USING SPACE WEATHER VARIABILITY IN EVALUATING THE RADIATION ENVIRONMENT DESIGN SPECIFICATIONS FOR NASA'S CONSTELLATION PROGRAM

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1. INTRODUCTION

NASA's Constellation program, initiated to fulfill the Vision for Space Exploration, will create a new generation of vehicles for servicing low Earth orbit, exploration of the Moon, and beyond. The space radiation environment specifications for hardware design are necessarily conservative to assure system robustness for a wide range of space environments. Design specifications for radiation environments implemented by the program range from solar wind at the lowest energies for evaluating optical properties of material surfaces to galactic cosmic rays at the highest energies for use in evaluating crew dose during long duration missions. Spectral models of the solar particle events and trapped radiation belts are necessary for the design requirements of total ionizing dose, displacement damage, single event effects, and spacecraft charging.

The space environments and effects community designs to the level of threat environment a system is required to withstand. These design environments are required for guiding design and construction of systems to withstand acceptable extremes in the space environment. Therefore, design environments are based on observations and empirical based models to assure the design is traceable to credible, measured extremes in the environment. What is considered acceptable depends on the program risk posture and the consequences of risk. For example, the consequences of lost science spacecraft or science payloads, denial of service from communications systems, prematurely aborted missions, or sickness or loss of crew will drive the risks. A program will determine the appropriate threat level they will design their systems to withstand and beyond which they are willing to accept the risk of exposure. Space weather monitoring is then required for operations in environments more extreme than the design environment.

The goal of this paper is to demonstrate the conservative nature of the space radiation design environments that have been established for design of Constellation systems. We first describe the solar energetic particle event and trapped radiation belt design environments specified for use in designing the Constellation hardware. We then compare the specified environments for each spectral model to space weather variations to demonstrate the conservative nature of the design specifications and the potential vulnerabilities of Constellation systems to extreme space weather events.

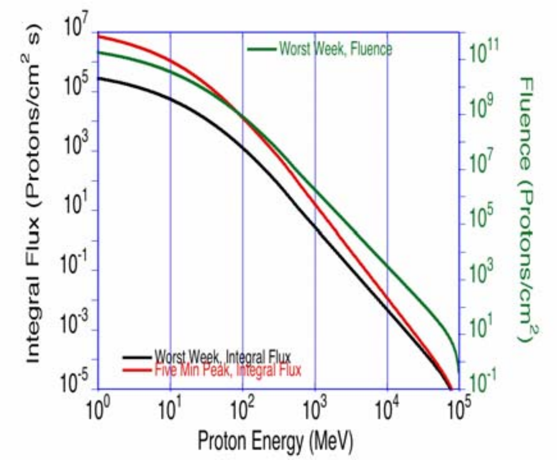

Figure 1. The SPE proton integral flux and the proton fluence (green) as a function of proton energy for the worst week (black) and the worst five-minute peak (red).

2. DESIGN ENVIRONMENT FOR SOLAR PROTON EVENTS

The SPE environment is the dominant dose driver for all but the lightly shielded components for a

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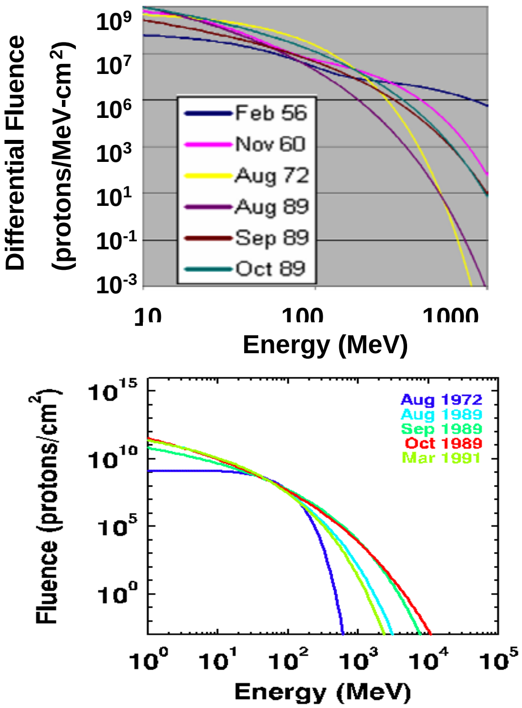

Figure 2. top) Differential fluence spectra for selected events (from Turner, 2005). bottom) Proton fluence normalized to the Carrington event for proton fluences greater than 30 MeV (based on Townsend et al., 2006).

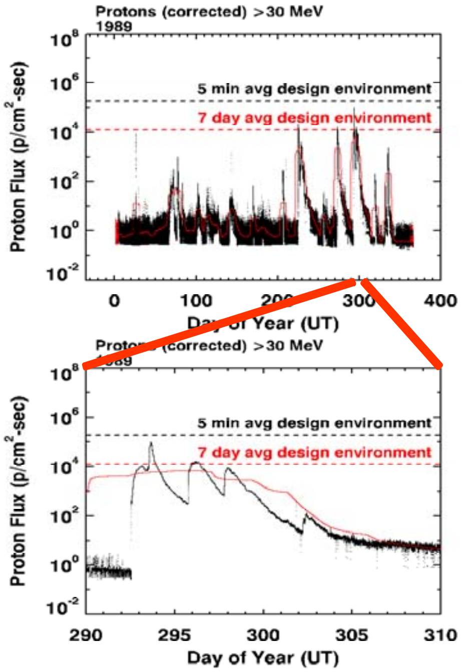

Figure 3. top) The measured >30 MeV proton flux from the GOES-7 satellite and the design specification for the complete year of 1989. bottom) The measured and design detail for only October, 1989.

Constellation mission. The current SPE design environment for the Constellation program is based on ~2x the solar proton environments associated with the October 1989 coronal mass ejection event. The SPE spectra for the 2x design is given in Figure 1. The SPE proton integral flux is shown for the worst week (black) and the five-minute peak (red) of the October, 1989 event. The fluence for the worst week is shown in green.

The five minute proton flux environments were established to assure that avionics systems will operate successfully through the high flux conditions encountered during passage of the shock peaks associate with coronal mass ejections. The long duration (one week) proton flux environments are established to constrain the total radiation dose environments for avionics and materials to the extreme solar proton event fluences accumulated during exposure to a series of coronal mass ejection events.

2.1 Variability in the SPE Spectra

The variability of the SPE is demonstrated by the spectral hardness comparison for selected large SPE events. The top panel of figure 2 shows the spectra of proton differential fluence as a function of energy for selected events and demonstrates the hardness variation for these events [Turner, 2005]. The October, 1989 event is shown in green. The bottom panel of figure 2 shows the same spectra of events normalized to the Carrington coronal mass ejection event of 1859. It gives the proton fluence normalized to the Carrington event for > 30 MeV energies [adapted from Townsend et al., 2006]. This shows that the Constellation SPE design environment is based on a hard, high flux spectrum exceeded by only a few events. This leads to conservative design environment.

2.2 Variability in the SPE Environment for >30 MeV Protons

We compare the SPE Design Environment for the >30 MeV integral proton flux to the measured high flux events in 1989. Figure 3 shows the observed measurements of the > 30 MeV proton flux from the GOES-7 satellite for the full year of 1989. The measurements for the 7-day mean and the 5-minute average peak are shown in red and black respectively.

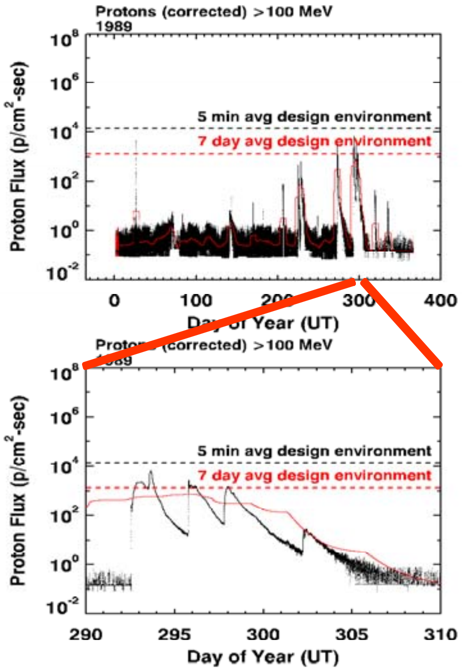

Figure 4. top) The measured >100 MeV proton flux from the GOES-7 satellite and the design specification for the complete year of 1989. bottom) The measured and design detail for only October, 1989.

The corresponding lines for the SPE design specification are shown on this panel. The same measurements for just the extreme month of October, 1989 are shown in the bottom panel. The 7-day mean (red) and the 5-minute peak (black) proton flux design environments exceed the corresponding averages of the measured flux through the October event. This again demonstrates the conservative nature of the Constellation SPE design environment.

2.3 Variability in the SPE Environment for >100 MeV Protons

We now compare the SPE Design Environment for the >100 MeV integral proton flux to the measured high flux events in 1989. Figure 4 shows the observed measurements of the >100 MeV proton flux from the GOES-7 satellite for the full year of 1989. The measurements for the 7-day mean and the 5-minute average peak are shown in red and black respectively. The corresponding lines for the SPE design specification are shown on this top panel. The measurements for just the extreme month of October, 1989 are shown in the bottom panel. Both the 7-day mean (red) and the 5-minute peak (black) proton flux design environments exceed the corresponding peak averages of the observed flux through 1989 and specifically for the October event. This again demonstrates the conservative nature of the Constellation SPE design environment.

2.4 Variability due to SPE Streaming Limits

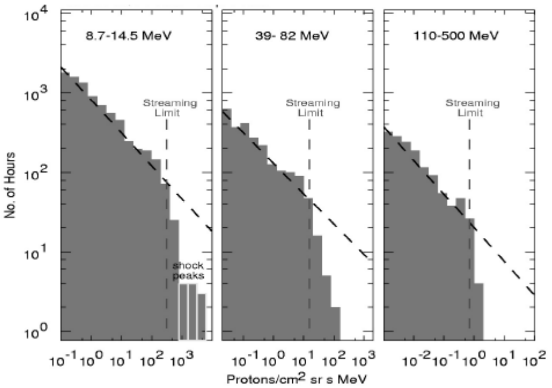

Figure 5. The Constellation 5-min (red) and 7-day (blue) design environments are compared to the *Reames* [2004] streaming limits (black) for the SPE proton flux. For comparison, the Constellation SPE Design Environment are integrated over the same GOES-7 energy bands used bv *Reames*.

The solar proton flux streaming from shock fronts is limited by wave particle interactions and establishes an upper bound for SPE events that arrive before the shock front [*Ng and Reames*, 1994, *Reames and Ng*, 1998]. This limits the SPE total dose environments in interplanetary space. For example, Figure 5 shows histograms of hourly averaged proton flux from GOES-7 in geostationary orbit over nearly a solar cycle for three selected energy bins [*Reames*, 2004]. The number of hourly intervals where a given proton flux is observed follows a power law up to the streaming limit where the observations of flux exceeding the streaming limit drops precipitously. The limited periods of high proton flux exceeding the streaming limit are due to shock peaks where protons accelerated at the coronal mass ejection shock front are measured directly.

The Constellation 5-minute (red) and 7-day (blue) design environments are compared in Figure 6 to the *Reames* [2004] streaming limits (black) for the SPE proton flux. For comparison, the Constellation SPE Design Environment are integrated over the same GOES-7 energy bands used by *Reames* to facilitate direct comparison. The *Reames* limits are similar to the 7-day design environment because it is due to the average flux over the full period of the October 1989

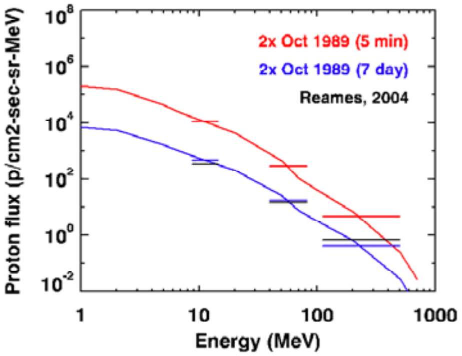

Figure 6. The Constellation 5-min (red) and 7-day (blue) design environments are compared to the *Reames* [2004] streaming limits (black) for the SPE proton flux.

event. The 5-minute environment exceeds the streaming limits because they are derived from the highest flux shock peak during the October 1989 events.

2.5 Comparison of Large SPE Event Fluence to SPE Design Environment Fluence

Constellation worst week environments establish the total ionizing dose that hardware will have to withstand due to solar proton events. Comparing the 8x10^9 p/cm^2 fluence of >30 MeV protons from the worst week design environment with a selection of historically large solar proton event fluences in Table 1 demonstrates the design environment is consistent with large proton events recorded during the space age and is within ~2x to ~3x the 1859 Carrington event fluence considered to be the worst case in the past ~400 years [McCracken et al., 2001a,b].

It is important to note that while the solar proton event design environment is based on extreme environments, the choice is not an arbitrary decision to implement over conservative design environments in an attempt to cover perceived uncertainties in the knowledge of the space radiation environment. Measurements of large solar proton event fluences exceeding >10^9 p/cm^2-sr do exist in the long term record of solar proton fluences and have been observed numerous times within last decade. Indeed, the “conservative” 8x10^9 p/cm^2 fluence of >30 MeV protons from the design environment is only ~1.9x the 4.3x10^9 p/cm^2 event fluence from the Bastille Day event in July 2000 and only ~2.4x the event fluence of three additional events during 2000 to 2003 listed in Table 1. High fluence solar proton events therefore represent credible threat environments that may be encountered for current and future programs.

Table 1. Event Fluence Comparison

Event	Max >30 MeV Proton Flux	>30 meV Proton Event Fluence
	(#/cm2-s-sr)	(#/cm2-sr)
1859/09/01	5 x 10^4	19 x 10^9
1960/11/15	-	9 x 10^9
1946/07/25	-	6 x 10^9
1972/08/04	2 x 10^4	5 x 10^9
2000/07/12	-	4.3 x 10^9
1989/10/19	-	4.2 x 10^9
2001/11/04	-	3.4 x 10^9
2003/10/28	4.5x10^3	3.4 x 10^9
2000/08/00	-	3.2 x 10^9
1959/07/14	-	2.3 x 10^9
1991/03/22	-	1.8 x 10^9
1989/08/12	-	1.4 x 10^9
1989/09/29	-	1.4 x 10^9

[Sources: Smart and Shea, 2002; Reedy, 2006; Smart et al., 2005]

The database of large solar proton event fluence measurements is based primarily on two sources. The first is approximately three solar cycles of in-situ energetic proton flux measurements from spacecraft in Earth orbit at distances where the Earth’s magnetic shielding is insufficient to significantly perturb the interplanetary particle flux. Even before the space age there are estimates of solar proton fluence derived from measurements of cosmic ray ground level events that provide information on large proton events that occurred during the first half of the 20th century. Over longer time scales, measurements of nitrate concentrations in polar ice core samples provide a proxy record of solar proton event fluences over a period of ~400 years because enhancements in nitrate concentrations over background levels have been shown to correlate with solar proton fluence during the space age when the two records overlap [McCracken et al., 2001a,b].

3. DESIGN ENVIRONMENT FOR TRAPPED RADIATION

Energetic charged particles trapped within the Earth’s magnetic field provide an additional source of radiation for missions to the Moon or Mars. The radiation belt environments encountered on Earth-Moon transit trajectories or Earth escape trajectories

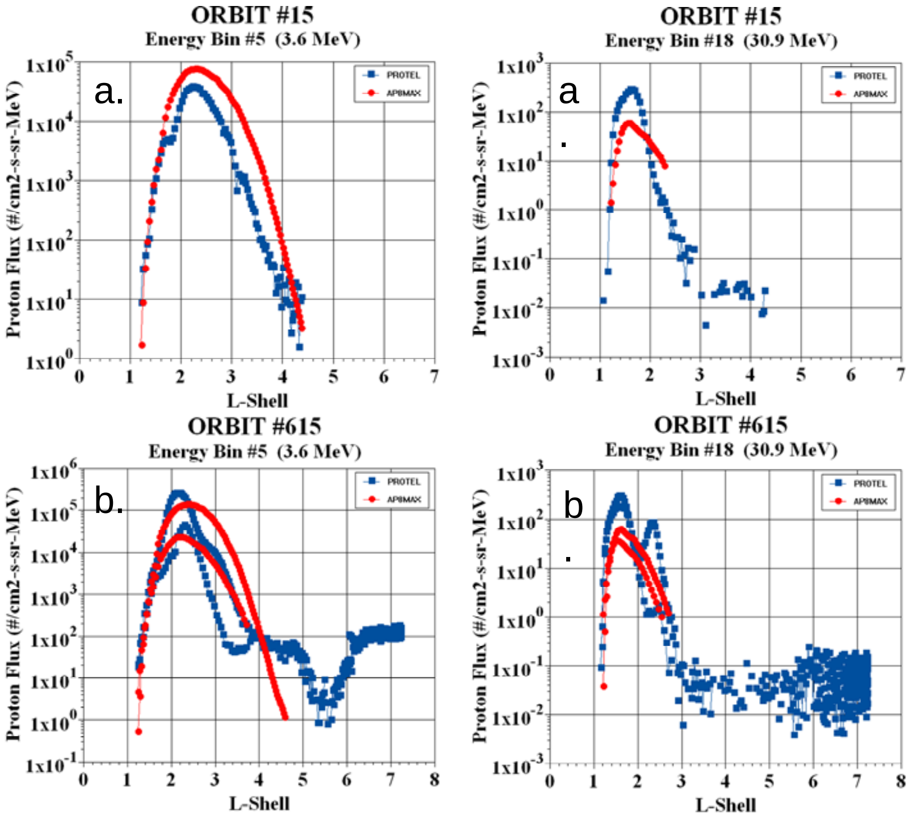

Figure 8. *Proton Telescope measurements (blue) compared to AP-8 Solar Maximum model values (red).*

to destinations beyond the Moon may dominate the radiation environment in the case where large solar proton events are not observed during the mission. Even in the case where large solar particle events are the primary driver for total dose the trapped radiation environments will be important for lightly shielded components.

The Constellation trapped radiation belt design environment shown in Figure 7 is currently based on the AP-8, AE-8 solar maximum models [Sawyer and Vette, 1976; Vette, 1991]. This spectra is the proton and electron fluence for a single approximately four hour transit through the Earth's radiation belts during an Earth-Moon transit. The trapped proton and electron fluence dominates the integral fluence design environments at energies less than ~1 MeV while the solar proton contributions dominate the design environments at greater energies.

3.1 Variability in the Trapped Radiation Environment

Figure 8-a shows an example of a quiescent radiation belt environment for 3.6 MeV and 30.9 MeV protons measured by the PROTEL instrument during Orbit 15 from the CRRES satellite. Measured proton flux is compared to the AP-8 model values to show how the environment varies from the modeled values used to construct the design environments.

In comparison, the 3.6 MeV and 30.9 MeV proton measurements from Orbit 615 shown in Figure 8-b gives a representative disturbed period following the onset of a strong geomagnetic storm. A new proton belt generated during the geomagnetic activity at L shells of 2 to 3 is evident.

The mean AP-8 Solar Maximum environment is sufficient for quiescent periods at low energies but at both energies the model underestimates the proton flux in the inner belts during disturbed periods.

Electron environments at 272 keV and 876 keV for the quiet Orbit 15 and disturbed Orbit 615 are shown in Figure 9. Electron flux measurements significantly exceed the AE-8 Solar Maximum design environments in the outer electron belts during the quiescent case and in the electron slot for the disturbed case. While AE-8 may be acceptable as a mean representation of electron flux for use in establishing fluence environments for spacecraft that will sample the radiation belts for long periods during the maximum phase of the solar cycle, it is not adequately conservative for use in specifying electron

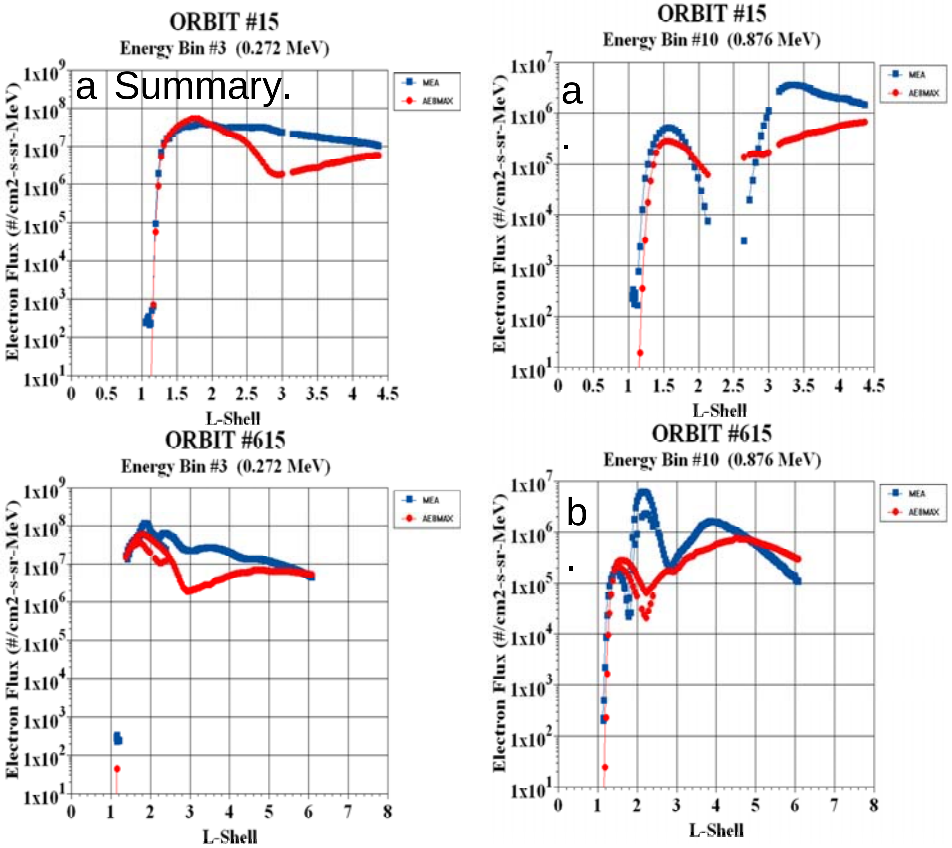

Figure 9. CRRES Magnetic Electron Spectrometer measurements (blue) compared to AE-8 Solar Maximum (red) model values.

environments for single transits of the Earth's radiation belts. Further analysis is warranted to determine either a better model for specifying the electron environments or alternative methods of utilizing the AE-8 model.

4. SUMMARY

We conclude by summarizing the results in this paper for the Constellation design specifications for SPE and trapped radiation environments.

4.1 Solar Particle Event Design Environment

- The Constellation 7-day SPE design environment is based on extreme solar energetic particle events that exceed the streaming limits at the lower energies and is on the order of the streaming limits at the highest energies.
- The SPE Design Environment for the >30 MeV fluence exceeds the >30 MeV fluence observed for most of the large SPE events during the historical space age and is within a ~2x to ~3x factor within the 1859 event fluence.
- The SPE design environment is sufficiently robust for use in designing systems for long-term use where the ionizing dose is dominated by SPE environments.
- The comparison to space weather data demonstrates the conservative nature of design environments particularly for SPE.

4.2 Trapped Radiation Design Environment

- The Constellation radiation design environment for hardware was established to support robust operation in extreme space environments.
- The current Constellation trapped radiation design environment is derived from AP-8, AE-8 Solar Maximum models which represent the mean environments present during the active phase of the solar cycle.
- We are considering options to modify the radiation belt design environment to better represent the extreme environments encountered during the Earth-Moon transit period.

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