Table 2 Inertia matrices for example case

$$I_{initial} = \begin{bmatrix} 29{,}290 & & \\ -8940 & 64{,}210 & \\ 1780 & 4903 & 78{,}660 \end{bmatrix} \qquad I_{final} = \begin{bmatrix} 25{,}210 & & \\ 0.0023 & 60{,}120 & \\ 0.3659 & -0.0322 & 70{,}960 \end{bmatrix}$$

The spacecraft bus is a solid rectangular structure 20 m long (length in x direction), 10 m wide (width in y direction), and 5 m deep (depth in z direction). The spacecraft has a mass of 1000 kg and the following inertia properties: I_{xx} = 5208 kg-m^2, I_{yy} = 17,703 kg-m^2, I_{zz} = 20,833 kg-m^2. The spacecraft inertia cross products are 0 due to symmetry about the body axes. In this example, the payload set consists of a group of 1-m cubes, each weighing 100 kg, uniformly distributed about the cube's volume and placed at arbitrary positions on the spacecraft. Each cube's inertia is also accounted for. The example case consists of a 10-instrument set distributed as follows: four on the positive z face of the spacecraft, two on the negative z face of the spacecraft, two on the positive y face, and two on the negative y face. In this case, the weighting factors γ_i were set to 1.0, and thus equal importance is placed on each inertia product.

The spacecraft and the instruments are represented as parallelepipeds. The program accommodates a complete mass-properties description of each item in terms of center-of-gravity placement and inertia properties.

After the optimization was performed, the results show a reduction of the inertia cross products by an average of four orders of magnitude. The initial and final positions of the instruments are shown in Table 1. The initial and final inertia matrices results are in Table 2. The gravity gradient torque magnitude was reduced from 1.95×10^{-2} to 1.37×10^{-6} N-m for a 250 n.mi. orbit. Based on these results, the amount of propellant budgeted for gravity gradient-induced momentum desaturation can be reduced, and additional instruments can be added.

Obviously, a simplistic rectangular structure may not be available for spacecraft optimization. Through the use of additional constraints, such as side constraints and equality/inequality constraints, the problem can be sufficiently tailored to a specific application. The inertia cross products are significantly reduced using this methodology. The objective function could be altered to account for other concerns, such as center-of-gravity location and weight, volume, or power requirements.

Optimization techniques can be used to determine the position of externally attached payloads on any arbitrary spacecraft, thus providing insight on the effect of mass-properties management on a spacecraft system. Given a set of payloads on any face of the spacecraft, a mathematical model can be created as point masses with individual inertia matrices, and optimization can be accomplished using available parameter optimization programs. Using an example spacecraft concept, this approach demonstrated that payload locations can be altered to reduce the inertia cross products. In this particular analysis, the inertia products were reduced an average four orders of magnitude. In the development of further mission constraints, many mass-properties analyses can be performed in a quick and efficient manner.

References

[1]Leondis, A., "Large Advanced Space Systems Computer-Aided Design and Analysis Program," Final Technical Rept., NASA CR-159191-1, July 1980.

[2]Meirovitch, L., *Methods of Analytical Dynamics,* McGraw-Hill, New York, 1970, p. 142.

[3]Ferebee, M. J., Jr., and Powers, R. B., "Optimization of Payload Mass Placement on a Dual Keel Space Station," NASA TM-89051, March 1987.

[4]Vanderplaats, G. N., "ADS—A FORTRAN Program for Automated Design Synthesis, Version 1.10," NASA CR-177985, Sept. 1985.

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Large Solar Proton Events and Geosynchronous Communication Spacecraft Solar Arrays

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Introduction

THE design levels of power margins in geosynchronous solar arrays and of weight penalties by solar array cover glasses depend not only on the magnetosphere electron fluxes but also on the solar flare proton fluence models used. The occurrence of the high fluence solar events in October 1989 has caused a re-examination of some of the assumptions made as to the appropriate energy spectral representations of the large solar flare proton events used for some engineering designs. We discuss several aspects of solar flare proton fluxes and conclude that exponential in rigidity spectral representations of the largest events in the last two decades should be used for design purposes.

Solar Proton Fluences

Charged-particle instrumentation flown on the first geosynchronous spacecraft, ATS-1, returned data that demonstrated the relatively ready access of solar flare particles to the Earth's magnetosphere.[1] Because of the easy access of solar flare particles,[2,3] it was readily evident that these particles had to be included in determinations of the radiation dosage expected for synchronous spacecraft components. In particular, the easy access of relatively low-energy solar particles ($\lesssim$ 10 MeV, and even $\lesssim$1 MeV) meant that these particles could be significant factors in producing damage to solar arrays, damage that could significantly influence the margins required in the power design.[4-6]

The relatively benign interplanetary conditions, in terms of high intensities of solar flare particle fluxes, that persisted for years following the August 1972 solar event and throughout

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the 21st solar cycle (peak of solar activity in 1979–1980) provided a sense of complacency in some aspects of spacecraft design for robustness to solar radiation conditions, including design considerations for geosynchronous solar power systems. The fluences from the August 1972 event have been a principal reference[7] by designers. Unfortunately, the King[7] flux model does not extend to actual measured levels for solar protons with energies < 10 MeV in the event. The estimates for design purposes for these lower energy protons are obtained by an extrapolation of the King model using an exponential in energy representation of the flux $J(E)$

$$J(E) = J_0 \exp(-E/E_0) \tag{1}$$

where E is the proton energy and E_0 is the exponential energy decay factor of the proton fluxes.

The occurrence, during the five-month interval July–November 1989, of a series of very large solar flare particle events[8,9] has produced a considerable concern in the solar power design community for communication and other spacecraft. Shown in Fig. 1a are the total fluences from the August 1972,[7] the October 1989,[8] and the July 1982[10] (the largest in solar cycle 21) events plotted in an exponential in energy representation. The 1972 event fluences are extrapolated to the 1–10-MeV range using the spectral representation given in Eq. (1), where the dashed line corresponds to $E_0 = 25.8$ MeV. Shown in the figure by the open circle is the five-times value of the 5 MeV fluences from the 1972 event, a frequently used design parameter for commercial communications spacecraft. This five-times value is obtained from the extrapolation, using Eq. (1), of the measured 1972 event fluences.

The 1989 event fluences at $E < 10$ MeV were considerably larger than the extrapolation of the 1972 event fluences. Nevertheless, the extrapolation by Eq. (1) to lower energies of the 1972 fluences to give the five-times fluence value at ~ 5 MeV implies that very large solar fluences in the 1–10-MeV range must be designed into systems. Solar array design to such large fluences (order 10^{11} protons/cm^2 at 5 MeV), if not warranted, can have significant impacts on spacecraft weight (in terms, for example, of increases in solar cell shielding) and thus in the margin of orbit control fuel that can be carried.

Plotted in Fig. 1b are the 1972, 1982, and 1989 event fluences as a function of particle rigidity R

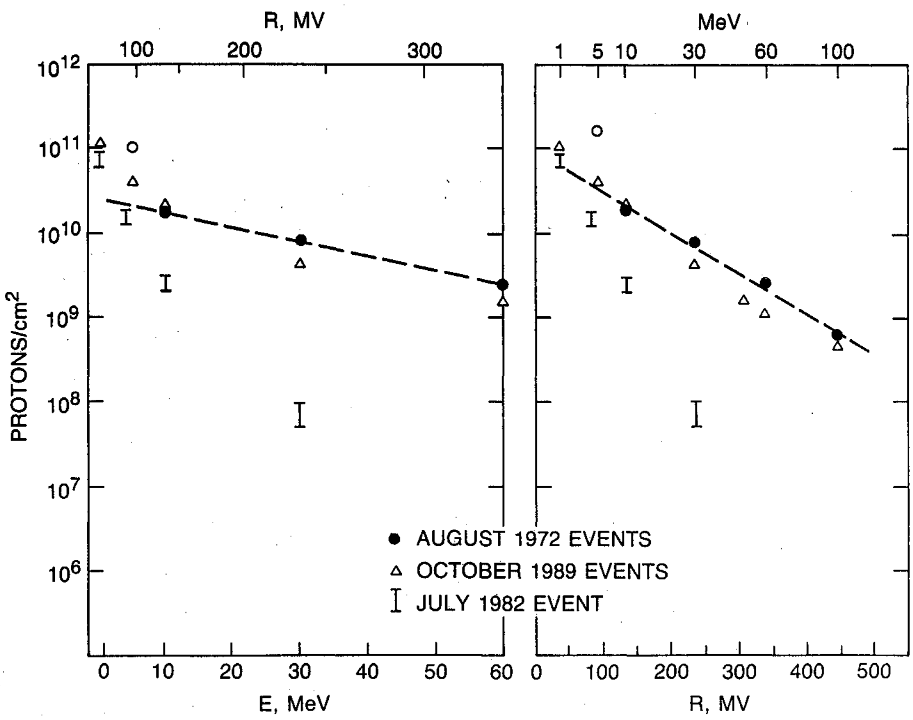
$$J(R) = J_0' \exp(-R/R_0) \tag{2}$$

where the particle rigidity $R(\text{MV}) = 43.3\sqrt{E(\text{MeV})}$ (nonrelativistic approximation; essentially a measure of the particle momentum) and R_0 is the exponential rigidity decay factor of the proton fluences. For the 1972 event, $R_0 = 88$ MV (dashed line fit); for the 1990 event, $R_0 = 82$ MV (again only for measured values of $E \geq 10$ MeV). As for Fig. 1a, the extrapolated five-times 1972 fluence at 5 MeV ($R = 96.2$ MV) is shown by the open circle. Now, the five-times fluence is 1.6×10^{11} protons/cm^2.

As Fig. 1a indicates, the five-times value of the 5 MeV fluences from the August 1972 data, extrapolated as an exponential in energy, is only slightly more than a factor of two larger than the measured October 1989 fluences at this energy. In contrast, when the 1972 event fluences are extrapolated as an exponential in rigidity, the five-times value (open circle in Fig. 1b) is nearly a factor of four times the measured October 1989 event value. These differences are produced by differences in the proton spectra for the two events. The August 1972 event is considerably harder (relatively more higher, as compared to lower, energy particles for energies $\lesssim 100$ MeV) than is the 1989 event. Hence, the five-times design criteria of 1972 event fluences, when obtained from an extrapolation of the event spectra as an exponential in rigidity, could provide sufficient solar array power design margin if the array shielding excluded protons with energies $\lesssim 5$ MeV.

Solar Event Characteristics

There are at least two basic mechanisms that can produce the differences in event spectral shapes and, thus, the particle intensities at the lower energies that can most damage solar arrays. Both mechanisms must be considered when discussing engineering design tradeoffs for the design of the power margins in new generations of commercial communication satellites, which are expected to be in service for considerably more than a decade. The two principal considerations are 1) the size



a) Fluences plotted as a linear function of proton energy **b) Fluences plotted as a linear function of proton rigidity**

Fig. 1 Proton fluences from three large solar flare events.

and location of the originating flares on the solar surface and 2) the acceleration, scattering, and trapping of particles in the interplanetary medium by the shock waves that result from the flares.

Those flares that produce particles that reach Earth with largest intensities occur within a region of about 30° E of solar central meridian to almost the west limb. Although it is not possible as yet to predict accurately the intensities of flare particles from a specific flare, the particle intensities at Earth tend to be larger for a specific size flare if the flare occurs in the region of ~30-60° W of the Earth-Sun line. The October 1989 event consisted principally of three separate solar flare injections of particles; all three injections resulted in similar magnitude fluences at Earth.[8,9] In contrast, the August 1972 event had two principal solar flare injections as distinguished at Earth.[11]

The other important factor is the effect of interplanetary shock waves on the observed energetic particles.[12,13] During the shock event on October 19, 1989, the integral flux of particles with $E < 10$ MeV increased by a factor of 10.[14] Smaller increases were observed in association with shock events in the other two October 1989 events; these served to maintain the intensities of low-energy solar-origin particles at high levels near Earth's orbit for eight or nine days. In contrast, the August 1972 event had two principal shock waves; the associated effects on low-energy particles following these shocks were not as large as those following the initial October 1989 event, and the elevated intensities did not persist quite as long.[15]

Design Considerations

The solar arrays of modern commercial communications spacecraft now provide many kilowatts of power at the beginning of mission life and have areas of many hundreds of square feet. With such large array areas, the cover glasses that protect the solar cells from low-energy proton damage contribute a significant amount of weight to the total spacecraft. For example, in a spacecraft with a 600-ft^2 solar array, the typical 12-mil quartz cover glasses contribute almost 100 lb of weight. Such a weight impact offers a potential for a weight savings as a tradeoff against the end of life power margin. The tradeoff consideration depends, of course, on the physical design of the array, the area constraints, thermal considerations, solar cell design and type, spacecraft design life, and ultimately, on the assumed model of the low-energy proton fluxes. With 12-mil cover glasses, protons with $E < 8$ MeV will be absorbed. If a 4-mil cover glass is used, protons with $E < 3$ MeV will be absorbed. A 4 mil-covering on a 600-ft^2 solar array will produce a weight savings of nearly 60 lb. Such a weight savings could translate into 9–10 months of additional stationkeeping fuel, depending on spacecraft mass and thruster design. Hence, it is certainly desirable to obtain as accurate as possible estimates of the solar proton fluences expected in the energy range of ~1–10 MeV in a mission lifetime.

Given the spectral shapes of the two largest solar particle events of the last two decades and the conclusion that the exponential in rigidity representation is best for expressing these shapes, a power system designer must make educated guesses as to the fluence levels expected in a spacecraft lifetime. For a 12–15 yr spacecraft life expectancy, for example, the considerations will also have to take into account the launch date in the phase of the solar cycle; that is, whether two solar maxima or one are likely to be encountered. The total fluence levels will depend on the number and character of the large events that are likely to occur, as these will dominate the solar cycle.[9,16,17] This involves the statistics of small samples and can be fraught with great uncertainties. King,[7] Feynman et al.,[18] Lal,[19] and Goswami et al.[10] have all approached these issues in different ways.

For engineering design purposes, from the discussions involving the data of Fig. 1 and the intensity vs time characteristics of the solar flare events, it is likely that the five-times rule of thumb of the August 1972 fluences, when the spectra are expressed as an exponential in rigidity, not as an exponential in energy, would provide sufficient design margin for a geosynchronous solar array power system. Such a rule would give a design fluence about a factor of four higher than the measured fluences of 5 MeV protons in the October 1989 event.

References

[1]Lanzerotti, L. J., "Penetration of Solar Protons and Alphas to the Geomagnetic Equator," *Physical Review Letters*, Vol. 21, No. 11, 1968, pp. 929–933.

[2]Paulikas, G. A., and Blake, J. B., "Penetration of Solar Protons to Synchronous Altitude," *Journal of Geophysical Research*, Vol. 76, No. A1, 1971, pp. 2161–2165.

[3]Lanzerotti, L. J., "Solar Energetic Particles and the Configuration of the Magnetosphere," *Reviews of Geophysics*, Vol. 10, No. 1, 1972, pp. 279–393.

[4]Lanzerotti, L. J., "Solar Proton Radiation Damage of Solar Cells at Synchronous Altitudes," *Journal of Spacecraft and Rockets*, Vol. 6, No. 9, 1969, pp. 1086–1087.

[5]Tada, H. Y., Carter, J. R., Jr., Anspaugh, D. E., and Downing, G. R., "Solar Cell Radiation Handbook," Jet Propulsion Laboratory, JPL Publication 82-69, Nov. 1982.

[6]Paulikas, G. A., "The Space Radiation Environment: Effects on Space Systems," *Solar System Plasma Physics*, Vol. 3, edited by L. J. Lanzerotti, C. F. Kennel, and E. N. Parker, North Holland, Amsterdam, The Netherlands, 1979, pp. 330–336.

[7]King, J. H., "Solar Proton Fluences for 1977-1983 Space Missions," *Journal of Spacecraft and Rockets*, Vol. 11, No. 6, 1974, pp. 401–408.

[8]Sauer, H. H., Zwickl, R. D., and Ness, M. J., "Summary Data for the Solar Energetic Particle Events of August through December 1989," National Oceanic and Atmospheric Administration, Publication, Dec. 1989.

[9]Zwickl, R., and Kunches, J., "Energetic Particle Events by NOAA/GOES During Solar Cycle 22," *EOS*, Washington, DC, Oct. 1989, p. 1258.

[10]Goswami, J. N., McGuire, R. E., Reedy, R. C., Lal, L., and Jha, J., "Solar Flare Protons and Alpha Particles During the Last Three Solar Cycles," *Journal of Geophysical Research*, Vol. 83, No. A7, 1988, pp. 7195–7205.

[11]Bostrom, C. O., Kohl, J. W., McEntire, R. W., and Williams, D. J., "The Solar Proton Flux—August 2-12, 1972," Johns Hopkins University Applied Physics Laboratory preprint, Laurel, MD, Nov. 1972.

[12]Reames, D. V., "Acceleration of Energetic Particles by Shock Waves from Large Solar Flares," *Astrophysical Journal*, Vol. 358, No. 3, 1990, pp. L63–L67.

[13]Cane, H. V., Reames, D.V., and von Rosenvinge, T. T., "The Role of Interplanetary Shocks in the Longitude Distribution of Solar Energetic Particles," *Journal of Geophysical Research*, Vol. 93, No. A6, 1988, pp. 9555–9562.

[14]Zwickl, R. D., Sauer, H., and Kunches, J., "An Upper Limit to >10 MeV Integral Fluxes from Solar Particle Events," *EOS*, Washington, DC, April 1990, p. 591.

[15]Venkatesan, D., Mathews, T., Lanzerotti, L. J., Fairfield, D. H., and Bostrom, C. O., "Cosmic Ray Intensity Variations During 0200-0700 UT, August 5, 1972," *Journal of Geophysical Research*, Vol. 80, No. 13, 1975, pp. 1715–1724.

[16]Gorney, D. J., "Solar Cycle Effects on the Near-Earth Space Environment," *Reviews of Geophysics*, Vol. 28, No. A10, 1990, pp. 315–335.

[17]Goldhammer, L. J., "Recent Solar Flare Activity and its Effects on In-Orbit Solar Arrays," *Proceedings of the 21st IEEE Photovoltaic Specialists Conference*, Vol. 2, May 1990, pp. 1241–1248.

[18]Feynman, J., Armstrong, T. P., Dao-Gilmer, L., and Silverman, S., "A New Interplanetary Proton Fluence Model," *Journal of Spacecraft and Rockets*, Vol. 27, No. 4, 1990, pp. 403–410.

[19]Lal, D., "Temporal Variations of Low-Energy Cosmic-Ray Protons on Decadal and Million Year Time-Scales: Implications to Their Origin," *Astrophysics and Space Science*, Vol. 144, No. 3, 1988, pp. 337–346.

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