AeroCube-6 Dosimeter Equivalent Energy Thresholds and Flux Conversion Factors

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Abstract

In this report, we describe energy thresholds and flux conversion factors that can be used to interpret the dosimeter data from AeroCube-6 in terms of isotropic particle number flux in integral energy channels for protons and electrons. We use a bowtie analysis to consolidate the full three-dimensional energy and angle response produced by Geant4 simulations [2] into relatively simple response parameters. Bowtie analysis involves the assumption that the incident particle flux is isotropic and that it follows one of several hypothesized spectral shapes. In our analysis, we use both power law and exponential energy spectra that are tailored to our a priori knowledge of the approximate energy range for each dosimeter's response.

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1. AeroCube-6 (AC6) Mission and Dosimeters

Note: This introduction draws heavily on the AC6 "README" [5].

The AC6 mission consists of two 0.5U (5 cm x 10 cm x 10 cm) CubeSats launched on June 19, 2014 into a 620 x 700 km orbit at 98° inclination. The two vehicles are designated AC6-A and AC6-B.

The primary objective of the mission is to demonstrate three new variants of the Aerospace microdosimeter (produced under license by Teledyne Microelectronics, Inc.). These additional variants enable more energy and species differentiation than is possible with the baseline dosimeter. The baseline dosimeters have been used to measure dose in lunar and Earth orbit [3][4][6].

Each AC6 vehicle carries three dosimeters, identified as Dos1, Dos2, and Dos3. The dosimeters are mounted on the antisunward side. Figure 1 shows the locations of the dosimeters relative to the spacecraft.



Figure 1. The locations of the dosimeters. The photograph depicts the locations of the three dosimeters on each AC6. Dos3 is internal to the spacecraft, just below the top panel. The red rectangle indicates the approximate location of its silicon detector. The GPS antenna is the largest component near the Dos3 field of view. The inset shows what Dos3 would look like with its Kovar lid removed.

Of the six dosimeters on the two AC6 spacecraft, five are new variants. On both vehicles, Dos1 and Dos2 consist of circular silicon detectors 1.8 mm in diameter and $60 \mu \text{m}$ thick. They are protected from the sun

by a 1.6 μ m piece of Al foil that covers their apertures. The electronic system requires a deposit of at least 30 keV for a particle to register in Dos1 and 300 keV to register in Dos2. A single dose count in Dos1 or Dos2 corresponds to 263.5 μ Rads of dose, which may arise from one or more particles. Taking into account the foils and the electronic thresholds, the minimum incident energy for Dos1 is >~50 keV for electrons and >~600 keV for protons. For Dos2, the electron response is negligible, while the proton minimum incident energy remains near >~600 keV.

The Dos3 sensors differ between AC6-A and AC6-B. On AC6-A, Dos3 is the standard or baseline Aerospace-Teledyne microdosimeter [3]. It is behind an Al lid of minimum 20 mils plus a 10-mil Kovar lid thinned to 4 mils over the detector for a total equivalent of 32 mils Al. An energy deposit of 100 keV is required for a particle to register in the AC6-A Dos3. In the magnetosphere, AC6-A's Dos3 responds to ~1 MeV electrons and >20 MeV protons. On AC6-B, however, Dos3 is a variant modified to require 1 MeV energy deposit. This higher threshold filters out most of the electrons. It also partially filters out protons with incident energies well above the >20 MeV threshold, so that the Dos3-B response function is only about 10% of that for Dos3-A for protons with energies of a few hundred MeV. Still, Dos3 on AC6-B measures mainly >20 MeV protons. Based on calibration with a Cobalt-60 gamma ray source, dose counts from Dos3 on AC6-A can be converted to dose using a nominal value of 14.33 µRads per count. For AC6-B, the counts-to-dose factor is also 14.33, although it leaves out substantial dose caused by particles not meeting the electronic energy deposit threshold.

One aim of this report is to refine the approximate energy thresholds given above.

Dos1 and Dos2 each have approximately a 60° axially symmetric full-angle field of view (FOV) through the thin foil. There is no barrier separating Dos1 and Dos2, so each also has a narrow secondary FOV through the other's foil. Dos1 and Dos2 also respond to penetrating radiation from all angles. The offangle response depends on the shielding through which the particles penetrate and can give rise to spin modulation of the dose count rate even when the vehicle is spinning exactly around the FOV axis. Dos3 has a rectangular slab geometry (3 mm x 7 mm x 0.25 mm) with a nearly 180° field of view. The nominal 32 mils Al equivalent shielding value applies at nearly normal angles. At nearly grazing incidence angles, the aluminum top panel is 30 mils thicker, and there are obstructions such as the GPS antenna. Because of its rectangular shape, Dos3 also can exhibit spin modulation, even when the vehicle is spinning about the FOV axis. We note that when defining the angle of incidence for particles, we consider particles moving into the detector, thus moving antiparallel to the central axis of the field of view. This is the spacecraft Z axis.

2. Method

Reference [2] describes the results of a full Geant4 simulation of all three dosimeters, including an omnidirectional simulation with particles incident on all surfaces and two focused simulations incident only on circles above Dos3 or covering Dos1 and Dos2. In each simulation, many test particles of different energies are launched, and any energy deposits in the detector silicon are recorded and converted to dose. We combine these three simulations to form a full 3-D (energy-angle-angle) response function that relates incident particle number flux to dose count rate. Because the simulation computes dose for each incident particle, we divided the deposited dose by the dose-per-count factor (14.33 µRads or 263.5 µRads) to provide the response in terms of dose counts. For each vehicle, this response function is captured in a file that complies with the draft standard response file format maintained by the International Radiation Belt Environment Model Library (IRBEM-LIB) (see irbem.sf.net and specifically svn.code.sf.net/p/irbem/code/docs/PRBEM_Response_Format.doc). These standard files are built to aid in sophisticated inversions of the sensor response, such as spectral or angular inversions or global data assimilation. However, for most uses, it is desirable to have simpler energy thresholds and flux conversion factors so that each dose channel can be converted directly to proton or electron flux (based on context). To this end, we perform the bowtie analysis.

The following treatment is based in part on Appendix A of [6]. For a given dosimeter, we start by integrating the simulated sensor response over all angles of incidence, which is equivalent to assuming that the incident flux is isotropic. This results in the response function, R(E), which has units of cm²sr and depends on energy *E*. Next, we consider the dose count rate we would expect if we knew the incident (isotropic) unidirectional differential flux j(E). That dose count rate, *r*, is given by:

$$r = \int_0^\infty j(E)R(E)dE \approx G \int_{E_0}^\infty j(E)dE = G j_>(E_0)$$

where E_0 is the desired energy threshold, G is the flux conversion factor (effectively a geometric factor) with units cm²sr, and $j_>(E_0)$ is the isotropic integral flux above energy E_0 , having units of #/cm²/sr/s. (Note that the dosimeters' output-accumulated dose counts and the dose-count rate must be derived in postprocessing.) We propose two forms for the assumed flux: a power law $j(E) = E^{-n}$ and an exponential $j(E) = \exp(-E/T)$.

Given R(E) and an assumed power law, we can relate the observed dose count rate r to the flux conversion factor G via the power law exponent n and vice versa:

$$r_n = \int_0^\infty E^{-n} R(E) dE = \frac{GE_0^{1-n}}{n-1}$$
$$G_n(E_0) = r_n(n-1)E_0^{n-1}$$

Likewise, we can perform the same manipulations for the exponential function with average energy T:

$$r_T = \int_0^\infty \exp(-E/T) R(E) dE = GT \exp(-E_0/T)$$
$$G_T(E_0) = r_T \exp(E_0/T)/T$$

If we chose a family of power laws (multiple *n*'s) and a family of exponentials (multiple *T*'s), then we get a range of *G*'s at any chosen E_0 . We choose the E_0 that minimizes the standard deviation of the log of *G* over all the proposed spectra. This approach minimizes the *relative* error in the flux conversion across the chosen variety of spectra. As we will see in the next section, the plot of the *G* versus E_0 relationships has some resemblance to a sartorial bowtie, and the best value of E_0 and *G* represent the knot in the bowtie.

3. Bowtie Results

It is essential when performing a bowtie analysis to choose spectra that are both representative of the environment in which the sensor will operate and also allow the analysis to converge. A typical issue is that sufficiently flat (or "hard") spectra will not allow the analysis to converge (there is no "knot" in the bowtie). This is a fundamental limitation of bowtie analysis and is common to nearly all attempts to convert an observed dose-count rate into a flux: if the incident energy spectrum is sufficiently flat, then the sensor background response from particles with penetrating energies far above the foreground threshold can dominate the foreground signal. Under such conditions, it is essentially impossible to compute the flux with a single channel. We suspect, for example, that parts of the low-altitude South Atlantic anomaly exhibit very flat proton spectra not discernable without multiple sensor channels. Nonetheless, we will proceed, as the bowtie provides arguably the best approach to obtaining flux conversion factors that are usually valid.

Based on our experience with Deal [6] and sensors on the Van Allen Probes [7], we have selected the spectral parameters given in Table 1. Only one power law index for the Dos1 and Dos2 proton response was selected.

| | Electrons | Protons |
|-------------|-----------------------------------|-------------------------------|
| Dos1 & Dos2 | <i>n</i> ~0.5,1,4 | <i>n</i> ~4.6 |
| | <i>T</i> ~20,40,…100 keV | <i>T</i> ~100,200,300,400 keV |
| Dos3 | <i>n</i> ~2,3,8 | <i>n</i> ~2,2.5,4 |
| | <i>T</i> ~0.2,0.4,0.8,1.6,3.2 MeV | <i>T</i> ~None |

Table 1. Spectra Assumed for Bowtie Analysis

Figures 2–5 show the bowtie analysis for individual channels. Each figure depicts the response function R(E), the $G(E_0)$ curves for individual spectra, and the adopted E_0 , G fit values from the bowtie analysis.



Figure 2. Bowtie analysis for the electron response of Dos1. The response function R(E) is in green. The solid black curves are $G(E_0)$ for power law spectra. The dashed black curves are $G(E_0)$ for exponential spectra. The blue circles indicate crossings of the different spectra. Red indicates the adopted bowtie values of E_0 and G.



Figure 3. Bowtie analysis for the proton response of Dos1, in the same format as Figure 2.



Figure 4. Bowtie analysis for the electron response of Dos3-A, in the same format as Figure 2.



Figure 5. Bowtie analysis for the proton response of Dos3-A, in the same format as Figure 2.

Figures 6 and 7 summarize the bowtie analysis for all dosimeter variants for protons and electrons, respectively. Figure 6 shows that, as designed, the electron response in Dos2 and Dos3-B are depressed. Figure 7 shows that, as designed, the proton response of Dos2 is similar to that of Dos1, allowing Dos2 to serve as a proton-only sensor, which can be used to extract the electron-only flux from Dos1. Likewise, Dos3-B has a proton response similar to that of Dos3-A, allowing Dos3-B to be used to subtract the protons from Dos3-A. Because of their elevated electronic thresholds, Dos2 and Dos3-B show lower response to very high energy protons than their low-threshold counterparts, Dos1 and Dos3-A, respectively.

In the figures, the horizontal extent of the deviations between the idealized integral channels and the actual response function gives a sense of how much spectral structure must be present in order for fluxes derived through the bowtie analysis to become inaccurate. However, for smooth spectra falling approximately within the power law and exponential shapes chosen for each dosimeter, the observed dose-count rate can be converted to flux simply by dividing by G.



Figure 6. A summary of electron response bowtie analysis results for all four dosimeter varieties. Solid curves provide the response function R(E), while dashed curves provide the fit results for E_0 , G.



Figure 7. A summary of proton response bowtie analysis results for all four dosimeter varieties. Solid curves provide the response function R(E), while dashed curves provide the fit results for E_0 , G.

The numerical results of the bowtie analysis are given in Table 2. The uncertainty in G is derived from the standard deviation of $\ln G$ over the various spectra at the knot in the bowtie. Comparing to Figure 6, we note that when the response function is not sharp near the turn-on or when the response continues to rise after the turn-on, the uncertainty in the flux conversion factors (G) tends to be larger. (This uncertainty can be artificially reduced by using only steeply falling spectra, which is why bowtie analysis must always be performed and interpreted carefully.)

| Channel | | Dos1 | Dos2 | Dos3-A | Dose3-B |
|----------------------|------------------------|--------------|---------|---------------------------|---------|
| Minimum Shielding | | 1.6 μm Al | | 20 mils Al + 4 mils Kovar | |
| Equivalent mils Al | | 0.06 mils Al | | 32 mils Al | |
| Electronic Threshold | | 30 keV | 300 keV | 100 keV | 1 MeV |
| | Eo | 43 keV | 310 keV | 860 keV | 1.8 MeV |
| llec | G (cm²sr) | 3.5E-4 | 6.7E-6 | 4.3E-3 | 8.8E-5 |
| ш | G uncertainty | 7% | 45% | 16% | 20% |
| | E₀ (MeV) | 370 keV | 530 keV | 12 MeV | 11 MeV |
| Prot | G (cm ² sr) | 3.0E-3 | 4.3E-3 | 8.8E-2 | 7.5E-2 |
| | G uncertainty | 14% | 6% | 2% | 3% |

Table 2. AC6 Dosimeter Bowtie Results

4. Summary

We have performed a bowtie analysis to obtain proton and electron equivalent energy thresholds and flux conversion factors for the four dosimeter types carried on the two AeroCube-6 vehicles. These factors consolidate the full 3-D response obtained from a Geant4 simulation into terms more practical for routine conversion from dose-count rates to particle number flux.

The bowtie analysis produces an energy threshold E_0 and a flux conversion factor G, such that the isotropic integral number flux above E_0 can estimated from the dose-count rate r according to:

$$j_{>}(E_0) = \frac{r}{G}$$

with units $\#/\text{cm}^2/\text{sr/s}$. It is also sometimes useful to compute an omnidirectional number flux $J_>(E_0)$ with units $\#/\text{cm}^2/\text{s}$, and this would be:

$$J_{>}(E_0) = 4\pi j_{>}(E_0) = \frac{4\pi r}{G}$$

The values in Table 2 can be used to evaluate either of these equations to obtain proton or electron number flux estimates from individual AeroCube-6 dosimeter dose-count rates.

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