NXT-CAL-102

Rev. (-)

Calibration Report

for the

EPS DOME Sensor Response to Protons

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Prepared for

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1. Introduction

The EPS DOME sensor for the GOES I to M spacecraft has a modified field-of-view (FOV) compared with the GOES D to H DOME sensors. The D3 DOME FOV was decreased slightly to reduce the integrated flux of electrons on the silicon surface barrier detector (SSD), and thus increase the in-orbit lifetime of the SSD by reducing radiation damage effects. The GOES I to M DOME sensor also has two added electron channels to provide a measurement of lower energy (>0.6 MeV) and higher energy (>4 MeV) electrons, in addition to the previous >2 MeV electron channel. The electron channels were calibrated with electron beams, with the results being reported in Ref. 1.

The previous GOES D to H DOME sensor design was calibrated with protons and alpha particles, with the results being reported in Ref. 2. The modified DOME design was calibrated with protons at the Harvard Cyclotron. The SN 001 and SN 002 DOME sensors were both calibrated, and the combined results are presented in the following Sections. Section 2 describes the calibration procedure, presents the measured geometric factor data, and compares the results of the modified design with the calibration data of Ref. 2. The higher energy "spurious" geometric factors of Ref. 2 are discussed at the end of Section 2.

The calibrated geometric factors of Section 2 are used to calculate the effective response factors of the DOME channels in Section 3. The response corrections required for different spectral shapes are also provided. These data can be used to provide corrected differential proton fluxes from the measured channel count rates. Section 4 contains a short summary and conclusions.

2.0 Proton Calibration

2.1 Calibration Configuration and Data Analysis

The proton calibration configuration is shown in Fig. 2.1. The Harvard Cyclotron provides a proton beam of 160 MeV energy at the exit from the accelerator vacuum. The exit beam is narrow and poorly suited for calibration where a wide area, moderately uniform proton beam is required. The 160 MeV proton beam must thus be spread in area by a combination of lead scatterers, which in the process also degrade the beam to about 144 MeV. Lower energy proton beams are obtained by the addition of polyethylene (CH_2), aluminum (Al), and copper (Cu) absorbers. The generation of the several beam energies by various absorber combinations is described in Ref. 3. A 153 MeV proton beam can be obtained by the removal of the first (112 mil thick) lead scatterer and the use of no absorbers. Some measurements in Ref. 2 were made at 153 MeV, though the measurements reported here only went up to 144 MeV.

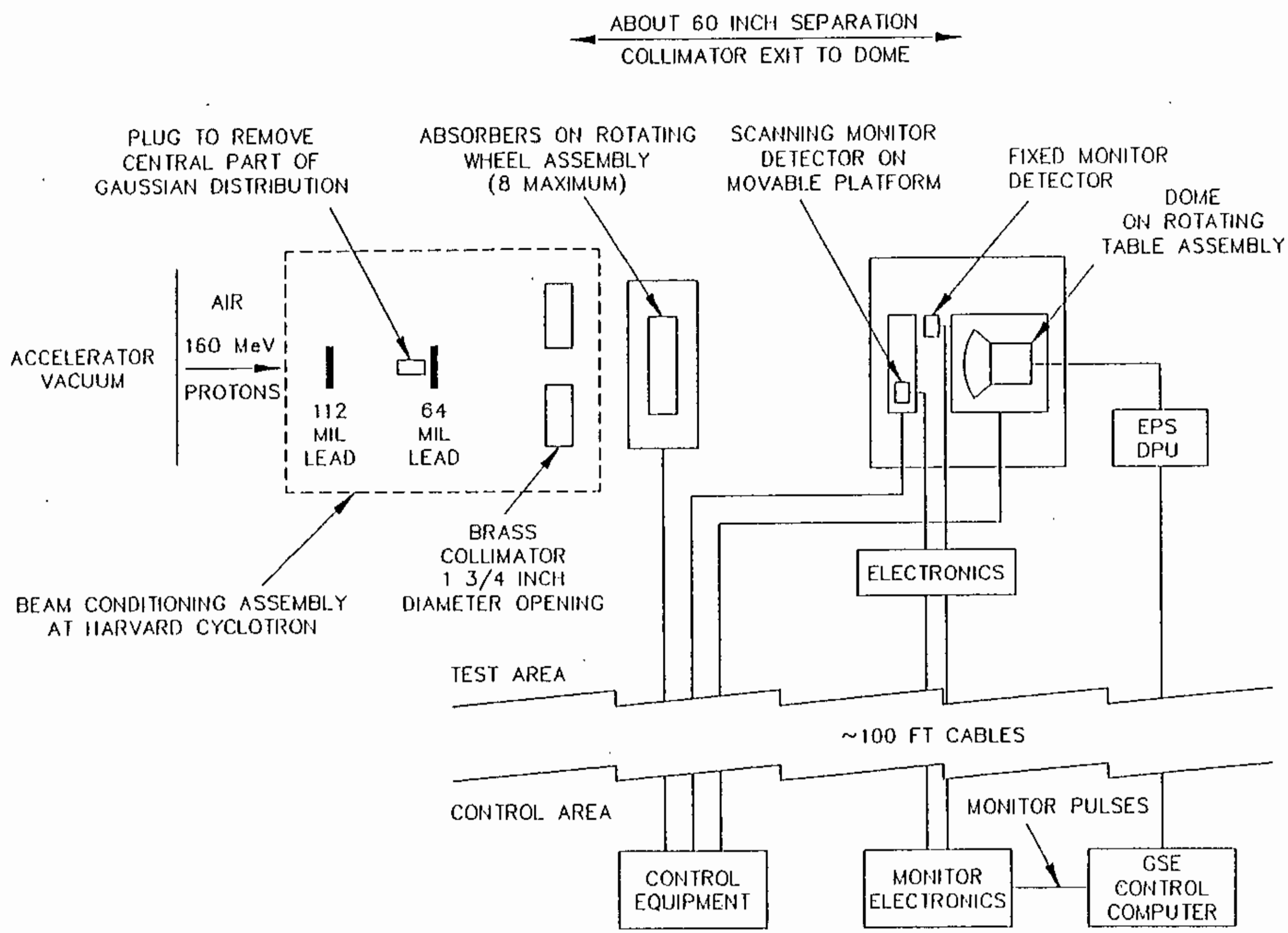

Figure 2.1. DOME Sensor Calibration Configuration at the Harvard Cyclotron.

The DOME sensor is calibrated by measuring its response (count rate) relative to that of the two monitor detectors, which have calibrated detection areas. Since the proton beam intensity can have significant time variations, it is essential that the monitor detectors are counted at the same time as the DOME channels that are being calibrated. Thus the monitor detector pulses are routed to the GSE computer, which counts all DOME channel and monitor detector pulses for the same time intervals. The GSE computer counts are then used to calculate the DOME channel proton responses.

The DOME channel geometric factors are calculated from response measurements made over one quarter of the total FOV, in an angular scan similar to that described in Ref. 2 (Ref. 2, Table 2.2, page 29). The angular steps in Ref. 2 were 15° in both θ (the angle in the plane containing the FOV centers of all three DOME detectors: D3, D4 and D5) and ϕ (the angle out of the θ plane), but the measurements reported here used a 10° step in θ and a 15° step in ϕ, since the θ response range is narrower than the ϕ response range. The channel responses are normalized to the fixed monitor response, corrected for the collimation effects of a 2 inch thick lead collimator in front of the monitor SSD. This lead thickness is necessary to provide collimation up to the maximum 153 MeV protons. The response of the moveable monitor SSD is used as a secondary check on the fixed monitor response. For each calibrated channel/energy pair the result is a set of measured areas for each angle pair. Since some responses fall off rapidly at the larger angles, not all calibrations used the full angle set.

The calibrated channel geometric factors for each proton energy are calculated from

$$G(E) = \sum A_{cal}(\theta,\phi) \times D\Omega(\theta,\phi) \times n(\theta,\phi) \qquad (1)$$

where the $A_{cal}(\theta,\phi)$ are the calibrated detection area measurements, $D\Omega(\theta,\phi)$ are the solid angles of the sectors associated with each measurement, and $n(\theta,\phi)$ are the number of sectors included in the total geometric factor. The values of $D\Omega(\theta,\phi)$ are calculated from

$$D\Omega(\theta,\phi) = (\phi_2 - \phi_1) \times (\sin(\theta_2) - \sin(\theta_1)) \qquad (2)$$

where $\phi_2 - \phi_1 = 15° = 0.2618$ radian, $\theta_2 = \theta + 5°$, and $\theta_1 = \theta - 5°$. The values of $D\Omega(\theta,\phi)$ and $n(\theta,\phi)$ for the calibrated sectors of (θ,ϕ) are listed in Table 2.1. A more detailed discussion of the data analysis is given in Ref. 2.

Table 2.1
Solid Angle Factors for Calibration Data

(θ,ϕ) (degrees)	$D\Omega(\theta,\phi)$ (steradians)	Number of bins from symmetry, $n(\theta,\phi)$
0,0	0.0456	1
0,15	0.0456	2
0,30	0.0456	2
0,45	0.0456	2
0,60	0.0456	2
10,0	0.0449	2
10,15	0.0449	4
10,30	0.0449	4
10,45	0.0449	4
10,60	0.0449	4
20,0	0.0429	2
20,15	0.0429	4
20,30	0.0429	4
20,45	0.0429	4
20,60	0.0429	4
30,0	0.0395	2
30,15	0.0395	4
30,30	0.0395	4
30,45	0.0395	4
30,60	0.0395	4
40,0	0.0350	2
40,15	0.0350	4
40,30	0.0350	4
40,45	0.0350	4

2.2 Calibration Results

The measured values for A(0°,0°) and the calibrated geometric factors G(E) for protons for the D3 DOME, channels P4, E1 and E2, are listed in Table 2.2. Geometric factor scans were not made at all energies, especially for the E1 and E2 channels which do not have a large amount of structure in G(E). The G(E) results are plotted in Fig. 2.2, along with the P4(old) and E1(old) results from Ref. 2. The P4(new) response is slightly lower in average energy than the P4(old) response, and this is due to the change in the ϕ range from ±60° (old design) to ±45° (new design). The P4(old) response at ±45° is thus larger than the P4(new) response, and that is where the highest energy proton response lies (see the D3 energy loss curves in Ref. 2). The E1(new) and E2(new) channel G(E) were calibrated at only three proton energies. The E1(old) corresponds to the E2(new) channel, and the data plotted in Fig. 2.2 show reasonable agreement between the new and old calibrations.

Table 2.2
D3 DOME Proton Calibration Results

Proton Energy E (MeV)	P4		E1		E2	
	A(0°,0°) (cm^2)	G(E) (cm^2sr)	A(0°,0°) (cm^2)	G(E) (cm^2sr)	A(0°,0°) (cm^2)	G(E) (cm^2sr)
13	0.108	0.107	0.020	-	0.100	-
17	0.132	0.157	0.021	0.041	0.097	0.166
25	0.190	0.191	0.014	-	0.112	-
30	0.184	0.177	0.013	0.041	0.179	0.267
32	0.167	-	0.013	-	0.192	-
38	0.054	0.102	0.022	-	0.284	-
44	0.012	0.044	0.036	-	0.315	-
51	0.010	0.022	0.048	0.083	0.322	0.469
59	0.008	-	0.061	-	0.341	-
66	0.006	0.010	0.060	-	0.362	-

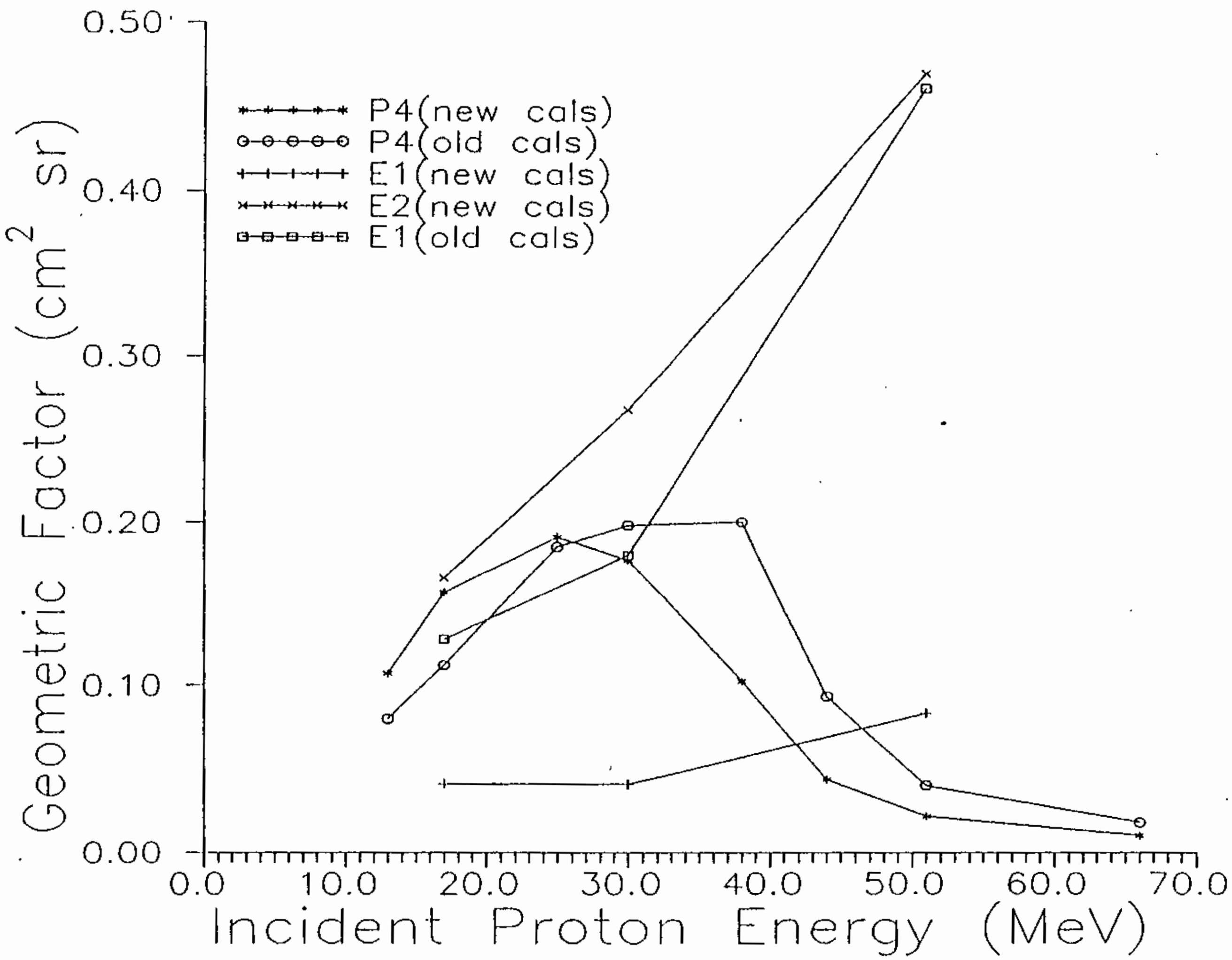

Figure 2.2. D3 DOME Proton Calibration Results.

The measured values for A(0°,0°) and the calibrated geometric factors G(E) for protons for the D4 DOME, channels P5 and E3, are listed in Table 2.3. Geometric factor scans were not made at all energies, but the data still show the general structure of G(E). The G(E) results are plotted in Fig. 2.3, along with the P5(old) results from Ref. 2. The data plotted in Fig. 2.3 show good agreement between the P5(new) and P5(old) calibrations, which is expected since the D4 DOME design was not changed.

Table 2.3
D4 DOME Proton Calibration Results

Proton Energy E (MeV)	P5		E3	
	A(0°,0°) (cm^2)	G(E) (cm^2sr)	A(0°,0°) (cm^2)	G(E) (cm^2sr)
13	0.0008	-	0.0002	-
30	0.009	-	0.008	-
32	0.022	-	0.013	-
38	0.137	0.208	0.024	0.048
44	0.247	-	0.040	-
51	0.292	0.357	0.061	0.128
59	0.229	-	0.128	-
66	0.178	0.254	0.141	0.253
79	0.069	-	0.224	-
84	0.035	-	0.239	-
94	0.015	0.059	0.271	0.434
111	0.013	-	0.319	-
121	0.011	-	0.300	-

The measured values for A(0°,0°) and the calibrated geometric factors G(E) for protons for the D5 DOME, channels P6 and P7, are listed in Table 2.4. Only two energies had geometric factor scans, but they show the general structure of G(E). The G(E) results are plotted in Fig. 2.4, along with the P6(old) and P7(old) results from Ref. 2. The data plotted in Fig. 2.4 show reasonable agreement between the new and old calibrations, with the new G(E) values being slightly larger. The G(E) values for P6 and P7 are not expected to change since the D5 DOME design was not changed. Since the A(0°,0°) values vary smoothly with energy, the straight lines in Fig. 2.4 are good indicators of the energy variation of G(E).

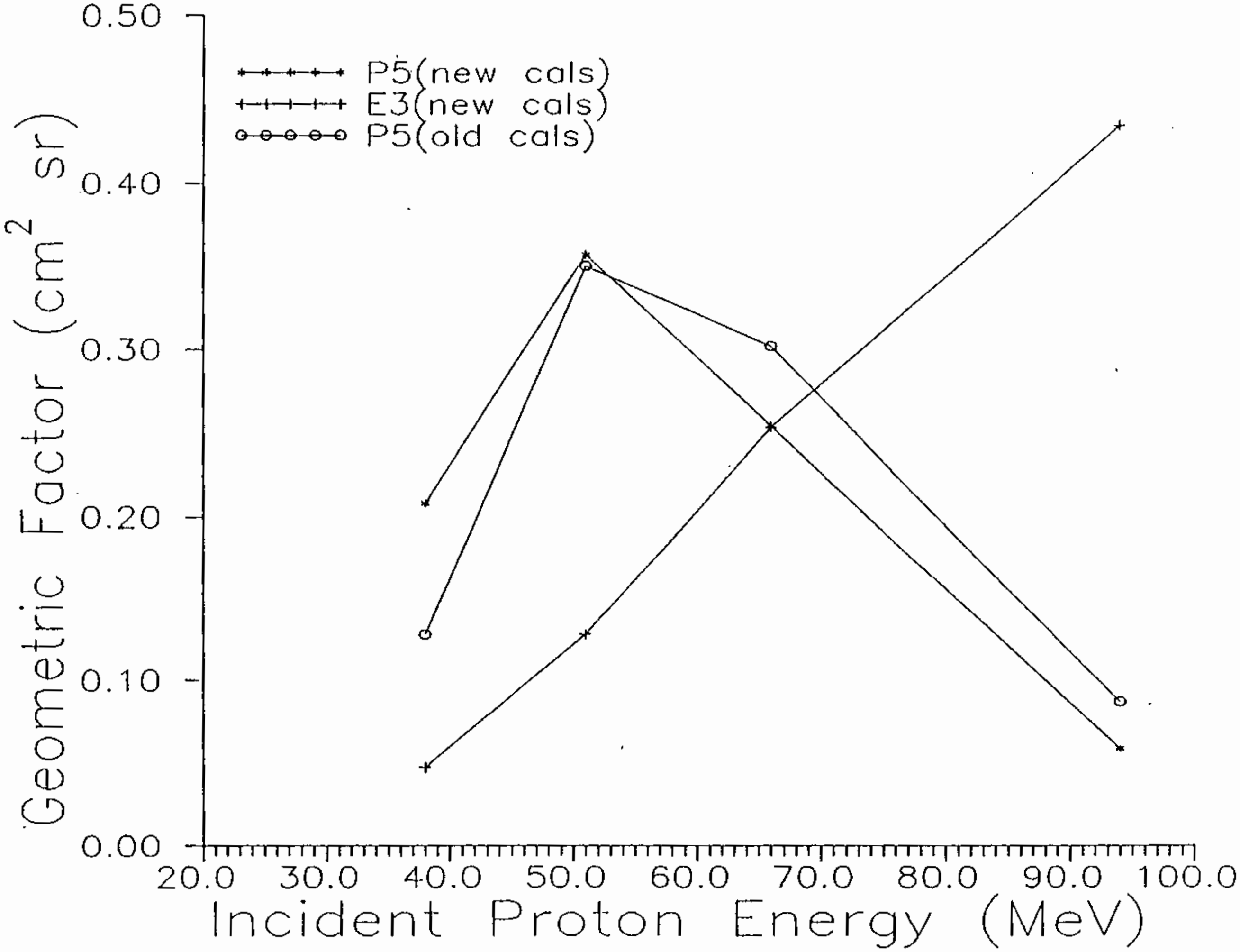

Figure 2.3. D4 DOME Proton Calibration Results.

Table 2.4 D5 DOME Proton Calibration Results				
Proton Energy E (MeV)	P6		P7	
	A(0°,0°) (cm^2)	G(E) (cm^2sr)	A(0°,0°) (cm^2)	G(E) (cm^2sr)
79	0.024	-	0.006	-
84	0.168	-	0.023	-
94	0.222	0.318	0.051	0.071
111	0.230	-	0.103	-
121	0.199	-	0.101	-
128	0.212	-	0.124	-
133	0.197	0.284	0.117	0.239
144	0.146	-	0.114	-

2.3 Spurious Geometric Factors

The "spurious" geometric factors are the out-of-aperture responses to high energy protons. Ref. 2 provides a partially calibrated set of spurious responses, based on calculations normalized by proton measurements at energies up to 153 MeV. The P4(old) and E1(old) spurious responses should be the same for the P4(new) and E2(new) channels, since the out-of-aperture shielding was not changed, and the added shielding from the reduced ϕ range is a small fraction of the total out-of-aperture solid angle. Because the out-of-aperture shielding and the energy loss threshold of the E3(new) channel are similar to that for the E2(new) and E1(old) channels, the spurious response of the E3(new) channel should be similar to that of E1(old) in Ref. 2. The P5, P6 and P7 channel spurious responses should not change, since the D4 and D5 DOME designs have not changed.

The spurious response of the E1(new) channel has been estimated on the basis of the ratio of the measured E1(new)/E2(new) A(0°,0°) values for the 44 to 66 MeV region, which is about 0.15. Since the higher energy E3(new) A(0°,0°) measurements are about the same as the E2(new) A(0°,0°) at lower energies, this E1(new)/E2(new) response ratio should be approximately valid for the higher energy spurious response energy region. The spurious responses are listed in Table 2.5, which is mostly taken from Table 3.4 of Ref. 2.

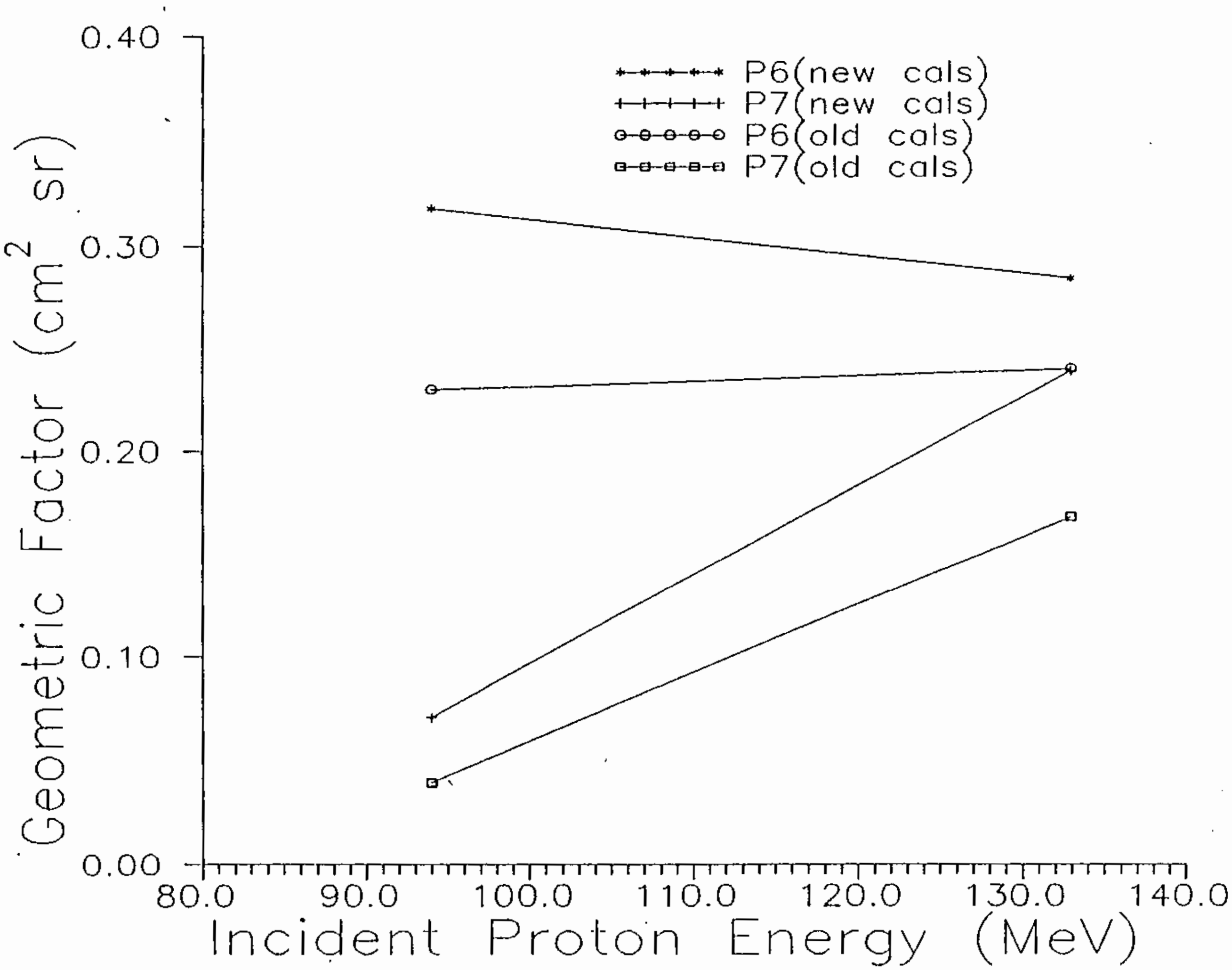

Figure 2.4. D5 DOME Proton Calibration Results.

Table 2.5
Spurious Geometric Factors for Protons

Particle Channel	Proton Energy Range (MeV)	Geometric Factor (cm^2sr)
E1 (estimate)	80 - 90	0.0008
	90 - 110	0.021
	110 - 125	0.024
	125 - 300	0.100
	300 - 1000	0.500
E2 and E3 (estimate)	80 - 90	0.005
	90 - 110	0.14
	110 - 125	0.16
	125 - 300	0.68
	300 - 800	0.19
P4	80 - 115	0.038
	115 - 150	0.25
P5	80 - 110	0.091
	110 - 150	0.57
	150 - 190	0.21
P6	80 - 110	0.15
	110 - 130	0.84
	130 - 200	0.80
	200 - 300	0.26
P7	80 - 110	0.03
	110 - 170	0.15
	170 - 250	1.5
	250 - 500	1.9
	500 - 900	0.56

3.0 Response Factors of the EPS Dome Channels

3.1 Method of Calculating Channel Response Factors

The channel response factors are calculated using either the direct FOV geometric factors (for P4 and P5), or using a combination of the direct FOV geometric factors and the spurious geometric factors (for P6, P7, E1, E2, and E3). The geometric factor G(E) is defined as a table of values (usually those taken from Tables 2.2, 2.3, and 2.4) and the response to different proton spectral shapes is then calculated by integration. For a flat proton spectrum the geometric-energy factor is defined as

$$GE_0 = \int G(E)\ dE\ \ (cm^2\ sr\ MeV) \qquad (3)$$

and this corresponds to a proton energy of

$$E_0 = (\int E \times G(E)\ dE)/GE_0 \qquad (4)$$

The results from (3) and (4) are used to calculate the differential proton spectrum from the channel countrate by

$$j_0(E_0) = (\text{channel countrate})/GE_0 \quad p/(cm^2\ sr\ s\ MeV) \qquad (5)$$

The result (5) is not correct for a proton spectrum which has a strong energy dependence, but it does provide a good first-order spectrum. The G(E) table is used to calculate corrections for power-law proton spectra of the form

$$j_p(E) = j_o \times E^{-\gamma} \quad p/(cm^2\ sr\ s\ MeV) \qquad (6)$$

by calculating

$$GE_\gamma = \int E^{-\gamma} \times G(E)\ dE \qquad (7)$$

and

$$EGE_\gamma = \int E \times E^{-\gamma} \times G(E)\ dE \qquad (8)$$

A correction factor for $j_0(E_0)$ is calculated from

$$CF(\gamma) = E_0^{-\gamma} \times GE_0/GE_\gamma \qquad (9)$$

where

$$j_{true}(E_0) = j_0(E_0) \times CF(\gamma) \quad p/(cm^2\ sr\ s\ MeV) \qquad (10)$$

is the true differential proton flux at energy E_0 MeV. The average energy of the detected protons is given by

$$E_\gamma(avg) = EGE_\gamma/GE_\gamma \qquad (11)$$

An alternate way of making the spectral correction is to calculate the proton energy where $j_0(E_0)$ from (5) is the true proton differential flux. This occurs at the energy E_γ, where

$$E_\gamma = (GE_0/GE_\gamma)^{1/\gamma} \text{ MeV} \quad (12)$$

Then for a true power law proton spectrum (6), the true differential flux is given by

$$j_{true}(E_\gamma) = j_0(E_0) \quad (13)$$

The difficulty of using (13) is that the energy of the channel spectral point varies with the spectral power law γ. In general it is preferable to use the correction factor (9) and calculate the true spectral point from (10). Tables in the following Section 3.2 provide values of $CF(\gamma)$ from (9), $E_\gamma(avg)$ from (11), and E_γ from (12) for all of the DOME proton and electron channels.

3.2 Channel Response Factors

3.2.1 P4 Channel Response Factors

The P4 channel response factors for proton spectra are calculated using only the direct FOV response. The spurious response of Table 2.5 is not used, and since most measured proton spectra have large γ values, the neglect of the spurious response is not important. The G(E) values used for the calculations are listed in Table 3.1, which is basically the calibration data from Table 2.2. This produces a flat spectrum response of

$$GE_0(P4) = 5.21 \text{ cm}^2 \text{ sr MeV}, \qquad E_0(P4) = 30.6 \text{ MeV} \quad (14)$$

The values of $CF(\gamma)$ from (9), of $E_\gamma(avg)$ from (11), and of E_γ from (12) are listed in Table 3.2. Note that the average energy of the detected protons, $E_\gamma(avg)$, decreases towards 13 MeV for very steep power law spectra, while the energy corresponding to the zero order spectral intensity decreases towards 17 MeV. For a typical power law spectrum with $\gamma = 4$ the correction factor $CF(\gamma=4) = 0.203$, about a factor of 5 decrease from the zero order spectral intensity.

Table 3.1 G(E) for P4 Channel for Response Calculations	
Proton Energy (MeV)	G(E) (cm^2 sr)
10	0.000
13	0.107
17	0.157
25	0.191
30	0.177
38	0.102
44	0.044
51	0.022
66	0.010
100	0.001

Table 3.2 Correction Factors for P4 Proton Response			
Power Law Exponent γ	Correction Factor CF(γ)	Average Energy E_γ(avg) (MeV)	Zero Order Spectrum E_γ (MeV)
0	1.000	30.6	30.6
1	0.834	25.5	25.5
2	0.593	21.7	23.5
3	0.367	18.9	21.9
4	0.203	16.9	20.5
5	0.1028	15.5	19.4
6	0.0486	14.5	18.5
7	0.0219	13.7	17.7
8	0.00945	13.2	17.1

3.2.2 P5 Channel Response Factors

The P5 channel response factors for proton spectra are calculated using only the direct FOV response. The spurious response of Table 2.5 is not used, and since most measured proton spectra have large γ values, the neglect of the spurious response is not important. The G(E) values used for the calculations are listed in Table 3.3, which is basically the calibration data from Table 2.3 with the low and high energy regions filled in from the Ref. 2 data. This produces a flat spectrum response of

$$GE_0(P5) = 14.49 \text{ cm}^2 \text{ sr MeV}, \qquad E_0(P5) = 63.1 \text{ MeV} \qquad (15)$$

The values of CF(γ) from (9), of E_γ(avg) from (11), and of E_γ from (12) are listed in Table 3.4. Note that the average energy of the detected protons, E_γ(avg), decreases towards 40 MeV for very steep power law spectra, while the energy corresponding to the zero order spectral intensity decreases towards 47 MeV. For a typical power law spectrum with γ = 4 the correction factor CF(γ=4) = 0.453, about a factor of 2 decrease from the zero order spectral intensity.

Table 3.3
G(E) for P5 Channel for Response Calculations

Proton Energy (MeV)	G(E) (cm^2 sr)
30	0.012
32	0.029
38	0.208
51	0.357
66	0.254
94	0.059
111	0.030
121	0.010
150	0.000

Table 3.4 Correction Factors for P5 Proton Response			
Power Law Exponent γ	Correction Factor CF(γ)	Average Energy E_γ(avg) (MeV)	Zero Order Spectrum E_γ (MeV)
0	1.000	63.1	63.1
1	0.917	57.9	57.9
2	0.776	53.4	55.6
3	0.611	49.8	53.6
4	0.453	46.8	51.8
5	0.318	44.4	50.2
6	0.214	42.5	48.8
7	0.139	40.9	47.6
8	0.0870	39.6	46.5

3.2.3 P6 Channel Response Factors

The P6 channel response factors for proton spectra are calculated using both the direct FOV and spurious responses. The calibrated direct responses of Ref. 2 are adjusted slightly based on the measured responses in Table 2.4, and the spurious response from Ref. 2 in Table 2.5 is added on. Since the spurious response overlaps most of the direct response, and actually dominates at the higher energies, it is essential to include the spurious response in the P6 calculations. The total $G_{tot}(E)$ values used for the calculations are listed in Table 3.5. This produces a flat spectrum response of

$$GE_0(P6) = 129.\ cm^2\ sr\ MeV, \qquad E_0(P6) = 165.\ MeV \qquad (16)$$

The values of CF(γ) from (9), of E_γ(avg) from (11), and of E_γ from (12) are listed in Table 3.6. Note that the average energy of the detected protons, E_γ(avg), decreases towards 100 MeV for very steep power law spectra, while the energy corresponding to the zero order spectral intensity decreases towards 120 MeV. For a typical power law spectrum with $\gamma = 4$ the correction factor CF(γ=4) = 0.426, about a factor of 2 decrease from the zero order spectral intensity.

Table 3.5 $G_{tot}(E)$ for P6 Channel for Response Calculations	
Proton Energy (MeV)	G(E) (cm^2 sr)
79	0.01
84	0.28
94	0.45
110	1.10
130	1.05
200	0.80
201	0.26
300	0.26
301	0.01

Table 3.6 Correction Factors for P6 Proton Response			
Power Law Exponent γ	Correction Factor CF(γ)	Average Energy E_γ(avg) (MeV)	Zero Order Spectrum E_γ (MeV)
0	1.000	165.	165.
1	0.910	151.	151.
2	0.759	138.	144.
3	0.587	128.	139.
4	0.426	120.	134.
5	0.293	114.	129.
6	0.1923	109.	126.
7	0.1217	105.	122.
8	0.0747	102.	120.

3.2.4 P7 Channel Response Factors

The P7 channel response factors for proton spectra are calculated using both the direct FOV and spurious responses. The calibrated direct responses of Ref. 2 are adjusted slightly based on the measured responses in Table 2.4, and the spurious response from Ref. 2 in Table 2.5 is added on. Since the spurious response overlaps most of the direct response, and actually dominates at the higher energies, it is essential to include the spurious response in the P7 calculations. The total $G_{tot}(E)$ values used for the calculations are listed in Table 3.7. This produces a flat spectrum response of

$$GE_0(P7) = 839.\ cm^2\ sr\ MeV, \qquad E_0(P7) = 433.\ MeV \qquad (17)$$

The values of $CF(\gamma)$ from (9), of $E_\gamma(avg)$ from (11), and of E_γ from (12) are listed in Table 3.8. Note that the average energy of the detected protons, $E_\gamma(avg)$, decreases towards 110 MeV for very steep power law spectra, while the energy corresponding to the zero order spectral intensity decreases towards 180 MeV. For a typical power law spectrum with $\gamma = 4$ the correction factor $CF(\gamma{=}4) = 0.127$, about a factor of 8 decrease from the zero order spectral intensity. The P7 channel has a very wide energy response for protons, and thus the spectral shape corrections are very important.

3.2.5 E1 Channel Response Factors

The E1 channel response factors for proton spectra are calculated using both the direct FOV and spurious responses. The calibrated direct responses are taken from the measured responses in Table 2.2, and the estimated spurious response in Table 2.5 is added on. Since the spurious response dominates at the higher energies, it is essential to include the spurious response in the E1 calculations. The total $G_{tot}(E)$ values used for the calculations are listed in Table 3.9. This produces a flat spectrum response of

$$GE_0(E1) = 686.\ cm^2\ sr\ MeV, \qquad E_0(E1) = 638.\ MeV \qquad (18)$$

The values of $CF(\gamma)$ from (9), of $E_\gamma(avg)$ from (11), and of E_γ from (12) are listed in Table 3.10. Note that the average energy of the detected protons, $E_\gamma(avg)$, decreases towards 13 MeV for very steep power law spectra, while the energy corresponding to the zero order spectral intensity decreases towards 38 MeV. For a typical power law spectrum with $\gamma = 4$ the correction factor $CF(\gamma{=}4) = 6.01\times10^{-4}$, about a factor of 1700 decrease from the zero order spectral intensity. The E1 channel has a very wide energy response for protons, and thus the spectral shape corrections are very important. The spectral corrections have a strong dependence on γ, so these corrections must be made.

Table 3.7 $G_{tot}(E)$ for P7 Channel for Response Calculations	
Proton Energy (MeV)	G(E) (cm^2 sr)
79	0.004
94	0.08
110	0.25
170	0.30
171	1.5
250	1.5
251	1.9
500	1.9
501	0.56
900	0.56

Table 3.8 Correction Factors for P7 Proton Response			
Power Law Exponent γ	Correction Factor CF(γ)	Average Energy E_γ(avg) (MeV)	Zero Order Spectrum E_γ (MeV)
0	1.000	433.	433.
1	0.816	353.	353.
2	0.539	286.	318.
3	0.289	232.	286.
4	0.127	190.	258.
5	0.0465	159.	234.
6	0.0147	137.	214.
7	0.00416	122.	198.
8	0.00109	113.	184.

Table 3.9 $G_{tot}(E)$ for E1 Channel for Response Calculations	
Proton Energy (MeV)	G(E) (cm^2 sr)
10	0.001
17	0.041
30	0.041
51	0.083
66	0.120
120	0.17
125	0.25
300	0.25
301	0.65
500	0.65
501	1.0
1000	1.0

Table 3.10 Correction Factors for E1 Proton Response			
Power Law Exponent γ	Correction Factor $CF(\gamma)$	Average Energy E_γ(avg) (MeV)	Zero Order Spectrum E_γ (MeV)
0	1.000	638.	638.
1	0.753	480.	480.
2	0.239	202.	312.
3	0.0176	47.	166.
4	6.01×10^{-4}	21.7	100.
5	1.59×10^{-5}	16.8	70.
6	3.75×10^{-7}	15.0	54.
7	8.26×10^{-9}	14.1	45.
8	1.74×10^{-10}	13.4	38.

The E1 channel will normally have a significant count rate from the ambient electron population, so the response to protons may not be easily seen. It is expected that the E1 channel will not normally be used for its proton response. It should be noted that the high energy part of the E1 proton response (above 100 MeV) is estimated, and has not been calibrated directly. Thus the E1 channel response to a hard proton spectrum has a substantial uncertainty.

3.2.6 E2 Channel Response Factors

The E2 channel response factors for proton spectra are calculated using both the direct FOV and spurious responses. The calibrated direct responses are taken from the measured responses in Table 2.2, and the spurious response from Ref. 2 in Table 2.5 is added on. Since the spurious response dominates at the higher energies, it is essential to include the spurious response in the E2 calculations. The total $G_{tot}(E)$ values used for the calculations are listed in Table 3.11. This produces a flat spectrum response of

$$GE_0(E2) = 536.\ cm^2\ sr\ MeV, \qquad E_0(E2) = 348.\ MeV \qquad (19)$$

The values of $CF(\gamma)$ from (9), of $E_\gamma(avg)$ from (11), and of E_γ from (12) are listed in Table 3.12. Note that the average energy of the detected protons, $E_\gamma(avg)$, decreases towards 14 MeV for very steep power law spectra, while the energy corresponding to the zero order spectral intensity decreases towards 31 MeV. For a typical power law spectrum with $\gamma = 4$ the correction factor $CF(\gamma=4) = 1.20\times10^{-3}$, about a factor of 800 decrease from the zero order spectral intensity. The E2 channel has a very wide energy response for protons, and thus the spectral shape corrections are very important. The spectral corrections have a strong dependence on γ, so these corrections must be made.

The E2 channel may have a significant count rate from the ambient electron population, so the response to protons may not always be easily seen. The E2 channel may not normally be used for its proton response. It should be noted that the high energy part of the E2 proton response (above 150 MeV) is based on lower energy data, and has not been calibrated directly (Ref. 2). Thus the response to a hard proton spectrum has a significant uncertainty.

Table 3.11 $G_{tot}(E)$ for E2 Channel for Response Calculations	
Proton Energy (MeV)	G(E) (cm^2 sr)
10	0.001
17	0.166
30	0.267
51	0.469
66	0.543
120	0.66
125	1.2
300	1.2
301	0.69
500	0.69
800	0.19

Table 3.12 Correction Factors for E2 Proton Response			
Power Law Exponent γ	Correction Factor $CF(\gamma)$	Average Energy $E_\gamma(avg)$ (MeV)	Zero Order Spectrum E_γ (MeV)
0	1.000	347.	347.
1	0.618	215.	215.
2	0.168	95.	143.
3	0.0185	38.	92.
4	1.20×10^{-3}	22.6	65.
5	6.12×10^{-5}	17.7	50.
6	2.75×10^{-6}	15.6	41.
7	1.14×10^{-7}	14.4	35.
8	4.48×10^{-9}	13.7	31.

3.2.7 E3 Channel Response Factors

The E3 channel response factors for proton spectra are calculated using both the direct FOV and spurious responses. The calibrated direct responses are taken from the measured responses in Table 2.3, and the estimated spurious response in Table 2.5 is added on. Since the spurious response dominates at the higher energies, it is essential to include the spurious response in the E3 calculations. The total $G_{tot}(E)$ values used for the calculations are listed in Table 3.13. This produces a flat spectrum response of

$$GE_0(E3) = 480.\ cm^2\ sr\ MeV, \qquad E_0(E3) = 360.\ MeV \qquad (20)$$

The values of $CF(\gamma)$ from (9), of $E_\gamma(avg)$ from (11), and of E_γ from (12) are listed in Table 3.14. Note that the average energy of the detected protons, $E_\gamma(avg)$, decreases towards 40 MeV for very steep power law spectra, while the energy corresponding to the zero order spectral intensity decreases towards 81 MeV. For a typical power law spectrum with $\gamma = 4$ the correction factor $CF(\gamma=4) = 0.0217$, about a factor of 50 decrease from the zero order spectral intensity. The E3 channel has a very wide energy response for protons, and thus the spectral shape corrections are very important. The spectral corrections have a strong dependence on γ, so these corrections must be made.

The E3 channel may at times have a significant count rate from the ambient electron population, so the response to protons will sometimes be contaminated. The E3 channel has such a wide energy response for protons that it should not normally be used for its proton response. It should be noted that the high energy part of the E3 proton response (above 125 MeV) is based on lower energy data, from both E3(new) and E1(old) of Ref. 2, and has not been calibrated directly. Thus the response to a hard proton spectrum has a significant uncertainty.

3.3 Summary of Channel Responses

The GOES D to H EPS/HEPAD channel responses were summarized in Ref. 4. The Ref. 4 summary is based on the EPS DOME and Telescope calibrations in Ref. 2 and 5, and on the HEPAD calibration data in Ref. 6. Since then the HEPAD calibration has been repeated, providing a more detailed and corrected response (Refs. 7 and 8). Also, the modified D3 DOME FOV results in some minor changes to the P4, A4 and E2(new) (=E1(old)) particle responses, and the added electron channels (E1(new) and E3(new)) requires particle responses for those channels. An updated set of channel responses is given in Table 3.15. The channel responses are taken from the several calibration reports cited, as well as the updated EPS DOME calibrations reported here.

Table 3.13 $G_{tot}(E)$ for E3 Channel for Response Calculations	
Proton Energy (MeV)	G(E) (cm^2 sr)
30	0.001
38	0.048
51	0.128
66	0.253
94	0.57
121	0.61
125	1.1
300	1.1
301	0.64
500	0.64
800	0.19

Table 3.14 Correction Factors for E3 Proton Response			
Power Law Exponent γ	Correction Factor CF(γ)	Average Energy E_γ(avg) (MeV)	Zero Order Spectrum E_γ (MeV)
0	1.000	360.	360.
1	0.704	254.	254.
2	0.327	167.	206.
3	0.100	111.	167.
4	0.0217	78	138.
5	3.58×10^{-3}	59	117.
6	4.91×10^{-4}	49	101.
7	5.98×10^{-5}	44	90.
8	6.71×10^{-6}	40	81.

Table 3.15
Summary of EPS/HEPAD Channel Response Factors

Channel	Particle Energy (MeV)	GE_0 (cm^2 sr MeV)	Particle Energy Range (MeV)
P1	2.5	0.194	0.74 - 4.2
P2	6.5	0.252	4.2 - 8.7
P3	11.6	0.325	8.7 - 14.5
P4	30.6	5.21	15 - 40
P5	63.1	14.5	38 - 82
P6	165.	129.	84 - 200
P7	433.	839.	110 - 900
P8[2]	375.	65.7	330 - 420
P9[2]	465.	65.7	420 - 510
P10[2]	605.	139.	510 - 700
P11[2]	(>700.)	(G=0.73 cm^2sr)	>700
A1	6.9	0.342	3.8 - 9.9
A2	16.1	0.638	9.9 - 21.3
A3	41.2	2.22	21.3 - 61.
A4	120.	21.	60 - 160
A5	210.	36.	160 - 260
A6	435.	176.	330 - (500)
A7[2]	2980.	613.	2560 - 3400
A8[2]	(>3400.)	(G=0.73 cm^2sr)	>3400
E1[1]	638.	686.	15 - 1000
E2[1]	348.	536.	15 - 800
E3[1]	360.	480.	38 - 800

[1] Electron channel responses listed are for protons.
[2] The HEPAD channel responses are for the PMT gain set to the correct value.

Note: all Pi channel responses are for protons; all Ai channel responses are for alpha particles.

In Table 3.15 the proton channel (Pi) responses are for protons, while the alpha particle channel (Ai) responses are for alpha particles. The electron channel (Ei) responses are for protons, and present the results of new data; the electron calibration data of Ref. 1 are not repeated in this report. The responses in Table 3.15 are obtained as follows:

P1 - This is the calibrated response of Refs. 5 and 4, with the low energy threshold corrected to the true value of 0.74 MeV. This correction adjusts the response to that for the actual thickness of the EPS telescope Al light shield. The adjustment changes E_0 from 2.4 MeV to 2.5 MeV, and GE_0 from 0.202 to 0.194 cm^2 sr MeV (a 4% decrease), so the changes are not large.

P2, P3 - The calibrated responses of Refs. 5 and 4.

P4 - The updated calibration response from Section 3.2.1. Compared with Refs. 2 and 4 this changes E_0 from 29.5 to 30.6 MeV, and GE_0 from 6.09 to 5.21 cm^2 sr MeV (a 14% decrease), so the changes are not large.

P5 - The updated calibration response from Section 3.2.2. Compared with Refs. 2 and 4 this changes E_0 from 60.5 to 63.1 MeV, and GE_0 from 15.5 to 14.5 cm^2 sr MeV (a 6% decrease), so the changes are not large.

P6 - The updated calibration response from Section 3.2.3. Compared with Refs. 2 and 4 this changes E_0 from 168 to 165 MeV, and GE_0 from 136 to 129 cm^2 sr MeV (a 5% decrease), so the changes are not large.

P7 - The updated calibration response from Section 3.2.4. Compared with Refs. 2 and 4 this changes E_0 from 427 to 433 MeV, and GE_0 from 891 to 839 cm^2 sr MeV (a 6% decrease), so the changes are not large.

P8 - P11 - These are calculated from the Ref. 8 calibrations, with the HEPAD PMT set to the proper HV step so that the gain is correct. Note that the channel responses change if the PMT gain is changed (see Ref. 8).

A1 - A3 - The calibrated responses of Refs. 5 and 4.

A4 - The P4 proton response of Section 3.2.1 multiplied by 4, to upgrade the response to alpha particles. Compared with Refs. 2 and 4 E_0 stays at 120 MeV, while GE_0 changes from 25.2 to 21. cm^2 sr MeV (a 17% decrease), so the changes are not large.

A5, A6 - The calibrated responses of Refs. 2 and 4.

A7, A8 - These are calculated from the Ref. 8 calibrations, with the HEPAD PMT set to the proper HV step so that the gain is correct. Note that the channel responses change if the PMT gain is changed (see Ref. 8).

E1 - The calibrated response of Section 3.2.5. Note that the high energy response is an estimate based on the Ref. 2 calculations for the E1(old) channel.

E2 - The updated calibrated response of Section 3.2.5, with the high energy (spurious) response of E1(old) in Ref. 2. Compared with the proton response of E1(old) in Ref. 9, E_0 changes from 310 to 348 MeV, and GE_0 from 435 to 536 cm^2 sr MeV (an increase of 23%).

E3 - The calibrated response of Section 3.2.5. Note that the high energy response is an estimate based on the Ref. 2 calculations for the E1(old) channel.

4.0 Summary and Conclusions

The EPS DOME sensor for the GOES I to M spacecraft uses a slightly modified design for the D3 DOME. This results in a slightly changed geometric-energy factor for the P4 and A4 channels. The DOME sensor also has two electron channels added to provide detection capability for lower and higher energy electrons. The DOME sensor was calibrated with proton beams to provide an updated calibration for the P4 channel and the E1, E2 and E3 electron channels. Some recalibration was also performed on the P5, P6 and P7 channels.

The updated calibration results are in reasonable agreement with the earlier DOME channel calibrations of Ref. 2. Using the updated calibration results, the response factors of the EPS channels have been recalculated. Response corrections for power law proton spectra have also been calculated. These data should prove useful for analysis of the GOES EPS particle data, and their reduction to actual proton spectra.

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