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Radiation-Induced Anomalies in Satellites

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Radiation-induced anomalies are discussed and a compilation of known events in semiconductor devices and electronic systems in commercial and government satellites is provided. The various types of anomalies that have been observed and the interactions of space radiation with devices are described. The number of events is limited to those occurring in some government (NASA, National Oceanic and Atmospheric Administration) and commercial spacecraft. In general, manufacturers are reluctant to disclose their failures, and so these sources of events are not readily available. In the case of government spacecraft, anomalies on Department of Defense classified and unclassified satellites are not often reported. Thus, the list of events here is not complete. It represents only the proverbial tip of the iceberg. An important message for satellite designers is to anticipate this environmental threat and provide remedies or safeguards.

I. Introduction

THE threat posed by the space radiation environment must be anticipated and addressed by spacecraft engineers. This paper describes the radiation-induced anomalies (RIAs) that have been observed, briefly explains how and why radiation interactions cause anomalies, and present a list of some of the anomalies and failures that have been reported. The results show that RIAs can be divided into three general categories, single-event effects (SEEs), electrostatic discharges (ESDs), and unknowns (UNK; no probable cause identified). Anomalous events attributed to unreliability or mechanical failures are not included.

The following definitions apply.

1) Total ionizing dose (TID) is the widespread generation of charge by many energetic charged particles and its collection across a die.

2) A SEE is the result of a single particle passing through a discrete volume, generating a charge sufficient to produce the effect. SEEs are subdivided into transient and permanent effects, with the latter being either catastrophic or noncatastrophic.

Before 1975, the electronics community was well aware of total dose radiation problems. In 1975 a new radiation-induced problem came to light, namely the SEE. Five types of SEEs have been identified: 1) single-event upset (SEU), recoverable; 2) single-event latchup (SEL), may be either recoverable or nonrecoverable; 3) single-event burnout (SEB), nonrecoverable; 4) single-event gate rupture (SEGR), nonrecoverable; and 5) single-event snapback, recoverable.

The radiation-induced event observed in 1975 was an SEU attributed to a single cosmic ray particle that caused a change in logic state of a memory device.[1] That report was followed by another study of SEUs in memory devices on board a Global Positioning Satellite[2] (GPS) in 1978. In that study, the SEUs also were attributed to galactic cosmic ray (GCR) heavy ions. From that time on, the observations of SEEs onboard satellites in space have increased to alarming proportions.

There are four basic reasons for the increase in RIAs in microelectronic devices, namely, 1) reduction in feature size, 2) increasing device complexity, 3) increasing size of system memories, and 4) lower operating voltages.

To achieve the integration growth in the design of semiconductor devices, the basic feature sizes of microprocessors, memories, power metal-oxide-semiconductor field-effect transistors (MOSFETs), logic, analog devices, and other supporting chips have decreased to fractions of a micron. This shrinkage in dimensions also has decreased the deposited energy (generated ionization charge) required to produce a SEE in these components. The parallel trend toward lower operating voltages has further contributed to greater device sensitivity.

The number of anomalies occurring in electronic systems in space is highly dependent on the orbit-specific radiation environment. Also, large variations in sensitivity between different part types and between parts of the same type must be expected.

II. Radiation Environments Producing Anomalies

There are four components of the radiation environment that must be considered in any assessment of the vulnerability and survivability of a satellite. They are 1) trapped energetic protons; 2) trapped energetic electrons; 3) solar-flare protons, electrons, and heavy ions; and 4) GCR heavy ions. All of these radiation sources are dynamic and strongly modulated by solar cycles, consisting of approximately 7 years of an active phase (solar maximum) and approximately 4 years of a quiet phase (solar minimum) for a total period of approximately 11 years.

Solar cycles 19 and 22 (the latter has now completed its active years) were the most severe cycles on record in recent history. Many extremely large (EL) solar-flare proton events (a solar flare with a proton fluence exceeding 10^9 p/cm^2 for $E > 30$ MeV) were observed in both cycles, whereas only one was observed in cycle 20 and cycle 21 had no such events.[3] Before cycle 19, no measurements are available. During cycle 22, five EL solar-flare proton events occurred for threshold energies $E > 10$ MeV (EL fluences >

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10^{10} p/cm^2), more than in any previous cycle for which data are available. The number of EL events for energy thresholds of $E > 30$ MeV reached a very high level of eight during cycle 22 (Ref. 3). Most of the spacecraft anomaly data are from this period. Remember that there were only a few spacecraft in orbit during the 19th cycle (1953–1964), but a very large number during cycle 22 (1986–1997).

Although this paper is mainly concerned with anomalies in spacecraft directly induced by radiation, it also reports other possible direct or indirect causes. One such case was a very large magnetic storm[4] that occurred on March 6, 1989. This storm was triggered by heavy solar activity including intense x-ray flares, prolonged solar proton flares with a high proportion of lower-energy particles, and a Forbush decrease. The latter effect is a decrease in the GCR flux, observed at Earth, attributable to an enhanced interplanetary magnetic field during the active phase of the sun. Another such magnetic storm occurred in January 1994 (see ANIK E1 and E2 discussion, Sec. IV.E).

When trapped and/or solar protons are present, they are the dominant factor in producing RIAs. For example, observations of SEUs made onboard several spacecraft [APEX (Advanced Photovoltaic and Electronics Experiment), Combined Release and Radiation Effects Satellite (CRRES), Solar, Anomalous, Magnetospheric, Particle Explorer (SAMPEX), Total Ozone Mapping Spectrometer (TOMS), Japanese GMS-3, European Space Agency's (ESA), MARECS (Maritime European Communication Satellite)-1, and other operational satellites, such as Voyager and Galileo] indicate that SEUs in sensitive electronic devices that have low linear energy transfer (LET, stopping power dE/dx, is the energy deposited per unit length in the sensitive volume of an electronic device by a traversing heavy ion particle, commonly given in units of MeV $\cdot$ cm^2/mg) SEE thresholds can be attributed to protons and/or solar-flare protons. In decreasing order of severity, trapped electrons and solar-generated electrons produce ESDs and/or noise, followed by cosmic-ray heavy ions from solar or galactic sources, causing SEE-induced anomalies or failures.

III. Description and Classification of Anomalies

SEUs can be classified as two types of upsets, namely, those that do not require intervention to recover and those that do require intervention. In the former, the device returns to its normal operation without assistance. This effect is simply a transient signal generated by the production of ionization charge in any semiconductor device that is subject to corpuscular radiation. If a memory cell is in a low state, it will swing to a high state and vice versa, returning on its own to its initial state.

In the latter case, a change in state or mode of operation occurs that requires intervention to recover to its initial state. For example, an upset of a stored bit in a memory device when a high state is changed to a low (SEU) requires that, in critical circuits, the system detect the error and restore the bit to the correct state (recoverable).

Permanent SEE effects are SEB and SEGR in power MOSFETs and SEL (with possible device burnout) in integrated circuits. SEB and SEGR are known to be caused by GCR heavy ions and recently have been observed in regions where trapped protons are present. In the past, latchup has been attributed only to GCR heavy ions; however, in recent publications,[5,6] protons also have been reported to cause latchup in the laboratory and in spacecraft. Latchup may or may not result in catastrophic failure, depending on the circuit design (i.e., current limiting) in which the part is contained. Latchup, burnout, and gate rupture all can be described as instantaneous responses to a hit by a single heavy-ion particle.

A transient or permanent change of state of integrated circuits also can be caused by electric pulses. These are produced by electrons that penetrate and are stopped in dielectric materials, such as insulators or room temperature vulcanizing coatings, which results in the buildup of an electric charge. Subsequent discharges of high voltage (as high as 10 kV) generated by that process produce electromagnetic interference, and voltage or current pulses that might cause device upsets. These effects are defined as ESD events.[7]

In contrast to the instantaneous nature of SEEs, there are the long-term effects of TID and lattice displacements attributable to protons or heavy ions. The TID effect is the dominant one for the majority of electronic components and systems and can cause the loss of functionality in semiconductor parts. For example, five gyros on the Hipparcos spacecraft failed because of total dose damage in the control electronics.[8] The buildup of ionization dose damage also can lead to an increase in SEU sensitivity or loss of functionality in semiconductor parts.[9]

Solar-cell degradation and eventual loss of spacecraft power is predominantly caused by proton-induced displacement damage. Electrons and solar-flare protons also contribute to solar-cell damage at geostationary orbits (GEO), but to a lesser degree. Communication satellites in GEO normally are designed to last at least 10 years in orbit. If they survive for their designed lifetime without any catastrophic failures, they ultimately fail because of either displacement damage in solar cells with the resultant loss of power, or because fuel required for attitude control has all been expended.

IV. Discussion of Observed Anomalies on Specific Spacecraft

A. CRRES

Because the majority of satellites are designed for purposes other than studies of the impact of total dose and single-event phenomena or anomalies, they lack the onboard instrumentation required to make TID and SEE measurements. However, the CRRES spacecraft[10] was designed specifically for the purpose of studying the radiation environment and the effects of radiation interactions with semiconductor devices.

This satellite contained 18 experimental instruments and a special microelectronics package (MEP), consisting of approximately 700 semiconductor devices that could be interrogated to determine SEUs and TID levels, including two dose-measuring systems. In addition to the expected SEEs in the devices under test in the MEP, the system electronics for the scientific instruments experienced eight different types of unexpected anomalies.[11] Table 1 contains a list of the instruments on CRRES that experienced about 674 such non-SEU anomalies.

These anomalies were shown[11] to correlate with an onboard internal discharge monitor (IDM) that measured the occurrence of internal ESDs. In turn, the IDM results were shown to correlate with the occurrence of high levels of energetic electrons during the 14-month mission life of CRRES.

In addition to these anomalies, the number of SEUs for various semiconductor memories in the MEP came to an approximate total of 30,000 for the entire mission life.[12] As reported, this total number of SEUs was mainly attributable to proton interactions.

B. GOES

The family of four GOES (Geostationary Operational Environmental Satellite) spacecraft, namely GOES 4, 5, 6, and 7, have experienced a large number of anomalies that have been classified into three categories: SEUs, ESDs, and UNKs. The total number of anomalies on these satellites equals 195 events, as shown in Table 2, covering a period of time from March 29, 1981, to Feb. 22, 1993. The 60 SEUs and 93 ESDs listed in Table 2 include only events identified as radiation-induced phenomena. A more recent occurrence was reported as taking place on GOES 8 when bit flips (change of logic state) in the attitude-control RAM[13] were attributed to ESDs.

Table 1 Instruments experiencing anomalies on CRRES

Instrument mode	Anomaly abbreviation	No. of cases
Langmuir probe mode anomalies	LPMA	100
Spectrometer for electrons and protons loss-of-synch anomaly	SEPA	122
Vehicle time code work jumps	VTCW	200
Internal discharge monitor anomalies	IDMA	203
Dosimeter mode change anomaly	DOSA	27
Proton telescope mode anomaly	PROA	9
Plasma wave mode anomaly	PLWA	12
Ion mass spectrometer Hi-V supply anomaly	IMSA	1

C. CRUX on APEX

The Cosmic Ray Upset Experiment (CRUX)[14] on the U.S. Air Force APEX satellite was specifically designed to validate the models that predict upset rates. To do so, it used specific part types that are popular with NASA designers as test parts. The experiment contained 125 short-range attack missiles of six different types with 256-kbit and 1-Mbit capacity with an approximate total memory of 70-Mbit. APEX was launched on Aug. 3, 1994, and data from CRUX have been processed and analyzed through April 1995. The recorded number of upsets for this period was enormous (>250,000) with the overwhelming majority attributed to trapped energetic protons. Several important findings from CRUX were reported at recent international conferences and are being published in the open literature.[14,15] CRUX was still operational in early 1996, and more data currently are being analyzed. Because of the orbit parameters (71 deg, 352 × 2544 km) and orbit precession, it is expected that CRUX will provide detailed mapping of the proton and heavy-ion environment in terms of SEUs for most low-Earth-orbit (LEO) applications.

D. Other Satellites

Table 3 lists the number of SEUs and ESDs and SEU rates for other spacecraft in addition to those discussed above, depending on how the data were reported.[12,14–22] The total number of SEUs is listed for CRRES, APEX/CRUX, Earth Radiation Budget Satellite (ERBS), Extreme Ultraviolet Explorer (EUVE), TOPEX/Poseidon and Pioneer/Venus 1 and 2 spacecraft, whereas the number of ESDs is shown for Voyager, Intelsat-K, ANIK E-1 and E-2. The SEU rates for another 14 satellites also are shown in Table 3. A significant total of anomalies is obtained when the rate, number of satellites in orbit, and orbit durations are taken into account. For example, the group of Tracking Data and Relay Satellites (TDRS)[16] are showing about 3 upsets/day in memory devices. Multiplying this rate by the number of spacecraft (5) and their individual orbit times, a significant total is obtained. In a similar manner, the totals for the GPS, navigation data satellites (NDS), Solar Maximum Mission (SMM), Hubble Space Telescope (HST), TOMS/Meteor-3, SAMPEX, the Space Shuttle, UOSAT-2, Mir, S80/T, KITSAT-1, UOSAT-5, SPOT 1, and SPOT 2 can be calculated. In addition, Table 3 contains the number of ESDs for those spacecraft for which data were reported in this manner.

The polar orbiting (300–800 km) UOSAT-2 satellite is a good example of the severe problem posed by trapped protons. Figure 1 shows on a world map the distribution of single and multiple upsets induced by high-energy protons and possibly some cosmic rays.[17] Note that the largest number of upsets occurs in the region of the South Atlantic Anomaly, indicating that the SEUs are induced by energetic trapped protons. A similar plot of SEU data for the TOMS/Meteor-3 spacecraft,[18] also in a polar orbit (700 km),

Table 2 GOES 4, 5, 6, and 7 anomalies[a]

Year	SEUs	ESDs	UNKs
1981	3	30	0
1982	3	33	1
1983	4	15	2
1984	5	4	3
1985	9	0	0
1986	5	2	3
1987	4	4	16
1988	6	1	13
1989	11	4	4
1990	1	0	0
1991	6	0	0
1992	2	0	0
1993	1	0	0
Total (195)	60 (38%)	93 (47.7%)	42 (21.5%)

[a]Data from Spacecraft Anomaly Database, courtesy of Dan Wilkinson, National Geophysical Data Center, National Oceanic and Atmospheric Administration, Boulder, CO.

Table 3 Radiation-induced SEUs[a]

Spacecraft	Literature Ref.	No. of SEUs	No. of ESDs	SEU rate, SEU/day
CRRES	12	30,000		
APEX/CRUX	14,15	>250,000		1400
ERBS		2		
EUVE		2		
TOPEX/Poseidon		853 (May 93)		
Pioneer/Venus 1 and 2		36		
Voyager			42	
Intelsat-K			1	
ANIK E-1	22		1	
ANIK E-2	22		1	
GPS				1
NDS				1
MMS/SMM				1
HST				1–2
TOMS/Meteor-3	18			350
TDRS	16			3
SAMPEX				10
Shuttle (STS-50)				2
UOSAT-2	17			0.5
Mir Space Station	19			1
S80/T	20			531
KITSAT-1	20			38
UOSAT-5	20			55
SPOT 1 and 2	21			0.02

[a]Some data were obtained from various NASA Goddard Space Flight Center reports, public announcements, and other sources.

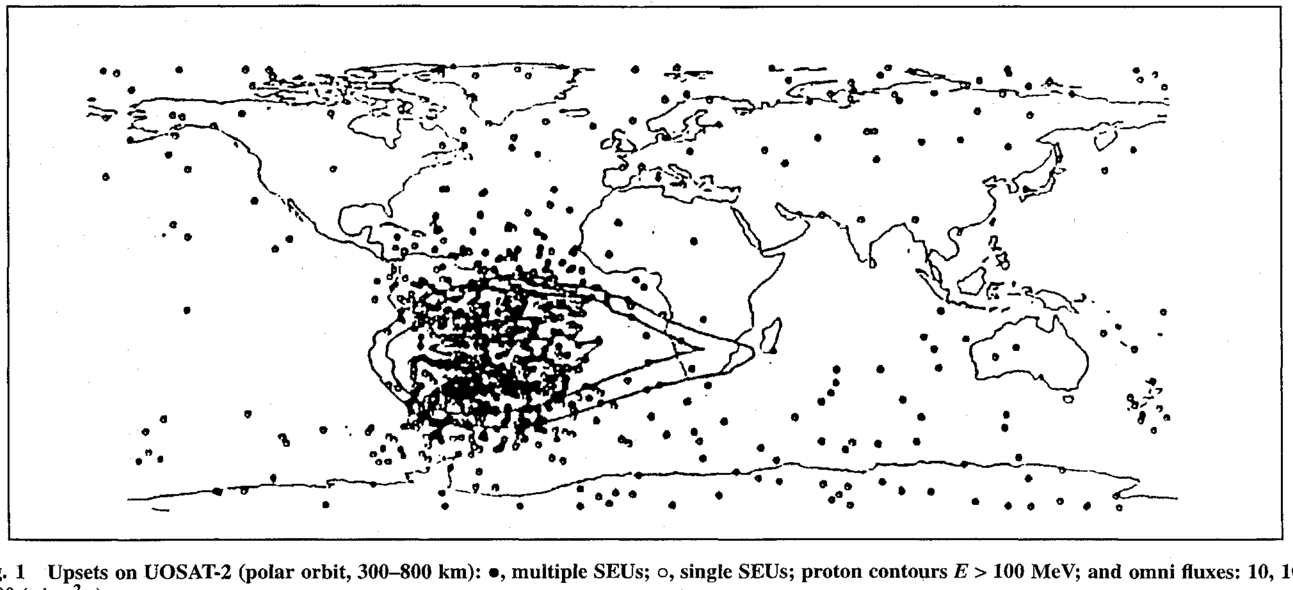

Fig. 1 Upsets on UOSAT-2 (polar orbit, 300–800 km): •, multiple SEUs; ○, single SEUs; proton contours $E > 100$ MeV; and omni fluxes: 10, 100, 1000 (p/cm^2 s).

is given in Fig. 2, where the occurrences of upsets are plotted by geographic latitude and longitude. The same high upset density in regions of high proton fluxes is also evident in the CRUX data.

There are several spacecraft [UOSAT-2, Superbird, Upper Atmospheric Research Satellite (UARS), ROSAT, and GRO] that have experienced specific system problems, anomalies, or failures. These satellites and their reported events are shown in Table 4 with orbital information. A more recent upset during launch of the Orbcomm spacecraft[22] was attributed to radiation-induced ESD.

E. ANIK ESDs

There are a number of spacecraft on which only one anomaly occurred; however, in some cases, that one anomaly led to a catastrophic functional or physical loss of the satellite. An example is the ANIK E-2 (communication satellite), which experienced a hard failure of its momentum wheel-control circuitry,[22] attributed to radiation, at approximately 0214 universal time (UT) on Jan. 21, 1994 (see Table 3). The backup or redundant circuitry failed to function and the spacecraft became inoperable for some time. This spacecraft eventually resumed operation.

The ANIK E-1, which is a sister satellite to the E-2, also suffered an operational anomaly in its momentum wheel-control circuitry[22] on Jan. 20, 1994. However, the Telesat Canada operators were able to regain control of the spacecraft after a period of 8 h. It recovered and returned to normal operations.

There is strong evidence that these two anomalous events were caused by a massive electromagnetic storm that occurred at the time of the ANIK failures, which most likely induced ESDs in both spacecraft. Figure 3 shows that the ANIK anomalies correlate well with the solar wind-speed data from the IMP-8 satellite[23] and the $E > 1$ MeV electron data from the SAMPEX spacecraft at $L = 6$, which was obtained from the heavy-ion large telescope. The observations show that the electron levels rise as the solar wind speed falls off. It can be seen from Fig. 3 that the ANIK failure took place when the solar wind speed decreased to a minimum on Jan. 20 and 21. It was the large increase in the population of electrons[24] in the solar wind that probably produced the ESD type of anomaly in the momentum wheel circuits of the ANIK spacecraft.

The Intelsat-K communications satellite also showed a loss of attitude control on Jan. 20 at 1443 UT in response to the same electron

Table 4 Satellites and their reported events[a]

Satellite	Description	Events
UOSAT-2	Polar orbiting (300–800 km)	Single and multiple SEUs from trapped protons, solar(?) protons, and galactic and solar(?) cosmic rays (see Fig. 2)
Superbird	Communication satellite (Japan)	Uncommanded thruster firing: total loss of spacecraft (believed to be SEU event)
UARS	Upper atmosphere research satellite (28.5 deg/≈ 600 km)	Index sequential access methods (ISAMS) instrument (UK) failed (believed to be power MOSFET)
ROSAT	Roentgen satellite (53 deg/580 km)	On Jan. 26, 1991, CPU for attitude control: lost control for 14 h (believed to be SEU event)
GRO	Gamma ray observatory (29 deg/450 km)	Problems with onboard tape recorders
Magellan, Viking, Pioneer, Voyager, Galileo		Several failures/upsets/errors, etc., were reported on the following satellites

[a]Some data were obtained from various NASA Goddard Space Flight Center reports, public announcements, and other sources.

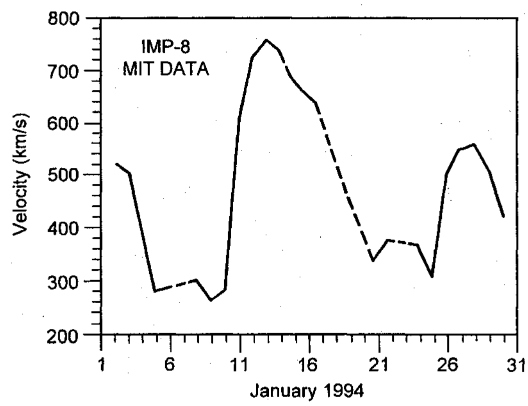

Fig. 3a Average solar wind speeds from IMP-8.

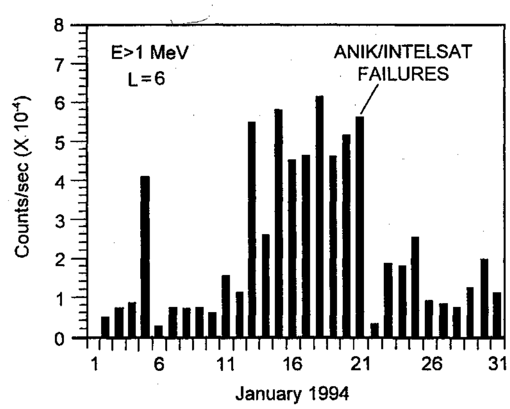

Fig. 3b SAMPEX daily average counting plates, $E > 1$ MeV, $L = 6$.

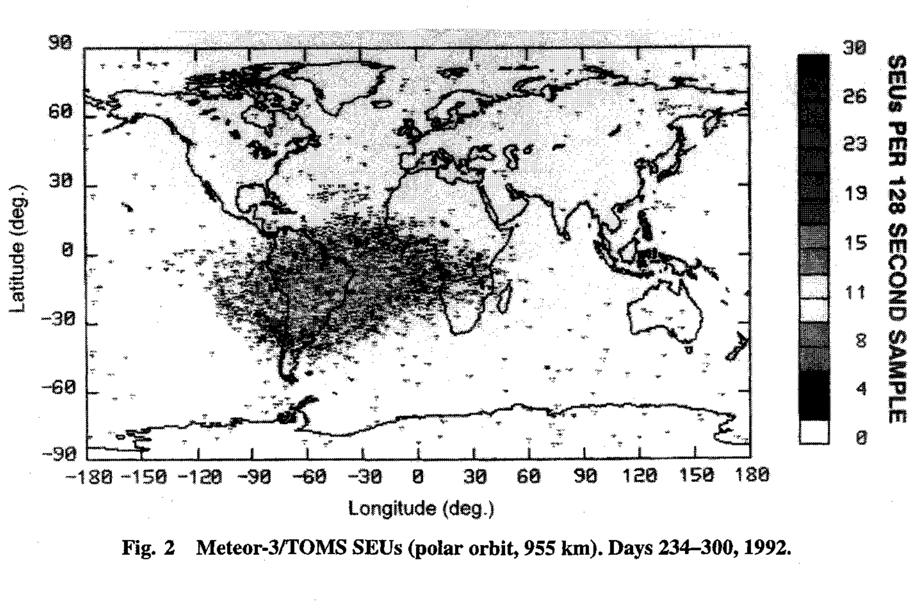

Fig. 2 Meteor-3/TOMS SEUs (polar orbit, 955 km). Days 234–300, 1992.

Table 5 Consequences of March 1989 activity effects on space systems[a]

TDRS-D reported anomalous behavior.
A LEO S/C ($i = 60$ deg, circular) began episodes of uncontrolled tumbling on 3/6, 3/8-9, and 3/14, that interfered with operational functions.
GOES-7 had a communications circuit anomaly on 3/12 and lost imagery.
Three low-altitude National Oceanic and Atmospheric Administration polar spacecraft (S/C) had trouble unloading torque because of large ambient magnetic-field changes.
The U.S. Air Force Defense Meteorological Satellite Program experienced the same trouble.
Japan's GEO S/C CS-3B had severe problem on 3/17—a permanent loss of half of command circuitry onboard.
MARECS-1 S/C of ESA had many switching events of 3/3, 3/17, 3/29
Operational Satellites of ESA experienced outages.
Seven commercial GEO comunications S/C had considerable problems maintaining operational attitude orientation. They required 177 manual operator interventions to make thruster adjustments to maintain required altitude.
Japan's GEO S/C GMS-3 suffered severe scintillations, and data transmissions were lost for ~1 h.
Several GEO communication satellites reported operational anomalies on 3/18 and 3/20, but not on earlier days.
NASA's SMM "dropped in altitude as if it hit a brick wall" during time of highest magnetic activity. It dropped by 4.8 km during the period of disturbance.

[a]Some data were obtained from various NASA Goddard Space Flight Center reports, public announcements, and other sources.

event that hit the ANIK spacecraft. The importance and significance of ESDs are again demonstrated by the recent occurrence of another electron-induced ESD event[25] that hit the Intelsat 511 satellite (communications spacecraft at GEO orbit, long. 180°E). As in these satellites, this ESD also caused a loss of attitude control. This outage lasted for several hours.

Note that deep dielectric charging is caused by very high-energy electrons trapped within the Earth's radiation belts. Normally, it has nothing to do with solar flares.

F. The 1989 Magnetic Storm

The massive solar magnetic storm of March 1989 and the accompanying electron and proton fluxes deserve special mention because so many anomalies occurred in orbiting spacecraft as a result. Some of these spacecraft already have been mentioned in this discussion, together with their anomalies. However, Table 5 groups the specific events[4] and the satellites in which they occurred for this particular time period of March 1989.

Some of the anomalies were the direct result of high magnetic fields, but others may be truly ESD types of anomalies attributable to discharges caused by rapidly fluctuating magnetic fields and electrons. It is possible that solar-flare proton-induced SEUs also occurred. A better classification may be to list all of these anomalies as caused by unknown mechanisms. It can be seen that, in this short period of time, the solar activity caused a larger-than-normal number of anomalies.

Spacecraft data have shown that a similar large event, which occurred in March 1991, generated a second proton belt in the magnetosphere between 2 and 3 Earth radii (equatorial distance) as reported in several publications.[26–31] It has been suggested that second proton belts are regularly being produced in this region of space by such events with lifetimes ranging possibly up to a year.

V. Conclusions

It can be concluded from these data that anomalies or failures attributable to the radiation environment in space, magnetic storms, and solar-flare events present a significant threat to the survivability and mission performance of spacecraft. Clearly, the challenge to engineers is formidable and the cost to the government and the commercial world is quite staggering. It is expected that further increase in the scaling of microelectronic devices will continue to increase the occurrence of radiation-induced anomalies. The engineering community should not underestimate this problem and should aggressively address the SEU and ESD issues in new spacecraft design.

In addition to using error detection and correction (EDAC) to correct SEUs, the approach of designers to mitigating the threat of spacecraft upsets has been to apply other circumvention and recovery techniques in subsystem designs. This approach has worked and is still working successfully in the orbiting SAMPEX satellite. The measures taken included Hamming EDAC for the solid-state recorder, overlying protocol (retransmission) for the 1773 fiber-optic bus, passive and active multilevel Watchdog® timers for all levels of the circuit-board box. There may be other fixes for the upset problem, but the SAMPEX solution appears quite effective in protecting future system designs.

In terms of the environment, the dominant mechanism for generation of upsets appears to be high-energy protons and electron-induced ESDs with cosmic rays as secondary causes. Note that the ESD type of event is not a negligible threat and can occur whenever a high-energy (i.e., $E > 1$ MeV) electron or a severe magnetic storm take place.

Finally, it is very important that spacecraft designers and operational personnel understand the differences between solar energetic particle events, surface charging, and GCR (SEE) phenomena. These various so-called space weather events have very different physical causes and, hence, require distinct preventative design approaches.

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