Solar Proton Events of 1989: Effects on Spacecraft Solar Arrays

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Three energetic solar proton events occurred in the August–October 1989 time period. The energetic (1–10 MeV) proton fluence from these events was among the highest fluence levels observed during the space age. The solar proton events were of sufficient magnitude to produce easily observable (several percent), irreversible losses in solar array output on geosynchronous and polar low-Earth-orbiting satellites. The degradation of solar array output was measured on the GOES-5, GOES-6,and GOES-7 satellites and on two other U.S. Government satellites in geosynchronous orbit. The observed solar array degradation was compared with that computed based on knowledge of the solar cell type, coverglass thickness, the operational mode of the array, the observed proton spectrum, and the length of time on orbit for each satellite. In each case, good agreement was obtained between the observed and the computed results.

Nomenclature

c = speed of light
I_{sc} = short circuit current
J = integral omnidirectional proton flux
J_o = spectral parameter
P_{max} = maximum power
R = proton rigidity
R_o = characteristic proton rigidity
V_{oc} = open circuit voltage

Introduction

THROUGHOUT 1989, the sun was extremely active, perhaps as active as it has been at any time during the space age. In particular, three solar proton events that occurred in the August–October 1989 time period had operational implications for several military, government, and commercial satellite systems. Operational effects on space systems included impacts on navigational, communications, and power subsystems.[1,2] The effects on power subsystems included the permanent loss of several percent of the power output from solar arrays on many high-altitude satellites. The purpose of this paper is to provide a description of the observed effects of the recent solar activity on solar arrays, to compare the observed effects with theoretical expectations, and to provide a qualitative comparison of the solar particle events of August–October 1989 with other events of historical importance. The first section of this paper describes the proton events of 1989, including their spectral and temporal characteristics. The second section shows examples of on-orbit effects of these proton events on operational solar arrays and compares the observed effects with modeling estimates. These estimates are derived from the measured solar flare proton spectra and the empirical knowledge of proton effects on solar cells.

Solar Proton Events of August–October 1989

Three significant solar particle events occurred in 1989. These events occurred on August 13–16, September 29–30, and October 19–23. Figure 1 shows the temporal evolution of the solar proton events of August 12–13, 1989, and August 16, 1989. This figure consists of consecutive stacked plots of GOES-7 satellite 1–8 Å solar x-ray flux (top panel), GOES-7 >2 MeV electron flux, and several channels of GOES-7 high-energy proton flux (bottom panel). In a similar format, the time evolution of the September 29, 1989, event is shown in Fig. 2, and the October 1989 event is shown in Fig. 3. Time-integrated energy spectra for each of these events are plotted in Fig. 4, along with an energy spectrum of the historic August 1972 event.

The solar proton events on August 12–13 and on August 16, 1989, were due to solar activity associated with region 5629, one of the most active regions of solar cycle 22, which began in September 1986. During a one-week period this region was responsible for five X-class x-ray flares, several more M-class flares, and two extremely large proton events, including one ground level event (GLE). (X-class x-ray flares are solar flares with observable x-radiation exceeding 10^{-4}W/m^2; M-class flares have fluxes in excess of 10^{-5}W/m^2. Solar protons must have incident energies higher than about 600 MeV to be observed at ground level.) The first proton event, which began about 1600 UT on August 12, 1989, was due to an X2 flare (i.e., x-ray flux = 2×10^{-4} W/m^2) which was observed at 1427 UT. High-energy (~ 10 MeV) proton fluxes remained elevated above "event" levels for 2–3 days following this event onset, while the very energetic component (> 100 MeV) diminished over several hours following the onset. Peak instantaneous proton fluxes (> 10 MeV) for this event reached well over 10^3 cm^{-2} s^{-1} sr^{-1} on August 13, 1989.

As 1–100 MeV proton fluxes were still at event intensities from the August 12 event, region 5629 produced another (larger) flare while near the sun's west limb. This flare, an estimated X20 x-ray flare (note that the GOES instrumentation saturates at flux levels of about X10) produced another proton event with a substantial high-energy component. This flare had a very long duration and it produced perhaps the largest time-integrated x-ray flux ever recorded. Although peak instantaneous proton fluxes for the August 16 event never exceeded those for the preceding August 12 event, the August 16 event had a much harder energy spectrum and produced a significant GLE. A ~6–7% increase of ground-level neutron flux was observed.

High levels of solar activity were observed again on September 29, 1989, when region 5698 produced an X9 x-ray flare at 1133 UT. The time evolution of this event is depicted in Fig. 2. This long-duration (~4 h) flare occurred slightly beyond the sun's west limb. Although the peak proton fluxes (> 10 MeV) were only comparable to those of the August 1989 events, the

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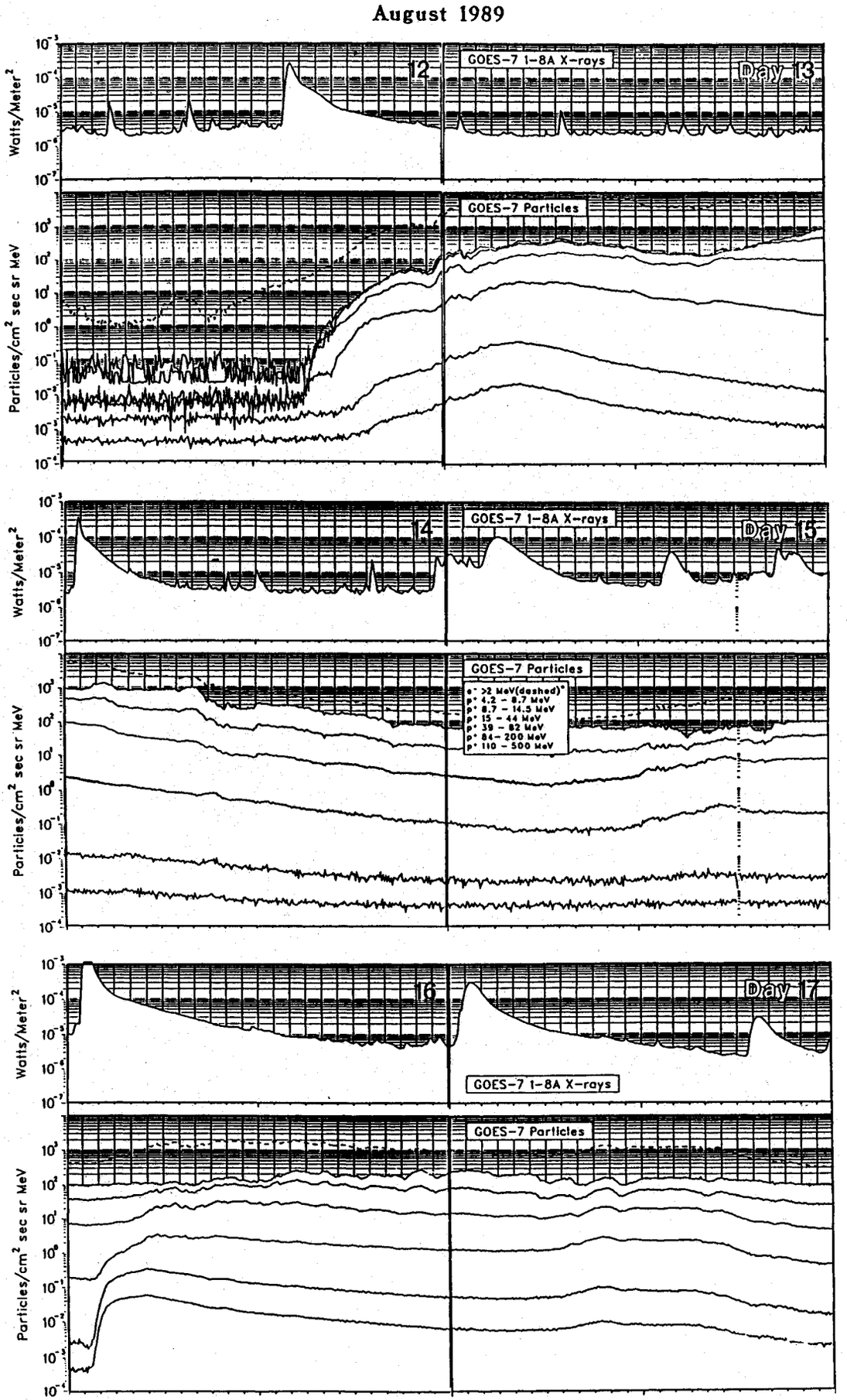

Fig. 1 Solar-terrestrial environment (August 1989).

September 29 event clearly had much higher intensities at very high energies. The September 29 event produced a GLE characterized by an increase in ground-level neutron flux of between 450 and 500%. This is the largest GLE observed in over 30 years. (The historic August 4, 1972, event produced a neutron monitor increase of about 20% over background.) Only a few events on record, in the 1956–1960 time frame, produced neutron fluxes near those observed on September 29, 1989.

The time evolution of the October 1989 event is shown in Fig. 3. The October event began at 1258 UT on October 19 with the occurrence of an X13 flare. Energetic protons arrived at Earth at about 1305 UT and increased toward a maximum at about 1530 UT on October 20. The brief enhancement of proton flux observed between 1300 UT and 1800 UT on the 20th is thought to be due to secondary acceleration of solar particles in the interplanetary medium, similar to that which occurred in association with the historic August 1972 event.[3] Subsequent enhancements of the proton flux occurred on October 22 and again on October 24 in association with X2 and X5 flares, respectively. Three ground-level events, having flux increases of 45, 25, and 90% over the cosmic background, were observed within this of period.

For most applications, including the computation of solar array effects, it is useful to examine the event-integrated fluxes as a function of proton energy threshold. These time-

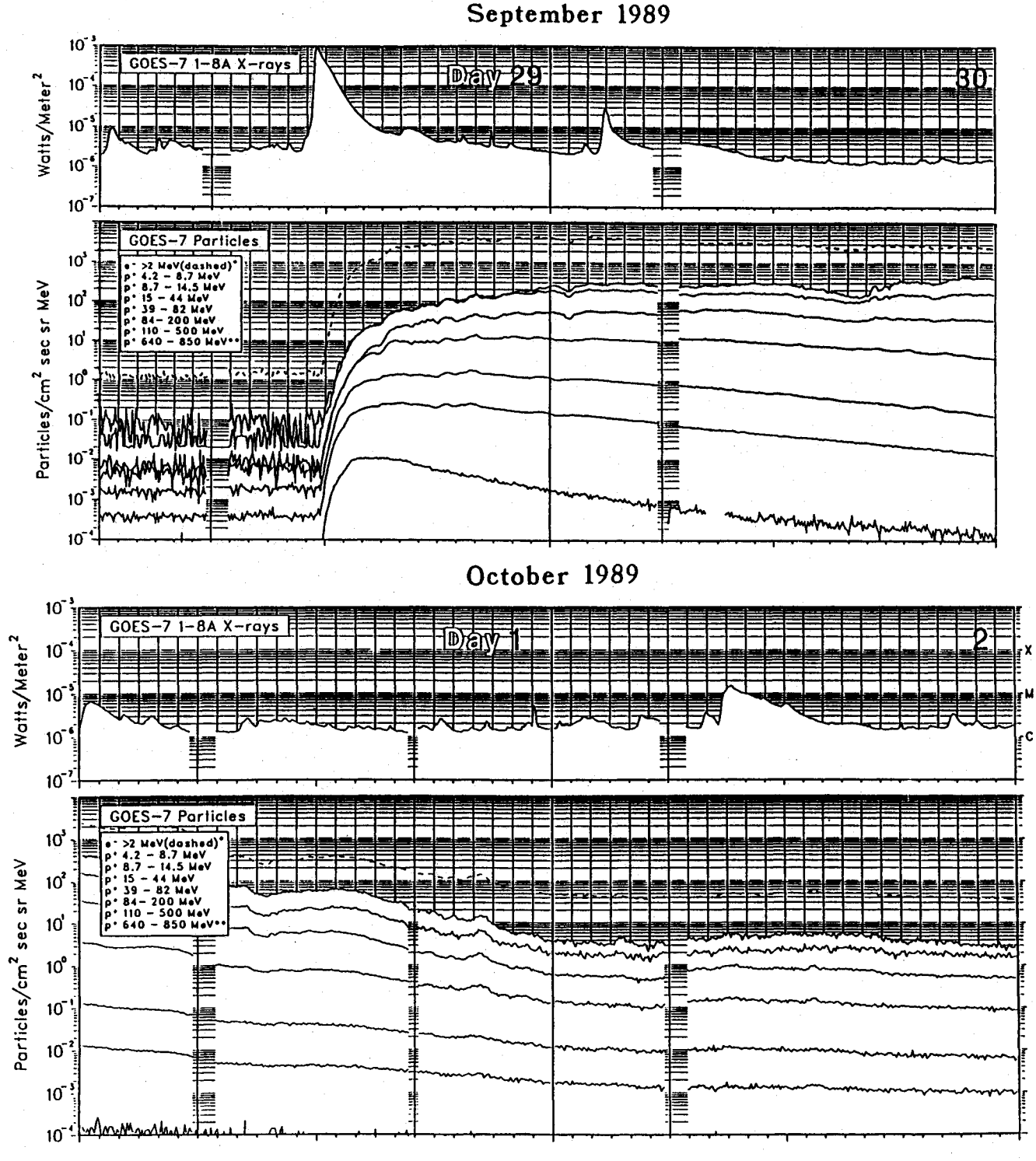

Fig. 2 Solar-terrestrial environment (September–October 1989).

Table 1 Parameters of an exponential fit to the rigidity spectra $[J(\text{cm}^{-2}) = J_o\exp[-R/R_o]]$ of three proton events observed in 1989

Event	Integration period, 1989	J_o, cm^{-2}	R_o, MeV/c
1	Aug. 12, 0:00 UT - Aug. 21, 0:00 UT	6.66×10^{10}	60.77
2	Sept. 29, 0:00 UT - Oct. 5, 0:00 UT	1.46×10^{10}	100.03
3	Oct. 16, 0:00 UT - Oct. 30, 15:00 UT	1.40×10^{11}	73.67

integrated spectra (in units of cm^{-2}) are shown in Fig. 4. The three recent events were fairly long-lived, leading to relatively high levels of accumulated fluence over the lives of the individual events. The event lifetimes as a function of proton energy were quite different for the different events. An overall conclusion is that each of the three recent events is significant compared to the standard observed intensity ranges for proton events.[4] The October event had the highest flux at low (~1-10 MeV) energies, whereas the September 29 event had the hardest energy spectrum. The August 1972 event had higher integrated fluence at the highest energies.

Each of the three recent proton events has an energy spectrum that is well represented by the following functional form:

$$J(>R) = J_o\exp(-R/R_o) \tag{1}$$

where $J(>R)$ is the integral omnidirectional proton fluence (protons/cm^2), and R is the proton rigidity (MeV/c). This functional form represents the proton spectra for each of the events that occurred in 1989, with an accuracy of a few percent

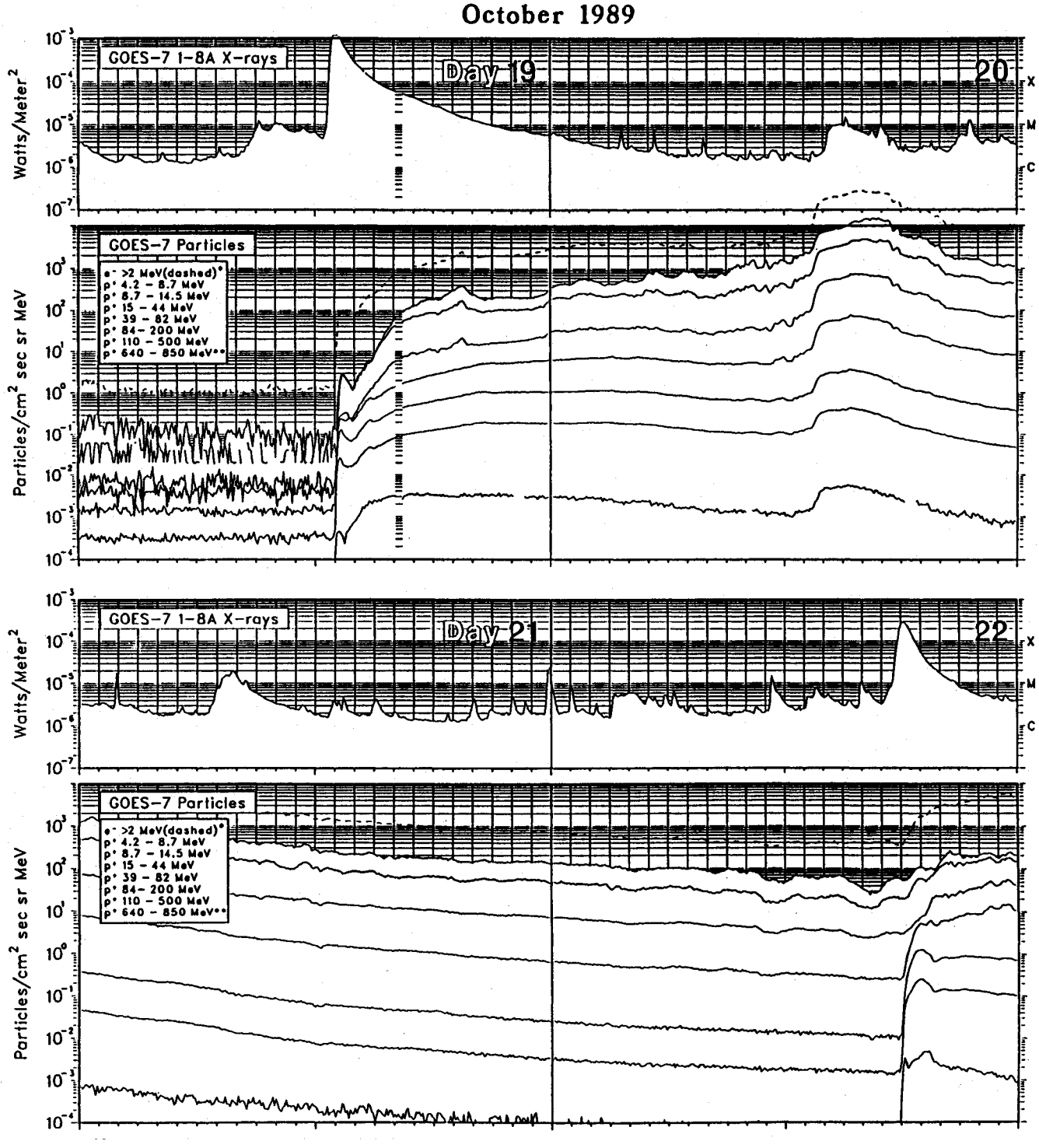

Fig. 3 Solar-terrestrial environment (October 1989).

Table 2 Integral fluences (cm^{-2}) of the three proton events listed in Table 1

Event	>1 MeV	>5 MeV	>10 MeV	>30 MeV	>60 MeV	>100 MeV
1	3.06×10^{10}	1.28×10^{10}	7.75×10^{9}	1.48×10^{8}	2.05×10^{8}	4.53×10^{7}
2	9.45×10^{9}	5.47×10^{9}	4.04×10^{9}	1.30×10^{9}	4.50×10^{8}	1.86×10^{8}
3	1.03×10^{11}	3.89×10^{10}	1.92×10^{10}	4.26×10^{9}	1.23×10^{9}	4.65×10^{8}

over the energy range 1–100 MeV. Table 1 gives the best-fit spectral parameters for the three events in 1989. Table 2 lists the integral fluence for each of the events, based on the spectral parameters in Table 1.

Together, the four events shown in Fig. 4 represent integrated proton fluences that exceed the sum of all other events that normally occur during a several-year time period. It is unlikely that any of these individual events represents a true worst case. Whether more events of this type are to occur in the remainder of cycle 22 is probabilistic,[5] but historical evidence indicates that several more significant events are likely to occur during the 1990–1995 time period.

Proton Effects on Solar Arrays

The solar flare proton events of 1989 are of sufficient magnitude to produce easily observed, irreversible losses in solar array output on geosynchronous and low-polar-orbiting spacecraft. The flight data in Fig. 5 show the effect of two events on the GOES-7 solar array. The exact magnitude of the effect depends on a number of factors. One important factor is the amount of radiation received prior to the flare occurrence. The integrated natural radiation dose is determined by the trapped electron and proton environment of the spacecraft orbit, the coverglass thickness used on the solar cells, and the amount of time the spacecraft has been on orbit. Solar cells do not degrade linearly with the accumulated fluence, but rather obey an approximately exponential loss of output with total fluence. A typical degradation function for an 8-mil-thick silicon solar cell[6] is shown in Fig. 6. The result of this characteristic of solar cells is that additional increments of fluence that occur later in a spacecraft's life cause smaller effects than increments that occur within the first year or two of operation. Another important factor is the solar cell design. Silicon cells degrade more rapidly than gallium arsenide cells, and, within the class of silicon cells, those with back surface fields (BSF) degrade more rapidly than non-BSF types. Finally, the operational mode of the solar array is important because the short-circuit current (I_{sc}) of the solar cell degrades at a different rate than the maximum power (P_{max}) capability. Most solar arrays (shunt regulated) operate well to the low-voltage side of the maximum power point at a fixed bus voltage, even near end of life (EOL). In this case the degradation of I_{sc} with radiation dose is the relevant parameter. However, some advanced arrays (series regulated) operate the solar cells on the high-voltage side of the maximum power point. In these cases, the degradation of P_{max} is a more appropriate measure of the array capability because the array voltage can be adjusted to coincide with the changing maximum power point.

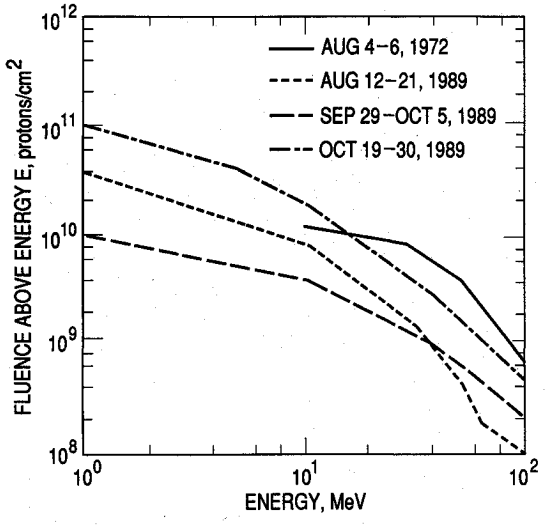

Fig. 4 Integrated proton fluence for each of the proton events depicted in Figs. 1–3, compared to the event of August 1972.

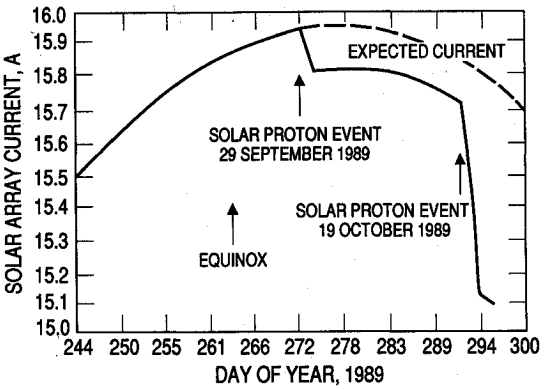

Fig. 5 Observed solar array current on GOES-7 during fall 1989.

The solar flare activity of 1989 provides an excellent opportunity to verify our understanding of these issues. Comparison of effects observed during the October 1989 flare on similar spacecraft of different ages were made using the GOES-5, GOES-6, and GOES-7 spacecraft. (Coincidentally, these satellites carry the detectors from which the spectrum of the solar flare protons is obtained.) These range in age from 3 to 9 yr, and all use the same type of solar cells in shunt-regulated arrays. Therefore, any difference in degradation should be due to the amount of previously accumulated radiation. Analysis of flight data showed that the two older satellites, GOES-5 and GOES-6, suffered less degradation in array output current than the youngest, as expected. The fact that the two older satellites degraded virtually the same amount, even though they are different ages, is consistent with the decreased sensitivity of solar cells to radiation later in life described above.

The amount of short-circuit current degradation predicted for all three satellites was computed using the measured spectrum of the October flare and ground test data showing the effect of these protons on the specific solar cell type used on GOES. The procedure for this computation is well documented[6] and is therefore summarized only briefly here. The spectrum of protons from a solar flare is converted to an equivalent fluence of 1-MeV electrons using damage-equivalence functions. These functions specify the number of 1-MeV electrons that cause the same amount of degradation in a selected solar cell property (I_{sc}, V_{oc}, or P_{max}) as one proton of specified energy. Given the set of functions to cover all relevant proton energies, the entire solar flare spectrum can be collapsed to an equivalent 1-MeV electron fluence. Extensive ground test data on silicon solar cells, of which Fig. 6 is an example, are available which show the effect of 1-MeV electrons on cell output. When referring to Fig. 6, the solar flare equivalent fluence must be treated as an increment added to the previously accumulated fluence. As expected, the results of these computations, shown in Fig. 7, indicate that the oldest satellite should degrade the least, while the youngest should degrade the most.

Table 3 Silicon solar cell type, coverglass thickness, and time on orbit for three spacecraft types studied

Satellite	Solar cell	Coverglass thickness, mil	Time on orbit, yr
GOES-5	Textured BSF/R[a] (K7)	9	8
GOES-6	Textured BSF/R[a] (K7)	9	6
GOES-7	Textured BSF/R[a] (K7)	9	2.5
A	BSR[b](K4¾)	10	>1
B	BSR[b] (K4¾)	6	>1

[a]Back surface reflector and field.
[b]Back surface reflector.

Calculations were also made for other geosynchronous spacecraft, designated A and B, which have solar cell types and coverglass thicknesses different from the GOES vehicles. These parameters are summarized in Table 3. Good agreement between flight data and calculations, shown in Fig. 7, was found in these cases also. The similar behavior of GOES-7 and satellite A is fortuitous. GOES-7 has been in orbit longer, but the K7 cells are more sensitive to radiation than the K4¾ cells used on satellite A. Satellite B degraded more than any other in this study, primarily because of its thin coverglass.

The accuracy of these calculations is determined primarily by uncertainties in the flare spectrum as measured by the GOES satellites, and in the understanding of proton effects in solar cells, as reflected in the damage-equivalent fluence functions.

Given the significant effects of these solar flares on geosynchronous solar arrays, additional analyses were performed to assess the practicality of using thicker coverglasses as protection. The penalty associated with the use of thicker covers is the increased weight of the solar array. As shown in Fig. 8, it was found that going beyond the nominal thickness of 6–12 mil provides some benefit in array short-circuit current capability after a solar flare with the spectrum of the October 1989 event. If the array operates near the maximum power point, there is a greater advantage that may make thicker covers attractive. However, before choosing to use thicker coverglasses, a vehicle-specific weight trade study should be made to compare the alternative of carrying more solar array area to offset the anticipated loss. No reasonable coverglass thickness will provide complete protection, however.

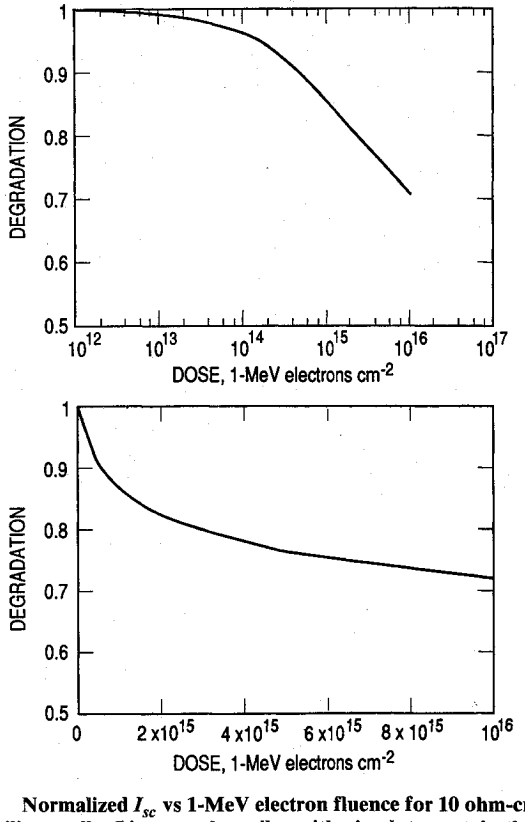

Fig. 6 Normalized I_{sc} vs 1-MeV electron fluence for 10 ohm-cm n/p, BSR silicon cells. Linear and semilogarithmic plots contain the same data.

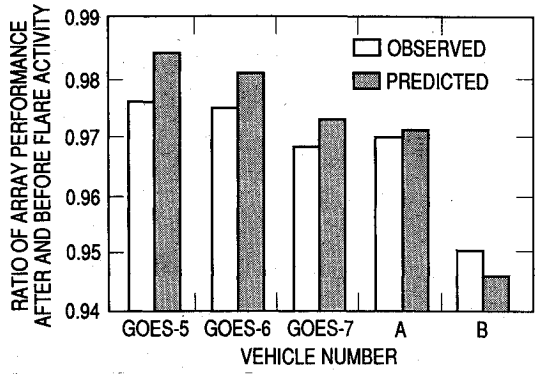

Fig. 7 Comparison of theory and observations.

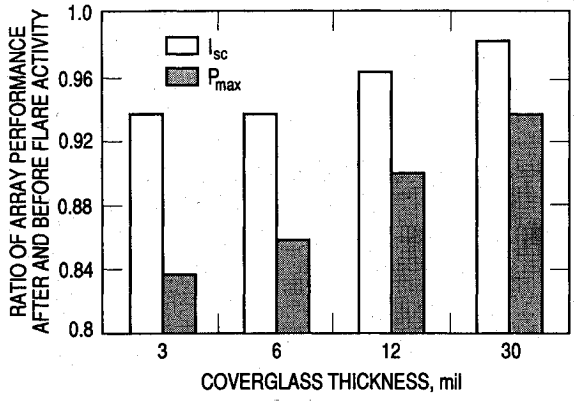

Fig. 8 Calculated effects of Oct. 20, 1989, flare on a K7 solar cell.

Although the cumulative effect of these intense flares may be only a 5–10% drop in the projected end-of-life power of a typical geosynchronous satellite, this can have important implications for the mission if it reduces the power system capability below that required to operate the payloads normally. As a result of the events of 1989, additional margin may be carried in future spacecraft.

Conclusions

The solar flare events of 1989 represent integrated proton fluences that exceed the sum of all other events of the past several years. The observed effect of these events on geosynchronous spacecraft solar arrays is consistent with modeling predictions. The effect amounts to an additional 5–10% loss in array output capability at end of life. The decision of whether to provide additional power margin, or additional coverglass protection, in future missions will continue to be based on the probabilistic treatment of solar flares and the predicted effects of these flares.

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