DOSE VARIATION DURING SOLAR MINIMUM

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Abstract

In this report we use direct measurement of dose to show the variation in inner and outer radiation belt populations at low altitude from 1984 to 1987. This period includes the recent solar minimum that occurred in September 1986. The dose is measured behind four thicknesses of aluminum shielding and for two thresholds of energy deposition, designated HILET and LOLET. We calculate an average dose per day for each month of satellite operation. We find that the average proton (HILET) dose per day (obtained primarily in the inner belt) increased systematically from 1984 to 1987, and has a high anticorrelation with sunspot number when offset by 13 months. The average LOLET dose per day behind the thinnest shielding is produced almost entirely by outer zone electrons and varies greatly over the period of interest. If any trend can be discerned over the 4 year period it is a decreasing one. For shielding of 1.55 gm/cm^2 (227 mil) Al or more, the LOLET dose is complicated by contributions from > 100 MeV protons and bremsstrahlung.

I. Introduction

This is the fifth in a series of reports whose aim is to improve specification of the low altitude radiation environment by using dosimeter data taken onboard the long-lived DMSP/F7 satellite [1,2,3,4]. In previous reports we: a) compared dose measurements made in 1985 to that predicted by the NASA radiation belt models [1]; b) characterized dose in solar flares during the recent solar minimum and measured the low latitude cut-offs of solar protons [2]; c) modelled the portion of the radiation environment responsible for single event upsets in microelectronic devices [3]; and, d) demonstrated long-lived changes in the proton radiation environment, including the formation of a second, outer proton belt, following the major magnetic storm of February 1986 [4]. Various aspects of the importance of accurate specification of the radiation environment are discussed in each of these reports and in a companion paper also published in this issue [5].

In this report we focus on a somewhat different aspect of radiation belt modeling: how the radiation environment at low altitude changes within the solar cycle. The NASA radiation models are static models and only give values for solar maximum and minimum conditions. We do not know how intermediate estimates should be made, or even whether the solar maximum and solar minimum conditions represent the extreme flux conditions. Thus, for missions occurring over a substantial portion of the solar cycle or for short missions in between solar extremes, design engineers are forced to take conservative, eg., maximum, dose estimates. Conservative estimates of dose lead to higher mission costs, lesser microelectronic capability and shorter manned missions.

We take advantage of the long life of the DMSP/F7 satellite to give a history of the low altitude radiation environment measured behind four thicknesses of aluminum shielding from the end of 1983 to the end of 1987 (~4 years). Longitudinal studies of particle flux have been made at geosynchronous altitudes for outer zone electrons [6] and are being compiled for protons using the low altitude NOAA satellites [7]. We are not aware of any such studies made with dose measurements. Here we show a systematic increase in proton dose throughout the entire period of measurement. The electron dose variations are much more erratic, but a decreasing trend can be identified. In Section 2 we describe the dosimeter, the DMSP orbit and the method of obtaining the monthly average of dose per day. In Section 3 we show the dose variations and in Section 4 we discuss the results.

II. The Satellite Orbit, Dosimeter, and Data Handling

The DMSP/F7 satellite (launched in November 1983) is a three-axis-stabilized spacecraft in sun-synchronous, circular, polar orbit at an altitude of 840 km. It has an inclination of 98.8°, and a period of 101 min. Since the orbit plane is always kept in the same orientation with respect to the sun, the relative position of the orbit with respect to the Earth is exactly repeated every 24 hours, as the Earth rotates underneath the orbit. This makes recognition of temporal changes in measured quantities relatively easy on a daily basis.

At low altitudes the radiation environment consists of a) inner belt protons and electrons reaching low altitude because of the offset dipole of the Earth's magnetic field in the low latitude region called the South Atlantic Anomaly (SAA); b) outer zone electrons at mid-latitudes in both hemispheres; and c) solar flare particles and galactic cosmic rays at high latitudes [1]. The satellite passes through different portions of the SAA for approximately five successive orbits, twice per day. The daily proton dose to the satellite is due almost entirely from these SAA crossings. Intense solar proton

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events will also contribute to dose. For the period of this study, 1983 December to 1987 October there were only 10 measurable solar proton events [2,8], but of these only those in April 1984 and February 1986 were of sufficient duration and intensity to inflate a monthly dose average. By contrast, the electron dose, particularly behind thin shielding, comes mainly from the outer zones. This population is highly variable, but is rather soft, falling off in intensity rapidly with increasing energy. DMSP crosses the outer zones four times an orbit.

The DMSP/F7 dosimeter measures the radiation dose from both electrons and protons occurring behind four different thicknesses of aluminum shielding. In addition, it provides information on the integral fluxes of electrons and protons at energies above the thresholds defined by the shields. Figure 1 is a schematic diagram of one of the detectors and its shielding. The basic measurement technique is determination of the amount of energy deposited in a simple solid-state detector from particles with enough energy to penetrate the shielding. The shields are aluminum hemispheres whose thicknesses are chosen to provide energy thresholds of 1, 2.5, 5, and 10 MeV for electrons, and 20, 35, 51, and 75 MeV for protons. The solid state detectors are planar p-i-n diffused junction silicon semiconductors, each with a guard ring. Particles that penetrate the shield and bremsstrahlung produced in the shield will deposit energy in the detector chip producing a charge pulse. The charge pulse is shaped and amplified. The pulse height is proportional to the energy deposited in the detector, and the dose is proportional to the sum of the pulse heights. The number of deposits is also counted; the number is related to the integral, omnidirectional flux. The characteristics of the detector and the threshold are such that energy depositions between 50 keV and 1 MeV give what is termed the low linear energy transfer (LOLET) dose. Depositions between 1 MeV and 10 MeV give what is termed the high linear energy transfer (HILET) dose. LOLET and HILET data points are recovered from each dome-detector combination. The LOLET dose comes primarily from electrons, high energy protons (above 100-200 MeV), and bremsstrahlung. The HILET dose is primarily from protons below 100-200 MeV. The properties of the four detectors and their shielding thicknesses are summarized in Table 1. The dosimeter was extensively calibrated before flight and has an onboard alpha source for periodic inflight calibration [9, 10].

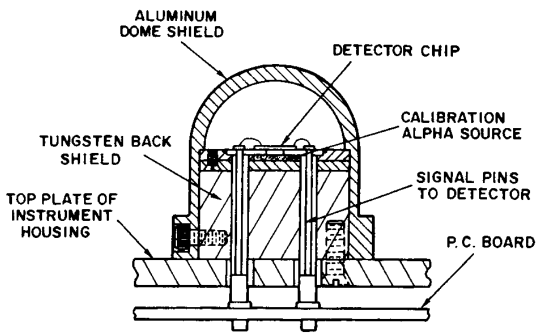

Figure 1
Schematic diagram of one detector-dome combination of the dosimeter.

The dosimeter makes dose and flux measurements in each detector every four seconds by means of a ripple counter. In addition the total dose counts are accumulated in mantissa, exponent form within the onboard data processing unit from the time of instrument turn-on. This allows the recording of every shaped pulse independent of transient satellite noise, small data gaps, and tape processing losses. The accumulated dose is known exactly at every mantissa increment. It can also be determined at any time by using the last mantissa increment and the number of ripple counter overflows up to the time of interest. We use the accumulated dose count capability, in this way, with a correction for the onboard radiation source to determine the total HILET and LOLET dose at the end of every month since launch. The monthly dose accumulations are used to calculate the average dose/day in rads (Si) for each month. The monthly averaged dose/day

TABLE 1
DMSP/F7 DOSIMETER CHARACTERISTICS

DOME	ALUMINUM SHIELD (gm/cm^2 [mils Al])	DOME THRESHOLDS ELECTRON (MeV)	PROTON (MeV)	DETECTOR THICKNESS (microns)	DETECTOR AREA (cm^2)	DETECTOR THRESHOLD LOLET (MeV)	HILET (MeV)
1	0.55 [80]	1.0	20	398	0.051	.05-1	1-10
2	1.55 [227]	2.5	35	403	1.000	.05-1	1-10
3	3.05 [444]	5.0	51	390	1.000	.05-1	1-10
4	5.91 [862]	10.0	75	384	1.000	.05-1	1.10

are the data reported here.

III. *Data Presentation*

A. Protons

Figure 2 shows the variation in the monthly averaged HILET dose/day over the near-four-year period that the DMSP/F7 satellite was in operation. The dose/day is given in rads (Si) and is plotted on a linear scale. The dose is plotted for the four shielding thicknesses which, given in gm/cm^2, identify each profile. The shaded regions show, for each shielding thickness, the range of dose/day values predicted by AP8MAX and AP8MIN [15]. (The method by which we calculate dose from the NASA models is outlined in a companion paper published in this issue [5]). The darkest shading represents regions of overlap for neighboring thicknesses. The smoothed monthly averaged sunspot number is plotted in the bottom panel. Solar minimum was in September, 1986, and is marked on the abscissa in Figure 2.

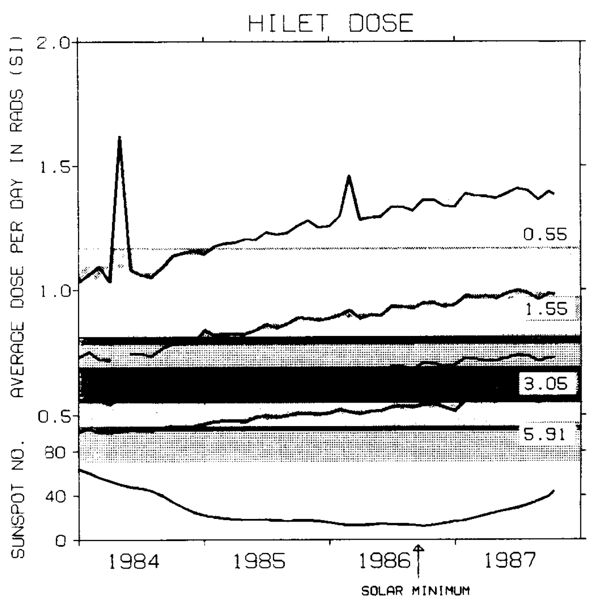

Figure 2
Variation of the monthly averaged HILET dose/day behind four thicknesses of Aluminum for the period December 1983 to October 1987.

Aside from two dose spikes in the plot for the thinnest shielding, the dose/day increases steadily from 1984 to 1987 in all four domes. The two spikes are due to the intense, long-lasting solar proton events discussed above. It is not clear whether the maximum dose rate is achieved by October 1987, when the plot ends. The rate of long-term increase in dose is greater prior to solar minimum than beyond solar minimum. As a more quantitative aid for comparing the NASA model HILET predictions to the DMSP measured values we list in Table 2 the AP8MAX and AP8MIN predictions for the given DMSP dome shielding as well as the measured values at the beginning of the period of DMSP measurements, labelled S(olar)MIN-33(months); the month of solar minimum, labelled SMIN; and the end of the period of DMSP measurements, labelled SMIN+13(months). Also given is the percent difference:

$$\frac{[\text{MEAS(SMIN)} - \text{MODEL}] \times 100}{\text{MEAS(SMIN)}},$$

where MEAS(SMIN) is the measured average dose/day for the month of solar minimum, and MODEL is the AP8MIN value. The following observations can be made from Figure 2 and Table 2:

TABLE 2
COMPARISON OF NASA MODEL PROTON DOSE RATES AND DMSP HILET DOSE RATES
(Dose/Day in Rads Si)

DOME	AP8MAX	AP8MIN	DMSP SMIN-33	DMSP SMIN	DMSP SMIN+13	%DIFFERENCE SOLAR MIN
1	0.781	**1.17**	1.03	**1.36**	1.38	14%
2	0.549	**0.814**	0.73	**0.93**	0.98	12%
3	0.436	**0.689**	0.56	**0.71**	0.73	3%
4	0.312	**0.453**	0.43	**0.54**	0.73	16%

SMIN-33 is Dec, 1983
SMIN is Sep, 1986
SMIN+13 is Oct, 1987

1) The overall agreement between the NASA models and the measurements for protons is excellent, well-within a factor of 2. This level of agreement was previously found to hold for data taken in 1985 [1], and here is shown to hold throughout the period of solar minimum. As the measured dose/day increases from 1984 to 1987, it exceeds the AP8MIN value, eg., the maximum predicted value, approximately two years before solar minimum. This is true for all 4 shielding thicknesses.

2) The measured values continue to rise after solar minimum, but the rise is slight in every case. The maximum radiation dose occurs 13 months or more after solar minimum.

3) The rate of increase over the four year period is almost identical for each shielding thickness, being somewhat more than 30% over the early low values. From the AP8 models, the rates of increase from solar maximum to solar minimum, if constant, are 43%, 20%, 63% and 53%, respectively, for Domes 1, 2, 3, and 4.

We relate the increase to solar activity by way of sunspot number. We assume that the dose rates peak 13 months after solar minimum, that is, at the end of the measuring period. We correlate the sunspot number projected forward by 13 months with the dose rate. The anticorrelation is shown in Figure 3 for Dome 1. The data for February and April 1984 (the months with high solar proton fluxes) are omitted. The correlation coefficient is -.97, indicating that the relationship is reasonably useful. Table 3 lists the results of performing the regression on the data for each of the four domes.

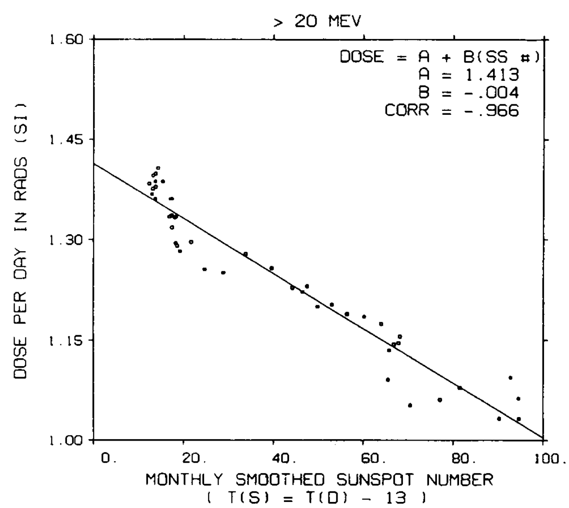

Figure 3
Monthly averaged HILET dose rate as a function of sunspot number. Linear regression coefficients (intercept, slope, correlation coefficient and number of points) are listed in the upper right hand corner. The regression line is drawn.

TABLE 3
LINEAR REGRESSION ON DOSE PER DAY VERSUS SUNSPOT NUMBER TAKEN 13 MONTHS PRIOR

DOSE/DAY (T) = A + B·SUNSPOT NUMBER (T - 13)

DOME	A	B	CC
1	1.41	-.00409	-.966
2	0.993	-.00299	-.960
3	0.735	-.00204	-.957
4	0.563	-.00152	-.954

· DOSE IS IN RADS (Si)

B. Electrons

Both electrons and high energy (>100 MeV) protons contribute to the LOLET dose measurement. Nevertheless, characteristics of the outer zone electrons and of the inner zone protons allow us to infer when contributions of one or the other population dominate the LOLET measurement. The >100 MeV population of the inner belts has not been well specified. We can, however, anticipate that the dose from this population will be similar in magnitude and temporal variation to the >75 MeV proton dose measured in Dome 4, HILET.

A second point to be made in discussing the LOLET dose is that the DMSP/F7 dosimeter operated out of its thermal specification during its entire lifetime, the temperature being several 10's of degrees Centigrade too high. Continual checks using the onboard alpha source showed that the instrument was not affected by this except in the two LOLET channels with the highest shielding, Domes 3 and 4. Noise in these measurements is apparent, in Dome 4 more than Dome 3, particularly in the winter months for the northern hemisphere. At these times the dosimeter ran hottest in the southern hemisphere where most of the dose is contributed.

Figure 4 shows the average monthly dose/day for the first two LOLET channels as a function of time. The format is the same as in Figure 2. Figure 4 shows several points of interest:

1) The LOLET dose behind the two thinnest domes spans a range of more than an order of magnitude and, unlike the HILET dose, is best shown on a log scale.

2) The dose behind, Dome 1, the thinnest shielding is large and highly variable, ranging from a monthly averaged dose per day of 0.6 to 6.2 rads (Si). Some, but not all the variability is associated with electrons accompanying solar proton events. For instance, the three highest average dose/day values at the end of 1984 are not associated in any way with solar events. Because the dose rate is so high in this dome it is attributed almost entirely to outer zone electrons.

3) The NASA model predicted dose for Dome 1 is

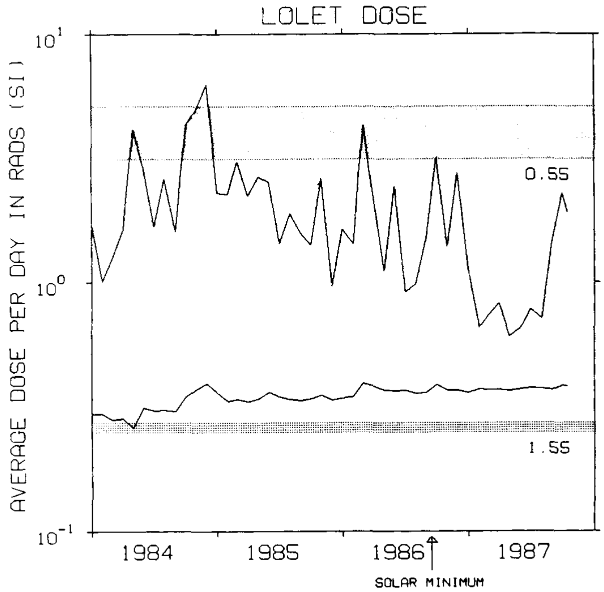

Figure 4
Variation of the monthly average LOLET dose/day behind the two thinnest thicknesses of aluminum for the period December 1983 to October 1987.

almost always too high, but for one month, at least, the measured dose exceeded the model.

4) The variability of the dose behind Dome 2 is considerably less than for Dome 1, and shows a systematic increase through and beyond solar minimum, much as did the HILET dose, indicating that a substantial portion of dose is contributed by the proton population with energies >100 MeV.

5) The NASA model predicted dose for Dome 2 is in reasonably good agreement with measured values throughout, but is almost always on the low side.

The variability of the outer zone electron populations is well-documented, although poorly understood [6, 11, 12, 13, 14]. This population is normally quite soft, falling off with energy as a power law of -3 to -4. At low altitudes the outer zone electron intensity increases in episodes lasting several days, during and following solar maximum, up to several tens of days near solar minimum. The change in variability of the outer zone electrons near solar minimum was shown by Gussenhoven et al. [4] using the flux measurement capability of the DMSP dosimeter. The outer zone episodes, periods of enhanced outer zone fluxes, became longer as the recent solar minimum was approached and continued to lengthen for almost a year beyond solar minimum. Many of the very long episodes have a sharp onset-slow decay characteristic shape, while the shorter episodes both rise and fall abruptly. Long periods of very low fluxes occur for about a year following solar minimum. The monthly averaged dose/day behind the thinnest shielding, shown in Figure 4, shows an overall lessening of the dose from the outer zone electron population in the vicinity of solar minimum. This is primarily due to a lengthening of time between outer zone episodes rather than a weakening of the strength of the flux at the episode peak. At the end of 1987 the number of outer zone episodes picks up rather rapidly on the upswing to solar maximum.

To make a direct comparison to NASA model predictions for electrons we present in Table 4 average dose/day values for three months, similar to those shown for protons in Table 2. In Table 4 we only use measured values from the first three domes. Dome 4 is eliminated for two reasons: the first is the thermal noise problem, and the second is the fact that the NASA electron model does not extend in energy to 10 MeV. Also in Table 4 we use as the three data points: solar minimum, solar minimum minus 22 months where the LOLET average dose/day in Dome 1 is maximum, and solar minimum plus 7 months where the LOLET average dose/day in Dome 1 is minimum. For the NASA model comparison we give both the solar maximum (first set of columns) and solar minimum (second set of columns) values. We show the contribution to dose from both protons (top number) and electrons (middle number). The total is given in bold (bottom row).

For Dome 1 the NASA models predict a dose rate that is a factor of 2 too small to almost an order of magnitude too large, depending on month. The NASA models show less than a factor of two difference between solar maximum and minimum values behind the thinnest shielding, while the measured variability between maximum and minimum values in the near-solar minimum period is about an order of magnitude. The proton contribution to the predicted dose for this shielding is extremely small, less than 4%.

For Dome 2, the proton contribution to the predicted dose is the same magnitude as the electron contribution. The total predicted LOLET dose varies little over the solar cycle. It is within 35% of the measured dose.

For the two thickest domes there is no electron contribution to the dose predicted by NASA models, and for Dome 3 the measured dose is a factor of 2 higher than the model dose. Since the HILET measured and predicted doses were is much better agreement than this, even for Dome 4, we conclude that there must be a substantial contribution from bremsstrahlung in the thicker domes.

III. Summary and Discussion

We have found trends in HILET and LOLET average dose rate measured at low altitude during the four year period that includes the last solar minimum which we summarize here.

The HILET average dose/day: a) comes primarily from the protons in the stable inner radiation belts; b) ranges from 1.03 to .43 rads (Si)/day behind 0.55 to 5.91 gm/cm^2 Aluminum shielding, respectively, three years before solar minimum; c) increases continuously from these values, in all four dome thicknesses, by about 30% one year after solar minimum; d) anticorrelates to a high degree, over this period,

TABLE 4
COMPARISON OF NASA MODEL ELECTRON DOSE RATES AND DMSP LOLET DOSE RATES
(DOSE/DAY IN RADS Si)

DOME	TOTAL	AP8MAX AE8MAX	TOTAL	AP8MIN AE8MIN	DMSP SMIN-22	DMSP SMIN	DMSP SMIN + 7
1		0.095		0.138			
		5.041		3.019			
	5.14		3.16		6.30	3.19	0.61
2		0.089		0.132			
		0.191		0.120			
	0.279		0.252		0.39	0.39	0.37
3		0.085		0.124			
		0.000		0.000			
	0.085		0.124		0.26	0.29	0.29
4		0.071		0.104			
		0.000		0.000			
	0.071		0.104		(DATA CONTAMINATED WITH THERMAL NOISE)		

SMIN-22 is Nov, 1984
SMIN is Sep, 1986
SMIN+7 is Apr, 1987

with solar sunspot number offset by -13 months; and e) at solar minimum is in excellent agreement with the dose rate predicted by the NASA AP8MIN model (less than 20% difference).

The LOLET dose behind thin shielding ($\sim$.55 gm/cm^2) comes primarily from the outer zone electrons which have high, variable fluxes. The average daily dose rate behind this dome varied erratically over the range .6 - 6.3 rads (Si) from 1984 to 1987. The measured dose rate is generally much lower than the 3.2 rads (Si) predicted by AE8MIN, but on occasion can be higher. The dose rate behind Dome 1 is definitely minimized in the period near solar minimum.

The LOLET dose rate in shielding greater than 1.55 gm/cm^2 has a different solar cycle dependence than that in Dome 1, rising steadily over the period of measurement. We interpret this to mean that a major contribution to LOLET dose behind these shieldings is from inner belt protons having energies > 100 MeV. For a shielding of 1.55 gm/cm^2 the NASA electron model dose rate prediction is within 35% of the measured value. For shielding $\geq$ 3.05 gm/cm^2 the NASA model dose rate is lower by a factor of two compared to the measured LOLET dose, indicating the importance of bremsstrahlung in thick shields.

This summary indicates the accuracy of the NASA models in estimating proton effects. For electrons the NASA models appear to be too high, on average, for thin shieldings. For thick shielding they are inappropriate because they do not extend in energy above 5 MeV for electrons. We have also shown that simple interpolation between solar maximum and solar minimum does not take into account the actual particle variation with solar cycle. For protons the dose rate minimum occurs more than a year after solar minimum, while outer zone electron variations, even though showing the lowest fluxes near solar minimum, appear too erratic to model. The outer zone electrons have soft spectra such that they can be effectively shielded. This is important because they produce much higher dose rates than protons behind thin shielding. For thick shielding the LOLET dose rate appears to minimize at about .3 rads/day which is apparently due to both high energy inner belt protons and bremsstrahlung from outer zone electrons. This may represent the lowest, unshieldable dose rate to which the DMSP satellites are subject.

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