Environment-Induced Anomalies on the TDRS and the Role of Spacecraft Charging

S. Daughtridge*
Contel Federal Systems, Chantilly, Virginia 22021
and
H. B. Garrett† and A. Whittlesey‡
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

The Tracking and Data Relay Satellites TDRS-A (F-1), TDRS-C (F-3), and TDRS-D (F-4) have all experienced environment-induced anomalies. These anomalies were determined to be related to spacecraft charging based on their occurrence frequency, distribution in local time, and the environment at the time of the anomalies. One type of anomaly occurring in F-1 is believed to be the result of buried charging with shadowing from the spacecraft's antennas being the discharge trigger mechanism. The circuitry in the F-3 and F-4 spacecraft were modified to make them immune to this type of anomaly. However, F-3 and then F-4 both suffered a second type of anomaly also attributed to buried charging effects. In addition, F-1 and F-3 have experienced a third type of anomaly that appears to be associated with surface charging. These anomalies, the local plasma environment, and their relationship to spacecraft charging are discussed.

Introduction

THE NASA Tracking and Data Relay Satellites (TDRS) are vital components of the overall Tracking and Data Relay Satellite System. Starting with TDRS-A (or F-1), these spacecraft have experienced several classes of anomalies that appear to be related to the natural environment. The most serious of these were ultimately traced to high-energy particle-induced single event upsets (SEU) in the RAM memory,[1] and are not discussed here. Aside from this problem, three other types of engineering anomalies on TDRS have subsequently been correlated with environmental effects. The objective of this paper is to briefly describe each of the types of anomalies and, following a short description of the nature of each anomaly, correlate these events with various environmental factors. In all three cases, there appears to be at least a causal relationship between spacecraft charging events and the anomalies. A brief description of the spacecraft charging phenomena and the geophysical data used in this paper are also provided.

Spacecraft Charging

Spacecraft charging will be shown to be the likely cause of the types of TDRS anomalies considered here on the basis of their occurrence frequency, distribution in local time (LT), and the environment at the time of the anomalies. Spacecraft surface charging, the most widely known form of charging, is brought about by the balance of currents to the spacecraft's surface.[2] In this process, the surface typically will charge to a potential in sign and magnitude roughly equal to the mean energy in eV of the dominant current to the surface. At geosynchronous orbit, surfaces in sunlight will charge a few volts positive because the photoelectron current away from the surface dominates and has a mean energy near 2–3 eV.[2] On shadowed dielectric or isolated surfaces (and sometimes in sunlight), the potential often can charge to about 1–10 kV negative because ambient electrons (often with a mean energy of 1–20 keV) are the dominant current source.[2-4] The satellite chassis also can assume the potential of the locally dominant source, usually 2–3 V positive in sunlight, and negative potentials in eclipses. Local time variations in the ambient electron current mean that these potentials will be modulated in LT. The region from 00 to 06 LT is a favored but not unique region for spacecraft surface charging-induced anomalies.[5]

The absolute spacecraft potential is not dangerous if the whole vehicle charges up uniformly (i.e., as in the case of a completely conducting spacecraft). It is only when potential gradients occur that problems are observed, because these gradients can lead to arc discharges. It is the arc discharge and the electromagnetic interference (EMI) associated with it that can induce impulses on spacecraft circuitry that will generate anomalous command executions. It is this arc discharge/EMI process that is suggested here as the primary cause of the TDRS anomalies discussed.

In addition to spacecraft surface charging, there is the so-called buried or deep (dielectric) charging process[6] that can also result in arc discharges and spacecraft anomalies. In this process, high-energy (typically $E > 100$ keV) electrons penetrate the surface of the vehicle. Their depth of penetration is about 10–100 times that of ions of comparable energy, so that a negative potential can be established on isolated parts within the spacecraft. In the case of dielectrics, the charge is deposited and is immobile within the bulk of the material, whereas for isolated conducting surfaces inside the vehicle, the charge is mobile within that conductor. After sufficient negative charge has built up (typically, the total fluence must be on the order of 10^{10}–10^{11} electrons/cm^2),[7,8] an arc may occur. Based on this scenario, a correlation is expected between the total fluence of $E > 100$ keV electrons and anomalies. The actual arc occurrence, however, is largely unpredictable and will be affected not only by the high-energy electrons but possibly also by surface potentials and physical configuration. In such a case, the arc would be between the surface charge and the internal charge. A maximum field gradient (i.e., electric field) might occur, for example, when the surface potential is positive or zero relative to the trapped (buried) negative electron charge. Thus, swings in the surface potential as a charged surface passes in or out of the spacecraft shadow may initiate this

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*Engineer; currently at INTELSAT, Washington, DC. Member AIAA.

†Research Scientist. Member AIAA.

‡Member of Technical Staff.

type of arc process. This effect would imply a correlation between the discharges and the orientation of the spacecraft and its surface shadowing.

Geophysical Data

Four measures of the geosynchronous environment were used in this study. The selected measures were the electron fluxes between 30 and 300 keV, the energetic electron fluxes above about 1.5–2.0 MeV, geomagnetic indices, and magnetic field records (magnetograms) from near the foot of the magnetic field line that connected to the spacecraft. They were selected on the basis of their immediate availability and on their ability to differentiate between the two different types of spacecraft charging phenomena (internal and surface charging). The 30–300 keV data overlap the 1–80 keV electron population usually associated with surface charging, and are indicative of the occurrence of this process. The energetic electron data are intended to give a measure of the variations in the electron population that causes buried or deep charging. The geomagnetic indices provide a global estimate of the state of the Earth's magnetosphere, and typically indicate the progress of geomagnetic storms and injections events. The magnetograms are meant to give a similar, but more local and higher time resolution, picture of the geosynchronous plasma environment in the absence of in-situ data. (Note: As the geomagnetic indices are based on global averages of the magnetograms, the two estimates of geomagnetic activity are strongly correlated.)

The in-situ electron data are from different instruments on several geosynchronous spacecraft. Three different energy ranges have been used in this study: the 30 keV $< E <$ 300 keV data are from the charge particle analyzer (CPA)[9] instrument on the geosynchronous Department of Defense spacecraft 1981-025, 1982-019, 1984-037, and 1984-129; the $E >$ 1.5 MeV data are from the spectrometer for energetic electrons (SEE)[10] on 1982-019; and $E >$ 2 MeV electron data are from the National Oceanic and Atmospheric Administration (NOAA) geosynchronous GOES spacecraft.[11] Although the preferred procedure would have been to use a single instrument, no one of the satellites had data available during all of the periods of interest. In any case, these energy ranges cover what is believed to be the two primary populations of electrons responsible for charging. Hence, increases in these quantities should indicate that charge is building up and that an arc or anomaly is possible.

The principle indices used for estimating global geomagnetic activity in this study were the 3-h a_p index and the monthly A_p (the a_p index averaged over a month) index. The first of these, the a_p index, is an indicator of global geomagnetic activity. It is an approximately linear measure of the global magnetic field deviation at midlatitudes from an average or quiet day level in a 3-h period and indicates how disturbed the Earth's magnetic field has been on an integer scale from 0 to 400. The a_p index (specifically, its semilogarithmic form K_p) has been used to identify the large plasma increases associated with the injection of plasma at geosynchronous orbit.[12] Spacecraft charging has been shown to be related to these increases in geomagnetic activity and to a_p (or K_p), hence the use of the a_p and A_p indices here.[13,14]

Magnetograms from specific high-latitude ground stations were additionally utilized to infer the immediate environment of the satellite at the time of the anomalies. This was necessary because the variations in the plasma fluxes at geosynchronous orbit can be very localized. Although increases in a_p and related indices can identify the generalized large plasma increases associated with the injection of plasma at geosynchronous orbit, they cannot necessarily identify very localized spatial variations. Further, the a_p index has at best 3-h resolution. One way to avoid these problems is to look at either the in-situ magnetic field or, better, the in-situ plasma variations. This is not possible for the TDRS, however, as it does not carry environmental sensors. An alternative is to look at magnetograms for stations whose magnetic field lines pass near the spacecraft. These magnetograms provide an estimate of the variations in the magnetic field and, hopefully, plasma variations near the spacecraft, since magnetic field changes at the Earth are intimately tied to the fluxes of plasma along the field lines.[12,13] Thus, the magnetograms should exhibit large variations from a quiet day median value when geomagnetic substorm plasma is observed along the field line. As these geomagnetic substorms are believed to be the source of the hot plasma that causes spacecraft charging,[13] a correlation with surface charging-related anomalies is expected. However, it should be emphasized that magnetograms are only an estimate of the geosynchrous plasma environment and only a general correlation with spacecraft charging events is expected.

In concluding this section, it should be remembered that, in general, environmental correlations with anomalies are never conclusive. Therefore, the correlation or lack thereof of a particular environmental parameter does not necessarily mean

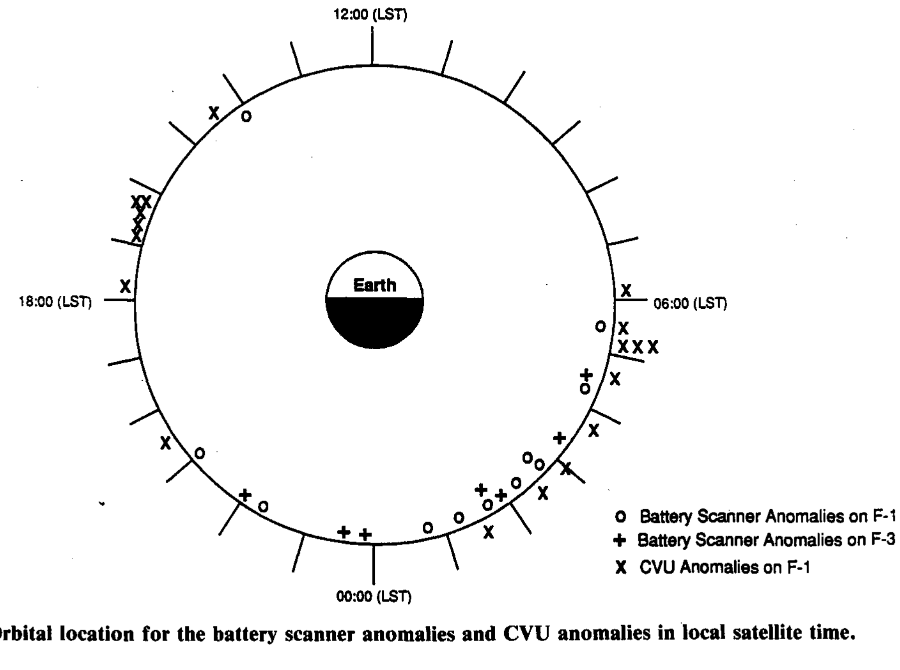

Fig. 1 Orbital location for the battery scanner anomalies and CVU anomalies in local satellite time.

Table 1 Comparison of F-1 battery scanner anomalies with various geophysical indices[a]

No.	Date	A_p index	Electron fluence >2 MeV	Magnetograms
1	July 1, 1986	9	Low	High
2	Aug. 30, 1986	22	High	High
3	Nov. 4, 1986	80	Low	High
4	Feb. 20, 1987	27	No data	High
5	March 31, 1987	4	No data	Low
6	July 16, 1987	18	No data	High
7	Jan. 12, 1988	18	Low	Moderate
8, 9	Jan. 28, 1988	18	Low	High
10	June 30, 1988	22	Low	High
11	Sept. 4, 1988	6	High	High

[a]For GOES > 2 MeV and SEE > 1.5 MeV data fluences, flux < 10^3 e/cm^2-s-sr is considered low, flux > 10^3 for up to 6 h is considered moderate, and flux > 10^3 for over 6 h is considered high (during the 48 h prior to the anomaly). For magnetograms, maximum H axis deviations of < 50 nT is low, > 50 and < 200 nT is moderate, and > 200 nT is high (during the 3 h prior to the anomaly). For the CPE data, flux < 5×10^4 e/cm^2-s-sr-keV is low, > 5×10^4 and < 5×10^5 are moderate, and > 5×10^5 is high (during the 1 h prior to the anomaly).

that the connection is valid or invalid. Typically, several correlations and a physical means of generating the anomaly given that the environment could cause a discharge are required. Here, where possible, each anomaly class will be identified with a specific environmental variation. Based on the preceding discussion, this correlation will be used to identify the physical processes (i.e., surface charging, buried charge, or combinations thereof) leading to the discharge. In lieu of independent onboard measurements of the environment and arc discharges, this will be as far as we can go in "proving" the actual cause.

It should also be noted that for all three types of anomalies, engineering functions were examined and essentially eliminated as possible causes of the anomalies, and a physical means by which a discharge could cause the observed anomaly was found and in each case substantiated by analytical analysis, simulation, and/or test.[15,16]

Battery Scanner Anomalies

The least damaging of the anomalies experienced on the TDRS spacecraft are the so-called battery scanner anomalies. Battery scanner anomalies take the form of an obviously erroneous telemetry voltage readout during routine monitoring of the spacecraft battery voltages. The nature of the anomaly appears to require that electrical noise transients (presumably due to arc discharges) on the battery scanner circuitry generate a false clock address that would cause accessing of a battery cell voltage when a calibration voltage was expected, or vice versa. When plotted in LT coordinates (Fig. 1), a pronounced pattern emerges. The data are preferentially grouped between local midnight and sunrise (00 and 06 LT), implying a geophysical origin for the anomalies. (Engineering functions were previously ruled out as a source of these events.) As a result of this pronounced local time grouping of the anomalies and the requirement for transients on the circuitry, the anomaly is assumed to be the result of spacecraft surface charging/discharging.

As a further step in identifying the spacecraft surface charging origin of the battery scanner anomalies, Table 1 compares the occurrence of F-1 anomalies with the high-energy electron fluxes (a measure of buried charge effects as previously discussed), the a_p index, and magnetograms from the base of the magnetic field line passing through the F-1 position. There is little or no correlation with the high-energy electrons. On the other hand, there is a correlation with the latter two parameters. Of these two, we believe that the magnetograms, as opposed to the coarser (temporally) a_p index, are better representative of the local environment at F-1. Disturbed magnetic field implies, in turn, that a plasma injection event is probably in progress at the spacecraft location. For event 5, which shows little correlation wtih the environment, F-1 may have passed through a cloud of hot plasma that can occasionally exist at geosynchronous orbit without causing fluctuations in the Earth's magnetic field lines.[17] In any case, both parameters show a good correlation between disturbed magnetic field and battery scanner anomalies. This, in turn, implies that surface charging (as opposed to buried charging) is a likely cause of these anomalies, in support of the earlier assumption.

Command Validation Unit Disable Anomalies

Starting in 1985, F-1 experienced on-orbit anomalies in its command and telemetry unit (CTU) to command validation

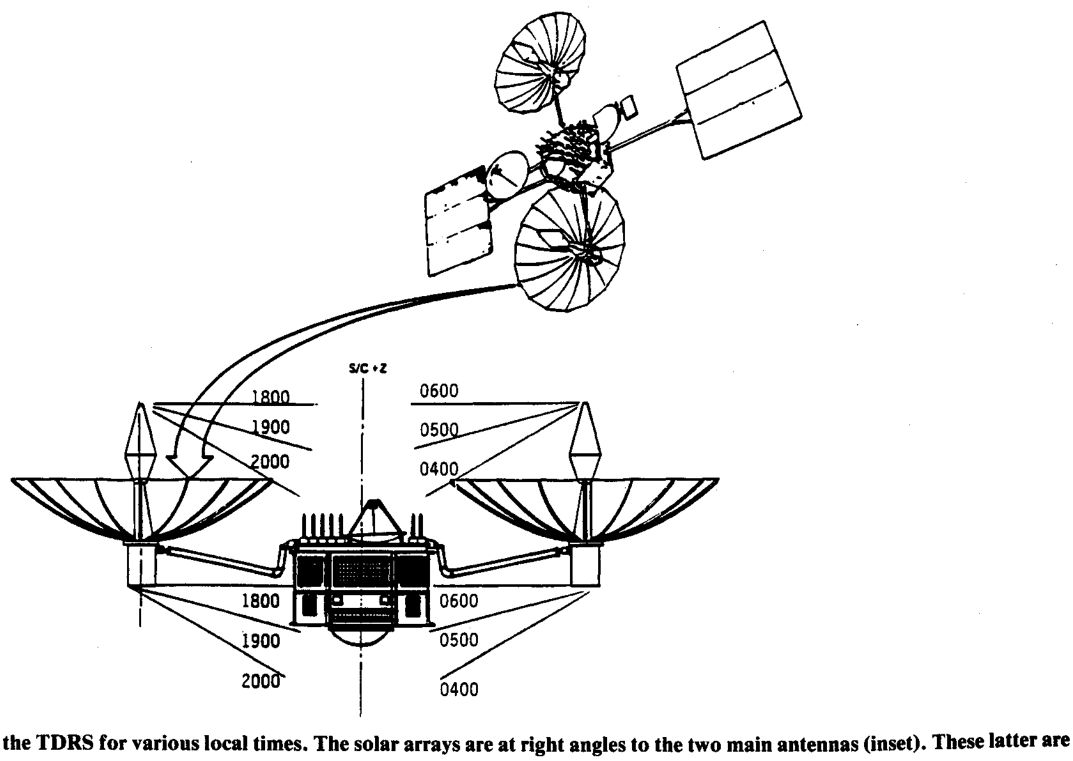

Fig. 2 Sun-shadow lines for the TDRS for various local times. The solar arrays are at right angles to the two main antennas (inset). These latter are the SAA antennas.

Table 2 Comparison of the CVU disable anomalies with the environment and a discharge mechanism

		Environmental		Discharge mechanism
Date	LT	Low energy,[a] 0–81 KeV	High energy,[a] >1.5 MeV	SAA shadow
353/85	1752	High	Moderate	Yes
311/86	0552	Moderate	High	Yes
070/87	1707	Moderate	Moderate	Yes
168/87	0301	High	Low	No
239/87	1417	High	High	No
244/87	1654	High	High	Yes
257/87	1643	High	High	Yes
258/87	1639	High	High	Yes
281/87	2022	High	High	Yes
283/87	0227	High	Moderate	Yes
287/87	0441	High	High	Yes
289/87	0510	High	High	Yes
295/87	0518	Moderate	High	Yes
299/87	1606	High	High	No
305/87	0141	High	High	Maybe
318/87	0405	High	High	No
028/88	0349	High	High	Maybe
168/88	0603	High	Moderate	Yes

[a]See footnote for Table 1.

unit (CVU) disable/enable interface. Electrical noise transients on the CVU disable command lines appear to be the physical cause of the anomalies. In support of this physical mechanism, no CVU disable anomalies have been observed on F-3 and F-4, on which that circuit was hard-wire grounded for flight. Although representing only a very small fraction of the total operating time of the spacecraft, the CVU disable anomalies suddenly began to grow in frequency from 2 between 1985 and 1987 to 14 between March and November 1987. Ultimately, a total of 18 CVU anomalies occurred before they ceased in June 1988. These anomalies are attributed to spacecraft buried (deep) charging effects, as presented in the following.

The F-1 CVU anomalies are plotted as a function of local time in Fig. 1. The clustering into two local time bins is very indicative of an environmental source of the anomaly. As before, the clustering between 00 and 06 LT implies that surface charging is a possible cause. The clustering between 16 and 18 LT can also be attributed to charging if the orientation of the spacecraft is considered. (Note: Spacecraft surface charging is not limited to the 00–06 LT region—indeed, Levy et al.[18] report strong evidence of surface charging/arcing between 12 and 18 LT.) Studies by Stevens[19] imply that the sun shadow from the single access antennas (SAA) can shadow the spacecraft in these two local time configurations (Fig. 2). As he notes, the resulting potential gradient on the spacecraft's thermal blankets and/or nonconducting optical solar reflectors as they pass in or out of the shadow could cause an arc discharge. The fairly strong correlation with these possible surface effects is demonstrated in the SAA shadow column in Table 2.

Due to the lack of hot plasma electrons in the 16 to 18 LT location, buried charge may also be involved in the F-1 CVU anomalies. As discussed earlier, rather than the arc being between differentially charged surfaces, the varying surface potentials could trigger an arc from the buried charge population. In this case, the charge would be accumulating inside the thermal blankets with the shadowing from one of the TDRS antennas (Fig. 2) causing the discharges. The very good correlation between the $E > 2$ MeV electron flux and the CVU anomalies during the fall of 1987 (Fig. 3) would imply that buried charge, if not the main source of the anomalies, is certainly a substantial factor in their cause.

The CVU anomalies abruptly ceased in June 1988. This has been attributed to possible changes in the material properties and/or discharge path. Both the natural geosynchronous environment and the repeated charging and discharging could induce these changes. Minor changes in the discharge characteristics have been shown to greatly affect the coupling

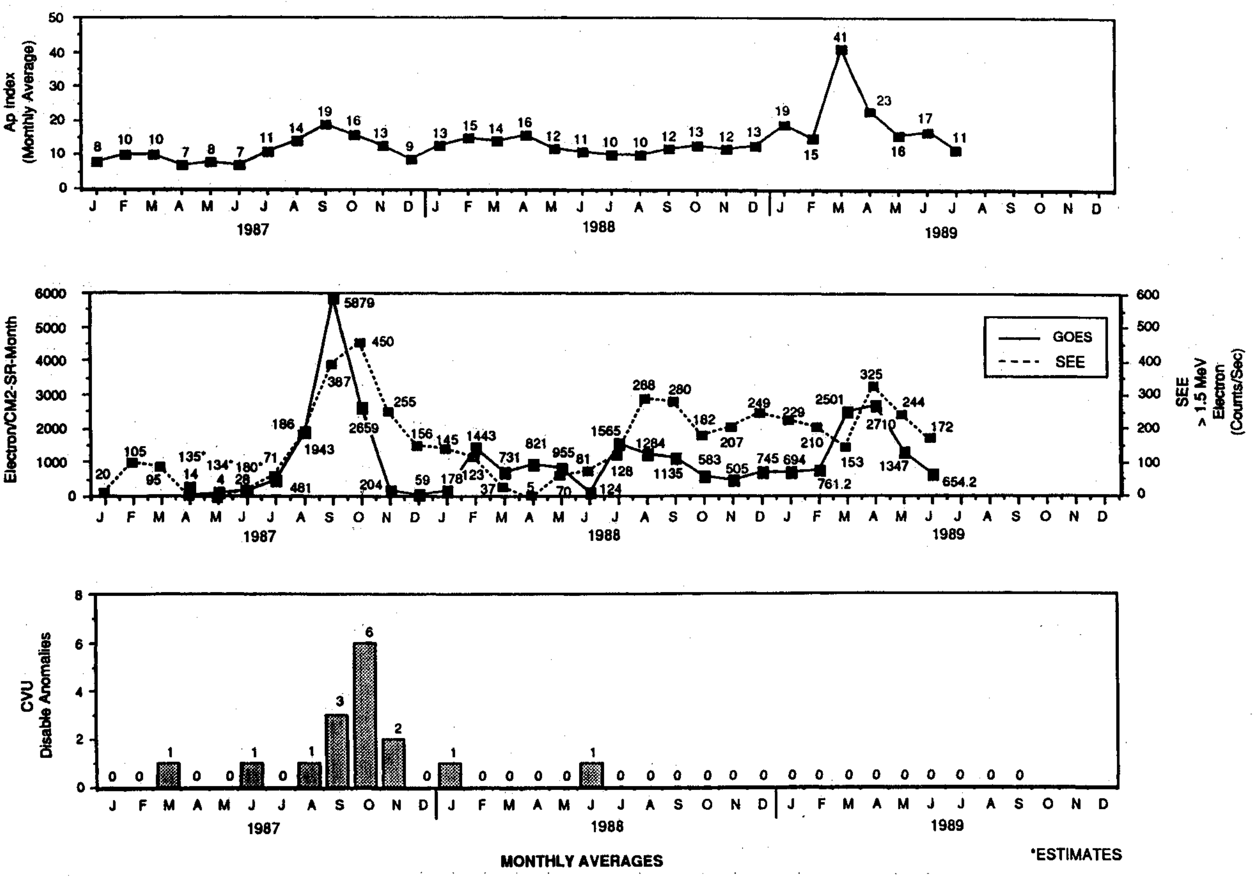

Fig. 3 The A_p index, the high-energy electron fluxes ($E > 1.5$ MeV and $E > 2$ MeV), and the CVU disable anomalies for 1987–1989.

characteristics of the spacecraft.[15] However, at this date no specific explanation for this sudden cessation has been found.

Control Processing Electronics Reset Anomaly

Perhaps most puzzling and dangerous of the three types of anomalies considered in this paper is the Control Processing Electronics (CPE) reset anomaly. The CPE provides the processing of the attitude sensor data for the spacecraft attitude control system. The CPE reset function was used for ground operations to reinitialize the attitude control system. In space, such a reset is usually inappropriate for the particular satellite situation, and needs operator intervention to avoid disruption of satellite services. As with the other anomalies, an electrical noise transient hypothesis is consistent with the spacecraft behavior. The event has been observed only once on F-3 and F-4 but has never been seen on F-1. The design of the F-3 and F-4 CPEs were modified from the F-1 design due to the SEU problems encountered with the F-1 CPE. The F-3 event occurred on Day 299, 1988, at 0455 GMT/1855 LT—27 days after launch. The identical event occurred on F-4 on Day 77, 1989, at 0731 GMT/2006 LT—4.5 days after launch. The physical process believed to be responsible for the CPE anomalies is an arc discharge-induced transient coupling onto a CPE circuit that resulted in the execution of a phantom CPE reset command.

The facts associated with the two events are difficult to reconcile. The anomalies both occurred shortly after the launches of F-3 and F-4 in conjunction with one of the first high-energy electron events encountered by each spacecraft (Fig. 4). The global geomagnetic activity was, however, low for F-3 and was just beginning to increase when the F-4 anomaly occurred. Surprisingly, F-3 was within 285 n.mi. of F-4 when the latter upset, whereas the former experienced no apparent anomaly. Although the operating configurations were slightly different at the time of the F-4 anomaly, the differences were minor. Also, it appears that whatever caused the anomaly was in some way modified so that the event did not occur again. (This is born out by the fact that no additional CPE anomalies have occurred, although there have been numerous high-energy electron events.) The authors have seen substantial materials changes as a result of laboratory arcing tests, such that subsequent arcs are redirected to different hardware locations. This is a possible cause of the lack of subsequent CPE reset events.

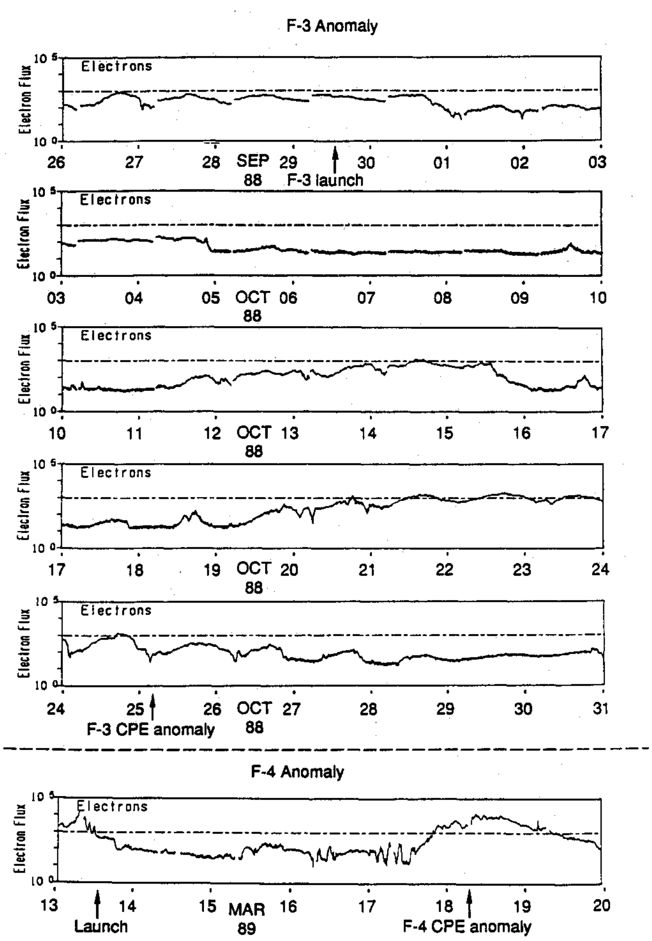

Fig. 4 GOES-7 $E > 2$ MeV electron data for the CPE anomalies on F-3 and F-4.

It is postulated, based on a correlation with the $E > 2$ MeV electron fluxes, that buried charge played a critical role in setting up the conditions of the anomaly. The triggering process, however, is not clear. Stevens[20] postulates, as in the case of the CVU anomalies, that changes in surface charging due to passage of surfaces in and out of the spacecraft shadows may have been the trigger (refer to Fig. 2 for the orientation of TDRS relative to the sun). He also goes on to postulate that the spacecraft Kapton thermal blankets were a primary source of the buried charge and that long-term exposure of the blankets to the solar extreme ultraviolet radiation (EUV) flux has gradually made the normally nonconducting material conducting. This would eliminate the Kapton thermal blankets as a source of the arcing for subsequent high-energy electron events. In any case, a form of spacecraft charging again appears to be the cause of the anomaly.

Conclusions

The TDRS F-1, F-3, and F-4 spacecraft have all experienced anomalies during their operations at geosynchronous orbit. After careful consideration of the environmental evidence, it is concluded that although the detailed breakdown process and coupling paths are not clearly defined, the causes of these three anomaly types appear to be associated with surface and buried (deep) charging. In the case of the battery scanner anomalies, the cause is postulated to be surface charging. The strong correlation of the events with the 00–06 LT sector and with geomagnetic activity support this assumption. The CVU anomalies, on the other hand, also show a strong local time correlation but the division into two LT groups and the correlation with the $E > 2$ MeV electrons appear to favor buried charge as the source, with shadowing from the antennas as a potential trigger. The singular nature of the CPE anomalies makes a definitive identification difficult, but the apparent correlation with $E > 2$ MeV events again supports a buried charge correlation. It should be noted in concluding this summary that none of the anomalies have yet significantly affected the operations of the TDRS system and have caused only short outages at worst.

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References

[1]Vinson, D., "TDRSS Anomalies," *Proceedings of Spacecraft Anomalies Conference,* edited by V. G. Patterson and J. S. Schleher, NOAA Pub. 30-31, Oct. 1984, pp. 94–109.

[2]Garrett, H. B., "The Charging of Spacecraft Surfaces," *Reviews of Geophysics and Space Physics,* Vol. 19, No. 4, 1981, pp. 577–616.

[3]Garrett, H. B., "Review of Quantitative Models of the 0 to 100

keV Near-Earth Plasma," *Reviews of Geophysics and Space Physics,* Vol. 17, No. 3, 1979, pp. 397–417.

[4]Purvis, C. K., Garrett, H. B., Whittlesey, A. C., and Stevens, N. J., "Design Guidelines for Assessing and Controlling Spacecraft Charging Effects," NASA TP-2361, Sept. 1984.

[5]Rosen, A., "Spacecraft Charging by Magnetospheric Plasmas," *IEEE Transactions on Nuclear Science,* Vol. NS-23, No. 6, Dec. 1976, pp. 4265–4276.

[6]Frederickson, A. R., "Radiation Induced Dielectric Charging," *Space Systems and Their Interactions with Earth's Space Environment,* edited by H. B. Garrett and C. P. Pike, AIAA, New York, 1980, pp. 386–412.

[7]Leung, P., Whittlesey, A. C., Garrett, H. B., and Robinson, P. A., Jr., "Environment-Induced Electrostatic Discharges as the Cause of Voyager 1 Power-On Resets," *Journal of Spacecraft and Rockets,* Vol. 23, No. 3, 1986, pp. 323–330.

[8]Robinson, P. A., Jr., "Spacecraft Environmental Anomalies Handbook," Geophysics Lab., Hanscom AFB, MA, GL-TR-89-0222, Aug. 1989.

[9]Baker, D. N., Belain, R. D., Higbie, P. R., and Hones, E. W., Jr., "High-Energy Magnetospheric Protons and Their Dependence on Geomagnetic and Interplanetary Conditions," *Journal of Geophysical Research,* Vol. 84, No. A12, Dec. 1, 1979, pp. 7138–7154.

[10]Baker, D. N., Blake, J. B., Klebasadel, R. W., and Higbie, P. R., "Highly Relativistic Electrons in the Earth's Outer Magnetosphere 1 Lifetimes and Temporal History 1979–1984," *Journal of Geophysical Research,* Vol. 91, No. A4, April 1, 1986, pp. 4265–4276.

[11]Grubb, R. N., "The SMS/GOES Space Environment Monitor Subsystem," NOAA TM-ERL-SEL-42, Dec. 1975.

[12]Mauk, B. H., and McIlwain, C. E., "Correlation of K_p with the Substorm Plasma Sheet Boundary," *Journal of Geophysical Research,* Vol. 79, No. 22, 1974, pp. 3193–3196.

[13]Garrett, H. B., "Low Energy Magnetospheric Plasma Interactions with Space Systems—The Role of Predictions," *Solar Terrestrial Predictions Proceedings,* Vol. II, edited by R. F. Donnelly, U.S. Government Printing Office, Washington, DC, 1979, pp. 36–70.

[14]Vampola, A. L., "Solar Cycle Effects on Trapped Energetic Particles," *Journal of Spacecraft and Rockets,* Vol. 26, No. 6, pp. 416–427.

[15]Stevens, N. J., and Elkman, W. R., "TDRSS CVU-Disable Investigation Report," TRW No. 29000-125-002, Sec. 5 and 6, Dec. 18, 1987.

[16]Daughtridge, S., "CVU Disable Anomaly Investigation/Summary Report," Contel Federal Systems, Chantilly, VA, SD88-005, Feb. 17, 1988.

[17]Mizera, P., private communications, 1990.

[18]Levy, L., Sarrail, D., Philippon, J. P., Catani, J. P., and Fourquet, J. M., "Sur la Possibilite de Charge Differentielle de Plusieurs Kilovolts dans le Secteur Jour de l'Orbite Geosynchrone," AGARD Conference on the Aerospace Environment at High Altitudes and Its Implications for Spacecraft Charging and Communications, The Hague, The Netherlands, June 2–6, 1986.

[19]Stevens, N. J., private communications, 1988.

[20]Stevens, N. J., "CPE Reinitialization Investigation Report," TRW No. 29000-150-001, Attachment 2, July 14, 1989.

Paul F. Mizera
Associate Editor