69 percent versus 36 percent).

The risk of any one 2 MeV electron, or 10 MeV proton, causing an anomaly is exceedingly small. However, as the exposure time and electron or proton flux increases, so does the risk. Tables 3.4 and 3.5 show the risk increasing with longer exposure times and higher thresholds.

The measurable environment clearly affected CRRES, being the likely cause of well over half of the 223 anomalies. Electrons or protons accounted for 166. The background level of two to three cosmic ray-induced single event upsets per month added another 24 to 36, making the total environmental contribution to the anomaly count nearly 200--almost 90 percent of the anomalies.

3.4 Effects of the Major Solar Event of 22 March 1991

The major solar flare, late on 22 March 1991, caused a near immediate three to five magnitude increase in proton flux and a three magnitude increase in electron flux. A severe geomagnetic storm started the following day. Surprisingly, no anomalies happened until 26 March, 3 days after the proton and electron flux shot up and 2 days after the geomagnetic storm began. Furthermore, referring to Table 3.1, 24 of March's 26 anomalies occurred after the twenty-fifth. Why the delay? Tables 3.6 to 3.8 show an apparent lower environmental risk before 26 March, compared to the overall time of the database. Tables 3.9 to 3.11 show the apparent higher risk after 26 March 1991. Only 36 of the 223 anomalies occurred in the 8 months before this major flare, but 187 occurred in the 5 months following the flare.

Table 3.6 Anomaly Occurrence Given Geomagnetic Storms Before 26 March 1991

	Threshold Occurred			
Geomagnetic Threshold	1/2-Full Day		<1/2 Day	
Minor Storm	3/14	21%	0/13	00%
Major Storm	2/6	33%	0/2	00%
Severe Storm	0/2	00%	1/2	50%

Note: #/# number of times with at least one anomaly/number of threshold occurrences

Table 3.7 Anomaly Occurrence Given Proton Enhancements Before 26 March 1991

	Threshold Occurred			
Enhancement Threshold	1/2-Full Day		<1/2 Day	
1 @ 10 MeV	2/7	43%	1/2	50%
1 @ 50MeV	0/5	00%	0/1	00%
10 @ 50MeV	0/3	00%	0/0	

Note: #/# number of times with at least one anomaly/number of threshold occurrences

Table 3.8 Anomaly Occurrence Given Electron Events Before 26 March 1991

	Threshold Occurred			
Event Threshold	1/2-Full Day		<1/2 Day	
1000 @ 2 MeV	2/7	43%	1/4	25%
10000 @ 2MeV	0/0		0/2	00%
100000 @ 2MeV	0/0		0/2	00%

Note: #/# number of times with at least one anomaly/number of threshold occurrences

Table 3.9 Anomaly Occurrence Given Geomagnetic Storming After 25 March 1991

Geomagnetic Threshold	Threshold Occurred 1/2-Full Day	<1/2 Day
Minor Storm	20/43 47%	12/24 50%
Major Storm	8/17 47%	10/21 48%
Severe Storm	2/3 67%	2/8 25%

Note: #/# number of times with at least one anomaly/number of threshold occurrences

Table 3.10 Anomaly Occurrence Given Proton Enhancements After 25 March 1991

Enhancement Threshold	Threshold Occurred 1/2-Full Day	<1/2 Day
1 @ 10 MeV	20/36 56%	0/3 33%
1 @ 50MeV	19/30 63%	1/1 100%
10 @ 50MeV	9/12 75%	0/2 00%

Note: #/# number of times with at least one anomaly/number of threshold occurrences

Table 3.11 Anomaly Occurrence Given Electron Events 25 March 1991 On

Event Threshold	Threshold Occurred 1/2-Full Day	<1/2 Day
1000 @ 2 MeV	35/47 74%	8/21 38%
10000 @ 2MeV	4/4 100%	4/5 80%
100000 @ 2MeV	2/2 100%	0/0

Note: #/# number of times with at least one anomaly/number of threshold occurrences

Table 3.11 shows the virtual assurance of an anomaly if the 2 MeV electron flux reached 10,000 and its likelihood if a flux of 1,000 was maintained for half the day. Certainly, electron flux can be used as alert or warning criteria!

Changes in the operating characteristics of micro-electronic components with accumulated dose can explain why CRRES became more vulnerable to upsets from energetic protons and electrons after 25 March. The operating characteristics of satellite components vary as they accumulate dose, well before such components fail. These shifts in operating levels can make the components more susceptible to upsets. The results range from a simple "bit flip" that can be easily reset, or a portion of the memory latching up and becoming useless, to possibly catastrophic failure in which the satellite is no longer usable. During the last week in March, CRRES received approximately the radiation dose it would normally get in 2 years.

Energetic electrons with the same energies as energetic protons have a greater penetrating capability, due to the electron's smaller cross sectional area. These electrons deposit charge on ungrounded components in the spacecraft, eventually producing a discharge. Particles can also embed themselves in the dielectric material, building up an electric field which can also produce a discharge.

Further radiation degradation was in evidence during the last 3 months of the database. Again, Table 3.1 and Charts 3-1 ,3-2 and 3-3 display the major activity in June and July. Sunspot region 6659 produced five major X-ray flares (X12+) and an X10 during the first 2 weeks of June. These flares caused long periods with proton flux two to four orders above background and electron flux one to two orders above background levels. July's three major flares caused similar increases in proton and electron flux. CRRES suffered the most anomalies, 46, in June and July. In August, the electron and proton activity dropped below May's, yet the number of anomalies remained near the total in March and higher than any other month but June and July. This clearly shows CRRES became more vulnerable to anomalies after the major flares in March, June and July.

3.5 Ramifications for Other Satellites

All satellites fly in the space environment and are exposed to various types of hazards. Whether the orbit is geostationary or low earth, the risk of cosmic particle-induced anomalies are the same. Energetic protons and electrons penetrate low orbits best near the magnetic poles. The auroral zone harbors charging and discharging hazards. Likewise, high orbits are vulnerable to charging, discharging and energetic particles. Environmentally, the safest orbit is low inclination, low earth. The low inclination and the earth's magnetic field shields this orbit from all but the strongest geomagnetic storms and the most energetic particles except for the South Atlantic Anomaly.

All satellites and their components have a certain degree of radiation hardness. Some can take larger doses of radiation before failing than others.

Any satellite built with components of similar hardness and placed in a similar orbit as CRRES can expect to see similar levels of anomalies.

4. CONCLUSIONS

1. CRRES was environmentally sensitive since:

a. Satellite anomalies, particularly needing to reconfigure on board experiments, occurred mainly during extended proton enhancements (1 particle @ 10 MeV) or extended electron events (1,000 particles @ 2 MeV).

b. The likelihood of an anomaly occurring during extended, heightened periods (at least half a day) of solar activity varied from 40 to 100 percent, depending on the threshold and phenomena considered. Electrons were the greatest threat.

c. Most (122 of 223) of the anomalies occurred during a proton enhancement.

d. Most (122 of 223) of the anomalies occurred during a electron event with a flux of at least 1,000.

e. Most (166 of 223) of the anomalies occurred during either a proton enhancement or electron flux of at least 1,000.

2. There are several usable criteria for alerts or warnings depending on the risk level to be warned against.

a. Extended periods (12 hours or more) of proton enhancements (1 particle @ 10 MeV) can be expected to cause an anomaly half the time.

b. Extended proton events can be expected to cause an anomaly 3 out of 4 times.

c. Extended electron flux of 1000 particles at 2 MeV can be expected to cause an anomaly 3 out of 4 times.

d. Electron flux of 10,000 particles virtually guarantees an anomaly.

3. CRRES became more susceptible to anomalies after each major solar event.

4. Satellites built with components with similar radiation hardness flown in similar orbits can expect similar levels of anomalies (2 to 3 per month background and more during active periods).

5. POST MORTEM

CRRES suffered the final catastrophic anomaly (believed to be a power system failure) on 12 October 1991, making any further communication with, commanding of, or obtaining any test results from the satellite impossible. CRRES was declared dead on 3 December 1991, after an extensive effort lasting several weeks to revive the satellite.

We evaluated the environmental conditions surrounding the final anomaly. None of CRRES's proven hazards reached threshold levels. The 2 MeV electron flux was above background levels, but below 1,000. The proton flux was at background levels and the geomagnetic activity was low. Perhaps the final anomaly was caused by a cosmic ray. Perhaps a critical component reached its total radiation dose limit prematurely, due to the extreme events of March, June and July of 1991. We will never know.

6. ACKNOWLEDGEMENTS

I would like to end this report by thanking the people listed below who helped prepare it. Their aid consisted of either technical knowledge, data gathering, or editing support.

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