# The Van Allen Probes Engineering Radiation Monitor: Mission Radiation Environment and Effects

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## ABSTRACT

*The engineering radiation monitor (ERM) measures dose, dose rate, and charging currents on the Van Allen Probes mission to study the dynamics of Earth's Van Allen radiation belts. Measurements from this monitor show a variation in dose rates with time, a correlation between the dosimeter and charging current data, a map of charging current versus orbit altitude, and a comparison of measured cumulative dose to prelaunch and postlaunch modeling. The measurement results and surveys of the radiation hardness for the spacecraft and science instrument electronics enable the team to predict the length of possible mission extensions. The ERM data have proved useful in investigations of two spacecraft anomalies.*


## INTRODUCTION

For more than a half century, The Johns Hopkins University Applied Physics Laboratory (APL) has designed spacecraft electronics and science instruments that are exposed to the space radiation environment and its effects. The design and fabrication of an accurate and reliable radiation monitor has become increasingly important for the unique and challenging missions now occurring in Earth orbit and interplanetary space. The space radiation environment is important for spacecraft operations, spacecraft system design, mission planning, and astronaut safety in manned missions.

In August 2012, the two Van Allen Probes spacecraft launched into an Earth geosynchronous transfer orbit (GTO). The engineering radiation monitor (ERM) captures data from the spacecraft, with the following goals:

1. Provide measurements that enable the mission planning team to adapt to the radiation environment.
2. Provide information to support decisions for future missions with longer mission lifetimes.
3. Provide measurements that allow correlation of anomalies with radiation environmental factors.
4. Provide data and knowledge to support potential mitigation of anomalies.
5. Acquire environmental data vital for future missions to the same region of space.
6. Provide feedback on the accuracy of the environmental models used to plan the original mission.

An engineering radiation monitoring experiment was devised for integration into the overall philosophy of the Van Allen Probes mission and to specifically track the total cumulative ionizing dose and dose rates due to Earth's trapped radiation belts and their dynamics resulting from solar events and storms. Explorer 1 discovered Earth's radiation belts at the beginning of the space age in 1958. Figure 1 shows a sketch of the spacecraft orbits and Earth's Van Allen radiation belts. The two space-

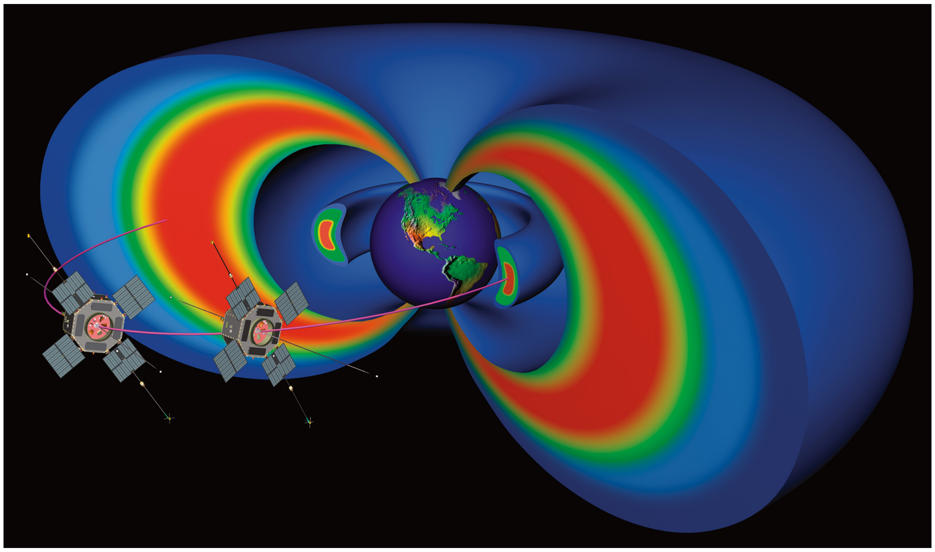

**Figure 1.** Both Van Allen Probes spacecraft operate in highly elliptical GTO orbits and spend a substantial part of their mission life in the Van Allen radiation belts. The two orbits have apogee altitudes between 30,050 and 31,250 km, perigee altitudes between 500 and 675 km, a period of 9 h, and inclination of 10°.

craft are positioned and phased such that one will lap the other approximately four times per year, providing coverage of many relative locations and times.

## THE ENGINEERING RADIATION MONITOR

The ERM (see Table 1 for specifications) was developed as a supplementary spacecraft experiment for NASA's Van Allen Probes mission. The mass is 1.5 kg, the power is 0.2 W when operating, and the dimensions are 18 × 18 × 6 cm. It was designed for the baseline ~800-day mission. See J. O. Goldsten et al. for a detailed description of the ERM and its operation.[1] In this article, we present a brief overview of its capabilities. The ERM monitors total dose, dose rate, and deep dielectric charging at each spacecraft in real time. Designed to take the place of spacecraft balance mass, the ERM contains an array of eight dosimeters and two buried conductive plates. The dosimeters are mounted under covers of varying shield thickness (0.05 mm Al, 0.39 mm Mg, 0.78 mm Mg, 1.16 mm Mg, 1.55 mm Mg, 2.32 mm Mg, 4.66 mm Mg, 9.0 mm Al) to obtain a dose–depth curve and to characterize the electron and proton contributions to total dose. The dosimeters are REM Oxford type RFT300 (300-nm gate oxide thickness) dual radiation-sensing field effect transistors (RadFETs) and operate at zero bias (with the gate held at 0 V during exposure) to preserve their response even when powered off for extended periods. The range of the RadFETs extends above 1000 krad(Si) to avoid saturation over the expected duration of the mission, and the resolution is about 10 rad(Si).

Two large-area (~10 $cm^2$) charge monitor plates set behind 1.0- and 3.8-mm-thick aluminum covers measure the dynamic currents of weakly penetrating electrons that can be potentially hazardous to sensitive electronic components within the spacecraft. The charge monitors can handle large events without saturating (~3000 $fA/cm^2$) with sufficient sensitivity (~0.1 $fA/cm^2$) to characterize quiescent conditions as well. High time-resolution (5 s) monitoring allows detection of rapid changes in flux and enables correlation of spacecraft anomalies under local space weather conditions.

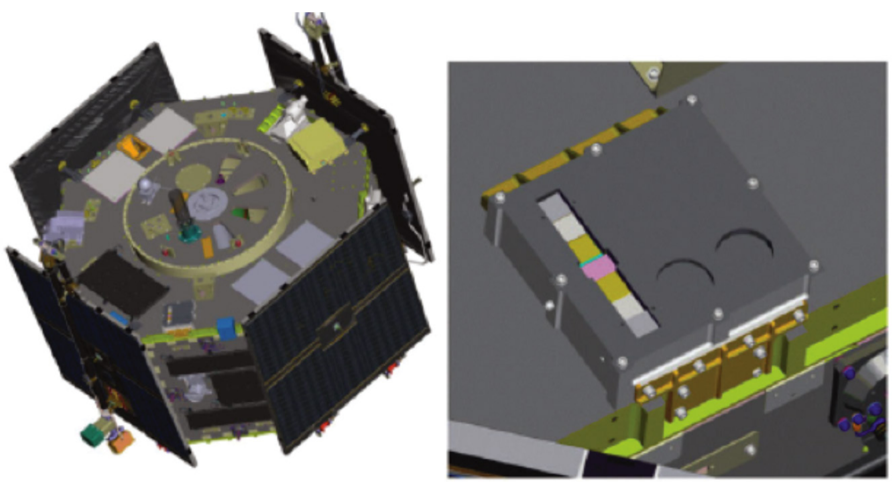

**Figure 2.** (Left) View of the Van Allen Probes spacecraft showing the location of the ERM near the bottom center between the two lower solar panels. The ERM is located toward the edge of the aft deck and mounts near a balance mass location. (Right) Zoom on the mounting detail (insulation blanket not shown for clarity).

Figure 2 shows the location of the ERM on the spacecraft. The mounting location near the edge of the deck assures a clear field of

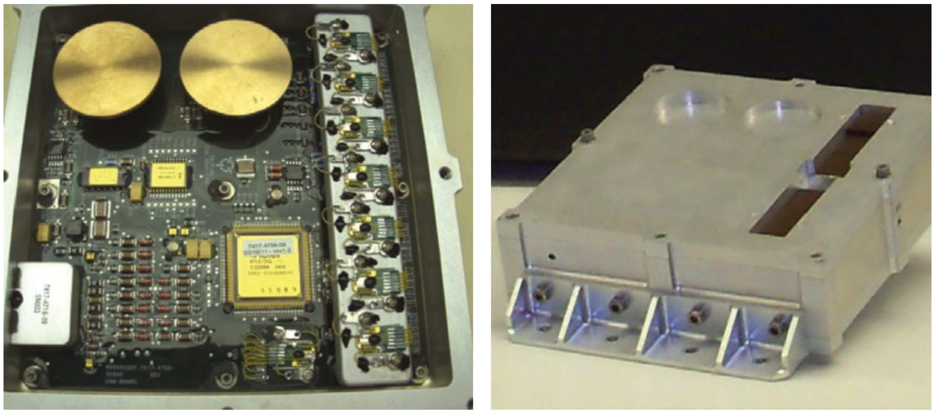

**Figure 3.** (Left) Flight ERM with its cover removed showing the locations of the individual RadFET dosimeters and the two charge monitors; the maximum shielded board-mounted RadFET is at the lower right next to and deeper than the RadFET bench. (Right) View with cover showing variable thickness absorber.

view for the two charge monitors (circular depressions in the cover) and the dosimeter array (the rectangular aperture with the thinnest absorber at its center). The small amount of absorption or shielding due to the multilayer insulation blanket (not shown) over the aperture is only significant when compared to the thinnest part of the cover and has been included in the design phase GEANT radiation transport model.

Figure 3 provides internal and external views of the ERM. The rectangular aperture in the cover spans the dosimeter array and contains a variable thickness absorber to characterize dose versus depth. The circular depressions above the charge monitor plates provide two levels of shielding thickness to gauge deep dielectric charging currents over an extended range. The ERM is sensitive to radiation penetrating these defined apertures as well as from the surrounding thick box walls, necessitating the derivation of an effective thickness for each RadFET by using the GEANT radiation transport modeling.

## Dosimeter

An objective of the dosimeter array is to characterize the dose–depth curve for comparison with model predictions. The array consists of seven RadFET dosimeters spaced ~2 cm apart to form separate pixels, where each pixel sits beneath a different thickness cover. The RadFETs are mounted along a raised aluminum "bench" that brings them in close proximity to the cover, increasing the portion of their field of view subtended by the variable thickness covers. An eighth RadFET dosimeter is mounted directly to the printed circuit board, providing a representative dose for the common box wall thickness on the Van Allen Probes. The variable thickness cover (guided by a GEANT4 modeling effort) is thinnest at the center and thicker toward the ends in a *v*-configuration. Given the closeness of the pixels to each other and the penetrating nature of radiation, there is considerable overlap of dose between adjacent pixels. This complication is accounted for in the modeling effort, which has recently been extended to derive the effective thicknesses for each pixel. The absorber material is primarily magnesium precisely machined to form steps at each pixel boundary. The desired thickness over the center pixel was too thin for accurate machining and was replaced with a piece of 40-μm-thick aluminum foil bonded to a framed cutout.

Each dosimeter is an integrated circuit (type RFT-300CC10G1, developed and manufactured by REM Oxford Ltd.) and contains two RadFET sensors and an on-chip diode. RadFETs are p-type metal oxide field effect transistors (p-MOSFET) with a thickened gate oxide region. Radiation-induced charge in the gate oxide ($SiO_2$) region can remain trapped for many years. The presence of this stored space charge produces a threshold voltage shift in the transistor as total dose accumulates. A thicker oxide region increases sensitivity but reduces dynamic range. The ERM employs devices with an oxide thickness of 0.3 μm, which provides an acceptable balance between sensitivity and dynamic range.

The RadFET oxide is sensitive to all types of ionizing dose and provides a linear energy transfer type response that is not overly affected by dose rate or particle species. The response to dose is most sensitive and linear if the gate is biased during irradiation, but an operational constraint of the ERM is that power might be removed at any time. Because of this risk, the team

**Table 1.** ERM summary specifications

| Specification | Value |
|---|---|
| Dosimeter range | 0–1000 krad |
| Dosimeter sensitivity | ~0.01 krad, TID < 10 krad<br>~0.1 krad, TID < 100 krad<br>~1 krad, TID < 1000 krad |
| Charge monitor range | 0–3 pA/cm$^2$ |
| Charge monitor sensitivity | ~1 fA/cm$^2$ |
| Mass | 2.9 kg |
| Power | 0.25 W |
| Envelope | 18 × 18 × 6 cm |
| Data rate | 16 bps |

decided to operate the ERM RadFETs in a zero bias mode (ZBM) so that they would respond to dose in a predictable manner whether powered on or off. As a consequence, their response is more uncertain and nonlinear, so a careful calibration was required to convert from threshold shift to dose; however, a benefit of the lower sensitivity and sublinear curvature or "roll-off" is a significantly extended dynamic range [>1000 krad(Si)] that will potentially allow operation for several years on orbit. The shape of the ZBM curve may be approximated as a power law with voltage shift varying as a function of dose.

Other accepted consequences of operating in ZBM include a larger percentage scatter in responses and increased "fade." Long-term loss of the stored charge in the oxide region (fade, or room-temperature recombination) occurs as a result of the slow emptying of some charge traps on the oxide. Most RadFET data for the RFT300 device have been collected under biased conditions; it has only recently been realized that fade for an unbiased RadFET is more significant. As a result, good accuracy required a new calibration curve to be captured at dose rates near expected mission values and operating temperatures, part of the ground calibration effort.

### Charge Monitors

The charge monitors are designed to measure the flux of charged particles that penetrate the cover and then stop in buried dielectrics, building up potentially hazardous amounts of charge. The ERM has two independent charge monitors beneath different thickness aluminum covers (1.0 mm and 3.8 mm) as a means of providing crude spectrometry (>0.7 MeV and >2 MeV for electrons and >15 MeV and >33 MeV for protons) and for extending the dynamic range of intensity measurements in case an unexpectedly large event saturates the more sensitive channel. The two identical charge plates are 38 mm in diameter and 2.5 mm thick. The plates are made of copper (as opposed to aluminum) to reduce the needed thickness to stop electrons penetrating the cover while minimizing the exposure to unwanted background from the sides. The cover itself extends downward to surround the charge plates with a thick baffle that further reduces background from the sides. The grounded baffle also reduces susceptibility to electromagnetic interference, ensuring measurement capability down to the electronics noise limit.

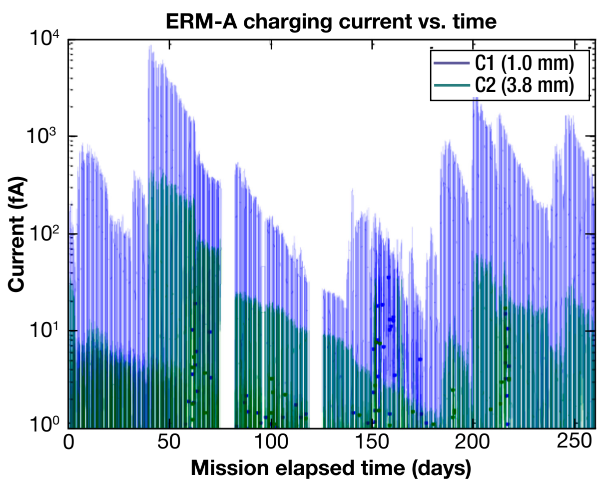


**Figure 4.** Charge monitor plate currents in femtoamps versus time for electrons > 0.7 MeV (upper blue) and > 2 MeV (lower green) for the first 260 days of the mission. Day 0 is 30 Aug 2012.

## RADIATION ENVIRONMENT MEASUREMENTS

The Van Allen Probes, now in the extended mission, have been in orbit for more than 1000 days; the original design was for 800 days. Measurements from the charge monitor for the first 260 days of the mission (see Fig. 4 and Refs. 2 and 3) illustrate the considerable variability in the energetic electron environment observed by ERM-A (the ERM on spacecraft A). Although these instruments are primarily intended to monitor deep dielectric charging conditions in the spacecraft, they also provide a convenient real-time view of space weather conditions in the electron-dominated Van Allen Probes environment. The sudden onset of major and minor storms is clearly visible with a ~400:1 variation in charge rate or current observed.

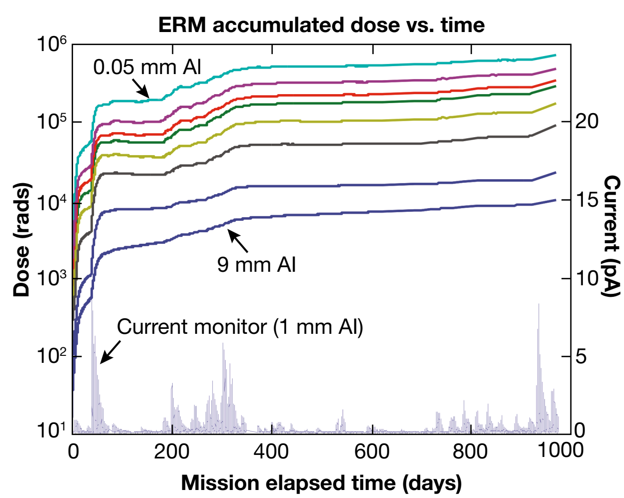


**Figure 5.** Dose in rad(Si) on the left ordinate logarithmic scale versus time up to 971 days of the Van Allen Probes mission for ERM-B showing data from the eight RadFETs (from the least shielded top curve to the most shielded bottom curve) correlated with current monitor data on the right ordinate (bottom) for ERM-A. The variability in dose rate clearly corresponds to the storm activity measured by the charge monitor (peaks greater than 5 pA) in October 2012, summer 2013, and March 2015. Day 0 is 30 Aug 2012.

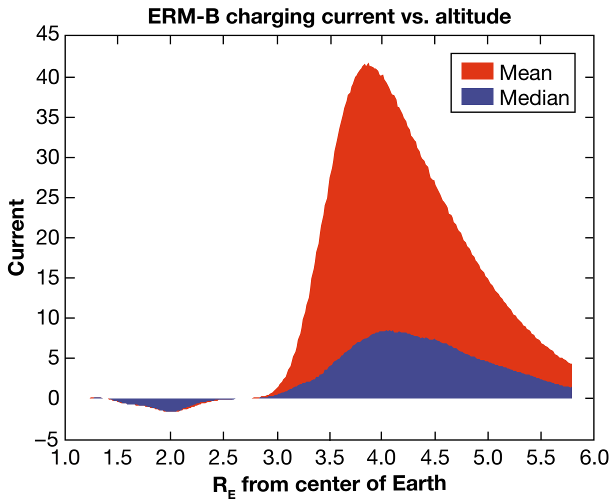


**Figure 6.** Charging current (electron current as positive) versus orbit altitude for more than 400 orbits below the 1-mm Al cover (electron energy > 0.7 MeV; proton energy > 15 MeV). Below ~2.5 $R_E$, protons dominate, and the median and mean plots are almost equal because of inner belt stability; above ~3 $R_E$, electrons dominate, and the peak of the mean plot is approximately eight times greater than the median plot because of outer belt variability.

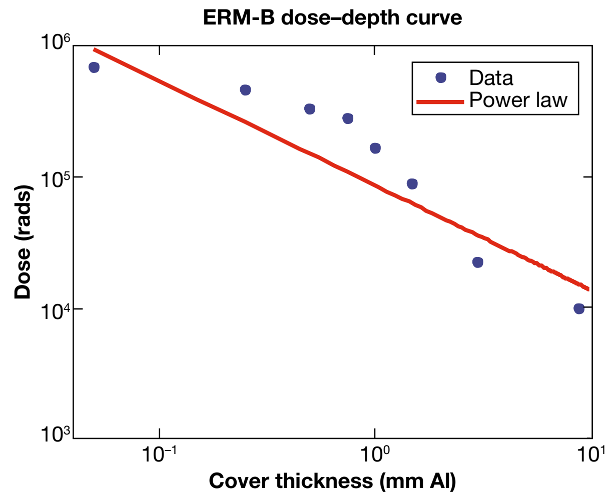


**Figure 7.** Measured cumulative dose in rad(Si) versus depth in equivalent mm aluminum for 971 days of the Van Allen Probes mission. The data point at 9 mm Al [~10 rad(Si)/day] represents the dose to all spacecraft electronics with similar thickness aluminum box walls.

Figure 5 shows the correlated charge monitor current and RadFET dose measurements plotted together versus time. A strong correlation between current (electron dose rate) and total dose is evident. To date, storm periods have contributed ~50% of the accumulated dose of 9.7 krad(Si) behind the maximum 9-mm Al shielding representative of the spacecraft electronics. The mean dose rate of 10 rad(Si)/day varies from 30 rad/day in active periods to ~6 rad(Si)/day during quiet periods.

Figure 6 shows the charging current versus orbit altitude underneath the 1-mm Al cover after more than 400 orbits. Below ~2.5 $R_E$, protons dominate, with the peak flux occurring at ~2.0 $R_E$. The small difference between the mean and median flux demonstrates the inner proton belt's relative insensitivity to storm conditions. Above ~3 $R_E$, electrons dominate, with the peak flux occurring at ~4 $R_E$. Here the large difference observed between the mean and median flux highlights the effect of storms on both the intensity and position of the outer electron belt. Real-time charge monitor data from the ERM (such as shown in Fig. 4) provides a view of the trapped radiation belts for the Van Allen Probes orbit.

Figure 7 provides the measured dose versus RadFET cover thickness curve. The measured points characterize the curve over a 100:1 range in dose. The six data points up to 1.5 mm Al shield depth are dominated by the electron dose in the outer Van Allen belt; the two data points at 3 and 9 mm Al are dominated by the proton dose in the inner belt. Table 2 shows the individual data points for the logarithmic plot in Fig. 7.

After 971 days, the measured ERM dose behind 9 mm Al (representative of the electronics on the spacecraft) is ~10.0 rad(Si)/day or 9700 rad(Si). The minimum shielded RadFET (0.05 mm Al) has seen 689,000 rad(Si) or 710 rad(Si)/day for near-surface locations (surface materials were tested to 10 Mrad). The robust aluminum shielding reduces the dose by a factor of ~70.

Before the spacecraft underwent a critical design review (CDR), the worst-case 3-D design prediction (RBSPICE electronics box) was a dose of 18,900 rad(Si). This prediction was made using the NOVICE transport modeling code for the AP8/AE8 static environment models with a radiation design margin (RDM) of 2 and extrapolated to 971 days from the baseline mission of ~800 days. The NOVICE prediction contained many radiation path lengths greater than 9 mm for the electronics box. Nevertheless, with an RDM of 1, this dose prediction is 9400 rad or slightly less than the mea-

**Table 2.** Data points for Fig. 7

| Depth (mm Al equivalent) | Dose (rad) |
|---|---|
| 0.05 | $6.89 \times 10^5$ |
| 0.25 | $4.59 \times 10^5$ |
| 0.50 | $3.38 \times 10^5$ |
| 0.75 | $2.76 \times 10^5$ |
| 1.00 | $1.66 \times 10^5$ |
| 1.50 | $9.03 \times 10^4$ |
| 3.00 | $2.41 \times 10^4$ |
| 9.00 | $9.66 \times 10^3$ |
| 13.5 (RPS depth) | $6.90 \times 10^3$ [a] |

RPS, Relativistic proton spectrometer.
[a] Extrapolation from 3- and 9-mm data points for proton dose.

surement of 9700 rad behind 9 mm Al; therefore, some margin in the prediction does prove necessary.

The two Van Allen Probes spacecraft also include measurements of total ionizing dose (TID) in the electronics box for the relativistic proton spectrometer (RPS).[4] The ERM has dosimetry based on the response of REM Oxford's RadFET transistors with specially designed thick gate oxides; the RPS dosimeter is based on a micron silicon p-i-n diode, also called a silicon test mass. A comparison can be made of the two measured doses at the large shield depth of the RPS dosimeter:

- RPS: The measured cumulative TID behind 540 mil (13.5 mm) Al after 971 days is ~6800 rad or a constant 6.8 rad/day dominated by the protons of the inner radiation belt (data from Joe Mazur of Aerospace Corp.). This dose rate has been roughly unchanged during the mission.
- ERM: The cumulative TID from the 971-day dose–depth curve (Table 2 and Fig. 7) extrapolated to 13.5 mm using just the last two depth points to emphasize the proton contribution is 6900 rad or ~6.9 rad/day.

The two proton dose measurements differ by less than 2%.

## HARDNESS ASSURANCE SURVEY AND MISSION EXTENSION

The Van Allen Probes observatories were originally designed for an on-orbit life of 2 years and 74 days. This encompasses a 60-day commissioning period after launch, a 2-year science mission, and 14 days at the end of the mission to disable the observatories. The 2-year lifetime of the science mission provided sufficient local time, altitude, and event coverage to improve our understanding of and determine the relative significance of the various mechanisms that operate within the radiation belts.

The success of the baseline Van Allen Probes mission in the harsh radiation environment, the interest in the science and engineering measurements, and the active years remaining in Solar Cycle 24 led to a desire to extend the mission. Proposing a mission extension required the team to survey the radiation hardness of the spacecraft's electronic parts to determine how long of an extension the devices, which were originally qualified for only an ~800-day mission, could tolerate.

### Spacecraft Electronics Survey[5]

According to the original Van Allen Probes TID evaluations, all electronic components were at least twice as hard as the AD7943 12-bit serial digital-to-analog converter (DAC) in the transceiver, which means this DAC is the radiation life pacing item by a factor of ~2. The as-built spacecraft electronics parts list was reviewed in 2013.

The AD7943ARS-B devices were originally tested for TID survivability several times before the spacecraft launched, the last being in 2-krad steps to 16 krad(Si). All tested devices functionally passed after 14 krad and after annealing, but all output voltages failed functionally after 16-krad exposure. Test results conclude that the AD7943ARS-B is a 15-krad device that can be used with additional spot shielding of 5 mil of tantalum or 31 mil of aluminum equivalent.

The pre-CDR (2009) NOVICE radiation transport ray trace analysis from the 3-D spacecraft design drawings showed that the maximum transceiver dose was 13.8 krad (RDM = 3 for spot-shielded devices) for the shielded AD7943 (total shielding was ~421 mil Al equivalent); a demonstrated 15-krad hard part had a 13.8-krad requirement with an RDM = 3.

After the spacecraft soft part survey was completed in March 2013, discussions among the spacecraft system, design, and radiation engineers resulted in a more detailed TID evaluation in which dose/anneal cycles would be interleaved in 2500-rad and 5000-rad steps immediately followed by a 1-week anneal at 100°C. Because the AD7943 is heavily shielded with 421 mil Al equivalent, the radiation dose that it experiences is almost solely due to protons in the inner Van Allen Belt near perigee. The receiver board sees exposure in a roughly ~2-h time period and then is free from proton flux for the roughly remaining 7 h of the orbit. The dose/anneal test was designed to simulate this exposure scenario for the AD7943.

The AD7943 12-bit serial DAC in the transceiver completed this additional high dose rate plus anneal cycles TID test in September 2013 after 25,000 rad were accumulated in 2500-rad and 5000-rad steps. The AD7943 devices behaved in a consistent manner through 20,000 rad with the supply current increasing linearly and then decreasing modestly after the postexposure interval anneal. However, after 25,000 rad, all four devices had no output and were functionally dead and drawing significantly lower supply current. After the 1-week anneal at 100°C, the devices were alive again but with a significant uptick in the supply current (~7 mA per device, the reverse of the previous intervals). We concluded that the AD7943 is actually a 20,000-rad hard part, a value that is 5000 rad harder than that determined with the original high-dose-rate evaluation that did not include the interleaved annealing intervals.

In addition, a FASTRAD modeling (conducted by D. R. Roth in June 2013) of the radiation transport shield path length distribution from the as-flown or as-built geometry (with only the immediate deck added to the transceiver configuration; Fig. 8) shows that the median of 129,600 path lengths is 757 mil Al—almost twice the shielding as in the pre-CDR NOVICE analysis

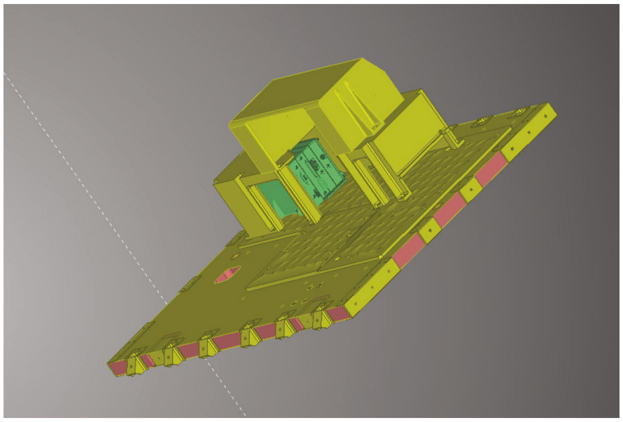

**Figure 8.** The June 2013 FASTRAD transport code analysis included just the transceiver subsystem and the deck on which it is mounted. The total mass in the simulation is 17 kg. The predicted maximum mission dose in the transceiver is 6 krad(Si).

mentioned above. Indeed, ~20% of the path lengths are greater than 1000 mil. The FASTRAD dose prediction with an RDM = ×2 for the mission is 6000 rad maximum or only ~30% of the AD7943 hardness determined in September 2013.

Much more shielding was used in the as-built configuration than was originally modeled. A factor of 3.33 (20,000 rad from September 2013 test hardness/6000 rad from June 2013 FASTRAD radiation transport simulation) × 800 days would mean a 2667-day mission or an ~5.1-year extension on the initial 2.2-year mission lifetime lasting until approximately November 2019.[6]

In contrast, extrapolating from the last two measured ERM data points in Fig. 7 to the 757 mil (19.2 mm) median depth of the FASTRAD simulation yields 5500 rad after 971 days of the mission. This approach yields a factor of 3.6 (20,000 rad test hardness/5500 rad ERM measurement), which multiplied by 971 days projects to a 3530-day (9.6-year) mission or an ~7.4-year extension on the initial 2.2-year baseline mission lasting until February 2022.[7]

To be conservative, the decision was to maintain the ×2 design margin on the mission TID (as in the FASTRAD simulation) because large solar events can still occur for the next 2 years during the declining activity of the solar maximum epoch and to project November 2019 as the end point dictated by the electronics radiation hardness. This conclusion is less restrictive than that of the propellant life but more restrictive than that from the decline in solar array output power for the extension of the Van Allen Probes mission.

R. Ecoffet[8] has addressed the overestimation of TID and the underestimation of shielding during the design phases of spacecraft development. He indicates that there are surprisingly few reports of satellite anomalies due to total dose failures of electronic components. This lack of total dose anomalies is due to excessive design margins in radiation environment models, radiation test procedures, component shielding estimates, and design safety margins in parts procurement. The most important contribution to the excessive shielding margin is situated in shielding calculations. Shielding has a strong impact on the dose level received, especially on the electron contribution to total dose. The main problem with shielding had been that it was difficult to account for complex mechanical structures, so the effective shielding thicknesses were systematically underestimated. Today, it is possible to run representative Monte Carlo simulations on complete satellite structures in a reasonable time (as discussed here for the transceiver), and this was done both during the design phase and after launch to model the exposure of the spacecraft electronics and RadFET dosimeters.

### Science Instrument Electronics Survey[9]

The six lists of electronics parts for the science instruments were reviewed in 2014. All devices were required to meet the 30-krad minimum total dose hardness requirement established by the program for the extended mission after review of the results of the 2013 spacecraft parts survey. In several cases, radiation-hardened parts replaced devices initially rejected by the Van Allen Probes parts control board.

The softest part, the AD822 operational amplifier in the electric fields and waves instrument, demonstrated 30 krad hardness when tested to the Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) program requirement in 2002. However, its actual hardness level is likely 40–50 krad because all DC parameters except the offset current annealed almost completely after 30 krad. The offset current was within the 10-pA specification after annealing. Even with an offset current greater than 10 pA, we would have derated the AD822 for such a small magnitude current that was not practically significant. The hardness level of the AD822 is at least twice as great as that of the AD7943 DAC in the spacecraft electronics discussed above.

## ANOMALY INVESTIGATIONS

Anomaly investigations are an important aspect of mission operations. The Van Allen Probes mission team anticipated that onboard radiation monitoring science and engineering sensors would provide key information to aid in these investigations.[10] Two major anomalies are discussed in this section.

### Solid-State Recorder Error Detection and Correction Scrubbing

One radiation-related anomaly was identified immediately after launch in 2012. The onboard error detection and correction (EDAC) scrubbing implemented in the solid-state recorder (SSR) hardware was compounding errors in memory when exposed to bursts of correct-

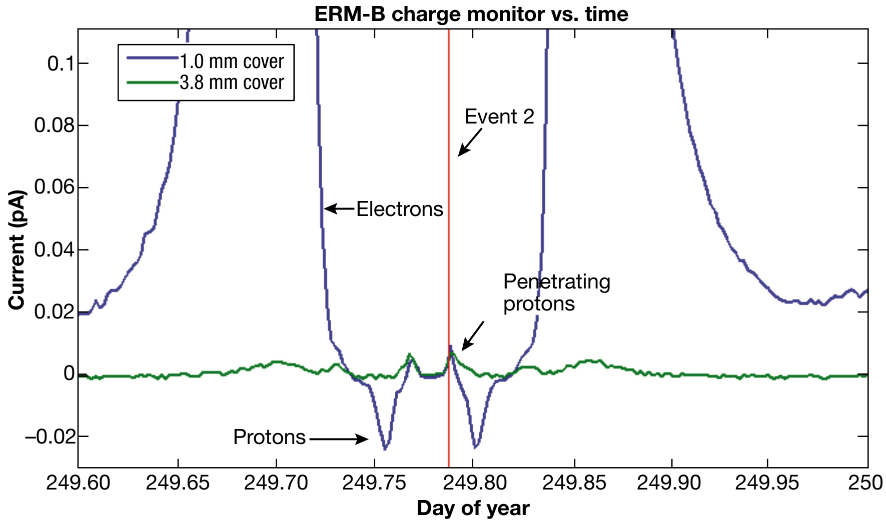


**Figure 9.** Plot of the current monitor data versus time for one orbit showing the correlation of an SSR memory error burst with penetrating protons observed just after launch in 2012. The vertical red line shows the occurrence of one error burst event. The proton high current peaks (plotted as negative currents in the figure) are adjacent to the error bursts in all investigated events.

able EDAC errors that were occurring as expected in the proton-flux-dominated region of the inner radiation belt environment. Initial attempts to increase the error scrub rate used in the onboard SSR memory appeared to exponentially increase the corrected error counts. An investigation was quickly undertaken to understand this phenomenon. Using breadboard hardware on the ground, it was demonstrated that the algorithm implemented in SSR static dynamic random access memory (SDRAM) had a timing issue with read and write cycles in the dynamic section of the memory that was only visible with multiple burst errors in a pattern that was not observed during prelaunch testing. The flight software team developed an alternative software-based error correction scheme and this was implemented in the command and data handling (C&DH) flight software for the Van Allen Probes mission. The updated software scrubs through the SSR data recorder memory and incorporates SDRAM mode register resets often during scrubbing. This significantly decreased the corrected error counts. The updated flight software was uploaded in October 2012 and has been effective in correcting EDAC errors in the data recorders on both spacecraft for the past 3 years of operation. The EDAC error rates are constantly monitored in spacecraft telemetry both for the SSR SDRAM and for the RAD750 processor SRAM.

The initial investigation into the memory scrubbing anomaly made use of the onboard ERM to demonstrate correlation between the peak intensity of penetrating protons and the error bursts (see Fig. 9). The radiation monitor is used on the Van Allen Probes mission both to rule out radiation as a culprit by demonstrating a benign environment and also to identify periods of high radiation activity around the spacecraft.

## RAD750 Processor Reset

Despite expectations that the Van Allen Probes spacecraft could be subjected to frequent radiation-induced resets, they have experienced autonomous resets on only two occasions during the first 2 years of uninterrupted spacecraft operations. In both instances, the spacecraft recovered autonomously and continued operations, working as designed, and the collection of science data was not interrupted. The first event occurred recently in the radio on spacecraft A, and the investigation into this firmware reset is ongoing.

The second also occurred recently in the spacecraft B RAD750 C&DH processor on day 2014-259 (16 September 2014). An instruction executed as part of a valid sequence of software calls was corrupted, most likely while residing in on-chip instruction cache, by a radiation event causing an "illegal instruction" exception. This caused a processor reset with automated recovery on board the spacecraft. This was a relatively benign reset in that mission elapsed time was maintained on the spacecraft, the data on the SSR were maintained, and instruments remained powered and sending data to the SSR. What was lost were time tag commands and instrument-stored buffer commands in the C&DH. Normal mission operations were

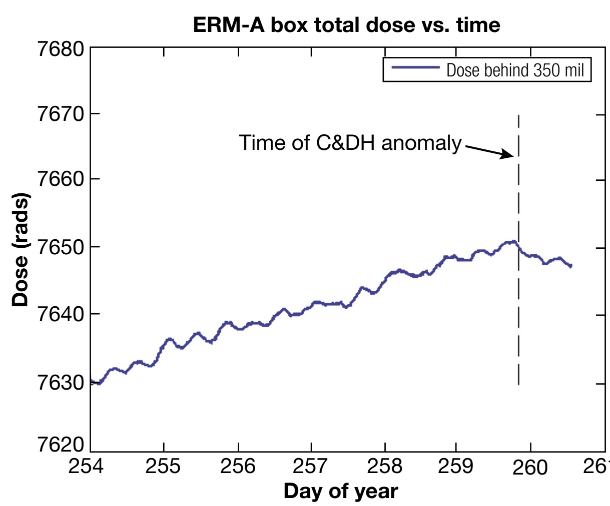


**Figure 10.** Dose versus time near the reset, showing no significant change in dose rate during the reset period.

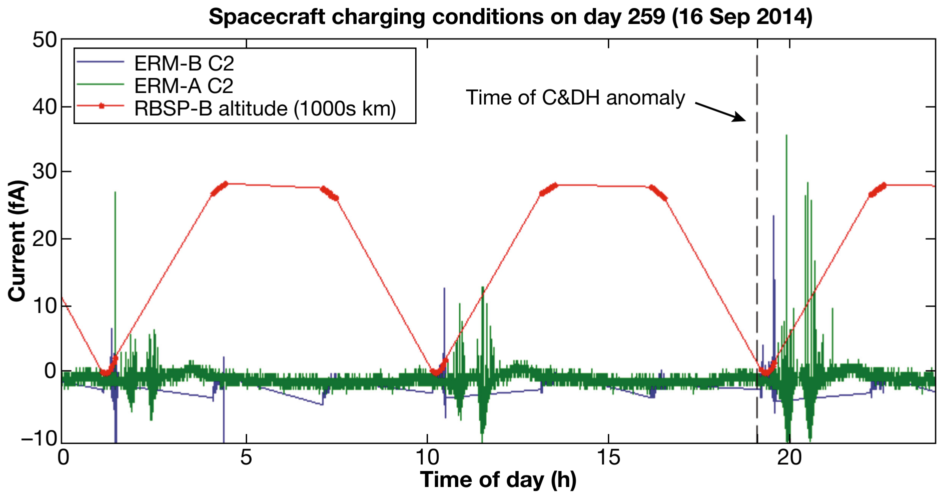


**Figure 11.** Charging currents in blue and green (femtoamps) and altitude in red (thousands of kilometers) with the same numerical values on the left ordinate versus time for day 259 reset.

recovered quickly, and lost commands were resent on the next contact.

The ERM has two types of sensors that monitor the radiation environment: (*i*) total dose and (*ii*) deep-dielectric charging. The ERM cannot directly sense and report an environmental increase in heavy ions of the type that typically cause single-event effects (SEEs), but it can detect penetrating protons that also cause SEEs if the RAD750 is sensitive to proton upset.

Although the C&DH anomaly occurred on Van Allen Probe B, the general space weather environment shown in Fig. 10 uses ERM-A data because ERM-B is currently set to a lower duty cycle in an effort to preserve its life throughout any extended mission.

The total dose plot for ERM-A (Fig. 10) shows no significant change in the dose rate throughout the reset period. Indeed, it exhibits some charge recombination after the reset. The key finding here is that the general trend represents an accumulation of only a few rads per day with no evidence of a sudden increase in dose rate from a solar storm.

The charging rate during this period was very low. Even the more enhanced levels observed during days 254–256 were nearly a factor of 30 down from the highest observed levels during the mission (~8 pA in the October 2012 event; see Fig. 5). The levels leading up to the C&DH anomaly are very small, suggesting that a deep dielectric discharge-induced anomaly is also highly unlikely.

Although the ERM is not designed to measure penetrating ions, Figs. 11 and 12 show transient spikes in the charge monitor data when the flux of >61 MeV protons is elevated, such as during certain passes through the inner proton belt. This response was validated by comparing our data to coincident data from the Aerospace RPS instrument (Fig. 12) that contains a >61-MeV proton particle counter for the March 2013 time frame. We also sometimes observe spike-like increased currents at higher altitudes when there is a significant solar particle flare (e.g., coronal mass ejection). Figure 11 shows high time-resolution charge monitor data from both spacecraft on 16 September 2014 along with the reported altitude for spacecraft B. The left-hand ordinate in the plots denotes both the charging current in femtoamps and the altitude in thousands of kilometers. The C&DH reset appears to

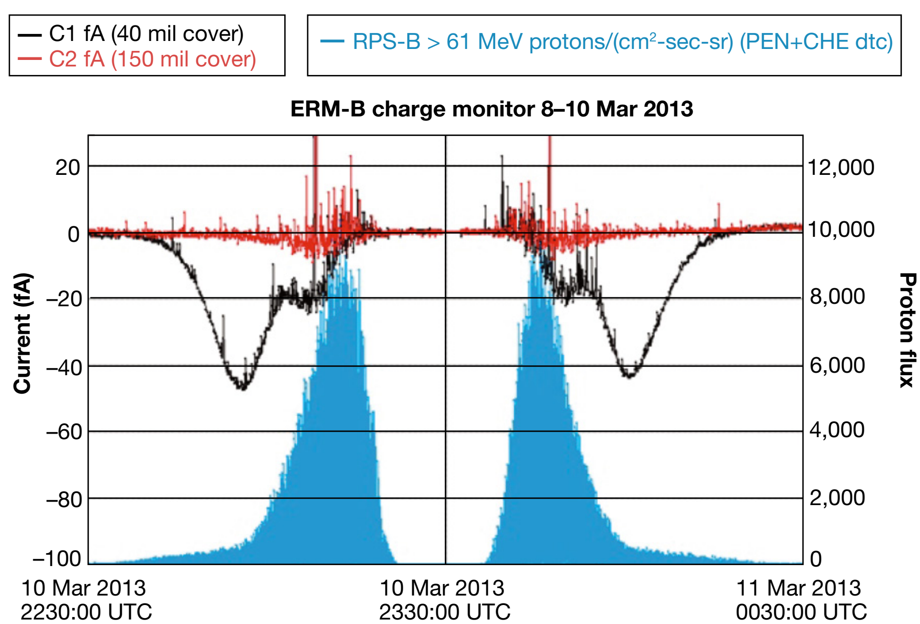


**Figure 12.** Correlation of the higher ERM-B charging currents from protons on monitors C1 and C2 with the Aerospace RPS proton flux data from March 2013 [right ordinate in p/(cm$^2$-sec-sr)]. Perigee occurs at the vertical line in the middle of the plot and is below the proton-dominated inner belt. (RPS data courtesy of Joe Mazur of Aerospace Corp.)

**Table 3.** Results of the RAD750 upset predictions from CREME96 and RPS proton data

| Environmental Conditions | Geomagnetic Shielding | SEE Rate per Device-Day | Days per Upset per Device | Van Allen Upset Every |
|---|---|---|---|---|
| HI solar min | Near Earth | $1.22 \times 10^{-4}$ | 8,197 | 11.2 years |
| HI solar min | Van Allen Probes (GTO) orbit | $9.54 \times 10^{-5}$ | 10,482 | 14.4 years |
| HI solar max | Near Earth | $4.05 \times 10^{-5}$ | 24,682 | 33.8 years |
| HI solar max | Van Allen Probes (GTO) orbit | $3.35 \times 10^{-5}$ | 29,835 | 40.9 years |
| HI worst week | Near Earth | $9.66 \times 10^{-4}$ | 1,035 | 1.42 years |
| HI worst week | Van Allen Probes (GTO) orbit | $9.70 \times 10^{-4}$ | 1,031 | 1.41 years |
| Protons | Van Allen Probes (GTO) orbit | $4.52 \times 10^{-4}$ to $4.52 \times 10^{-3}$ | 220–2,200 | 0.30–3.01 years 110–1,100 days |

All data are behind 500 mil aluminum shielding for the IEM. The Van Allen Probes' orbits are essentially GTO. HI, Heavy ion.

have occurred about 14 min before perigee, which corresponds to an altitude in the inner proton belt, and the ERM data show that this particular pass through the belt was more "active" because of the magnetic field orientation. BAE Systems' SEE testing did observe a low linear energy threshold for the RAD750[11] in heavy ion testing, so a proton can cause an upset in the C&DH subsystem.

Figure 12 shows a correlation of the ERM-B charging currents (left ordinate) at two shield depths and the proton flux greater than 61 MeV (right ordinate) from the Aerospace RPS science instrument during March 2013. Near perigee, the mean proton flux is 31,400 protons/cm$^2$-sec (2π steradians × the mean of 5000 protons/cm$^2$-sec-sr in the symmetric plots) for a cumulative exposure time of 40 min per orbit due to the two traversals per orbit. Because there are 2.67 orbits per day when the orbit is properly aligned with the geomagnetic field, we estimate 4E8 protons/cm$^2$-day >61 MeV are available to cause proton-induced upsets. Even if only one in 10,000 such protons creates a proton–silicon nuclear interaction with a heavy ion recoil fragment whose ionization can cause an SEE, there are plenty of opportunities on such active days for an upset with the right recoil fragment trajectory.

## Calculation of Upset Rates to Compare to Anomaly Data

The upset rates for the RAD750 32-bit radiation-hardened microprocessor are calculated from the BAE heavy ion and proton single-event data in Ref. 11, the individual heavy ion Weibull fits to both the 133-MHz single-event transients and cache storage upsets in Ref. 12, and the typical Aerospace Van Allen Probes RPS proton flux data near perigee (Fig. 12).

The heavy ion upset rates are from the CREME96 computer code at solar minimum quiet, solar maximum quiet, and worst week epochs behind 500 mil aluminum shielding, representative of the integrated electronics module (IEM) on the spacecraft, for both the near-Earth space environment and Van Allen Probes orbit with its geomagnetic shielding[13]—a total of six different combinations.

The proton upset rates are calculated from the proton flux for the near-perigee environment (where the reset occurred) in Fig. 12 and the BAE proton upset data in Ref. 11. The results of these calculations are shown in Table 3.

Some additional information is required to explain the proton upset calculation.

1. Only protons with energies greater than 55 MeV can penetrate to the C&DH behind the 500-mil-Al walls of the IEM. The proton energy threshold for SEE is about 20 MeV[11] for the various test modes of the RAD750 (pseudo-static to fast Fourier transform). Thus, protons in the Van Allen Probes environment must have energies of 75 MeV or more to both penetrate to the C&DH card and initiate a proton-induced upset.
2. Figure 12 presents environmental data for proton fluxes greater than 61 MeV; data from Ref. 11 show that the range of the RAD750 proton upset cross section above 75 MeV is about $2 \times 10^{-12}$ to $2 \times 10^{-11}$ cm$^2$ per device depending on the static or dynamic processor mode. We will conservatively use the >61-MeV proton data for the >75-MeV upset rate.
3. Figure 12 gives a mean value of about 5000 protons/(cm$^2$-sec-sr) for the instantaneous proton flux near perigee. There are 2π steradians for the forward or top direction or a flux equal to $3.14 \times 10^4$ protons/cm$^2$-sec in the appropriate units. There are two or three orbits per day through perigee (a mean of 2.67 orbits per day for the 9-h orbit). The conservative figure of three orbits is used. Figure 12 also shows that ERM-B is in the proton flux region near perigee for 40 min (two traversals per orbit) or 120 min per day for three orbits.

Thus, the RAD750 upset rate is calculated as

$3.14 \times 10^4$ p/cm$^2$-sec × 60 sec/minute × 120 minutes/day × [$2 \times 10^{-12}$ to $2 \times 10^{-11}$] cm$^2$ per device = $4.52 \times 10^{-4}$ to $4.52 \times 10^{-3}$ upsets/device-day or one upset every 220–2200 days per device.

Because there are two IEMs or RAD750s on the Van Allen Probes, the prediction becomes one upset every 110–1100 days. The reset was seen after 748 days.

BAE's testing showed statistically that protons induced "data hang" or necessitated reset in only 3.5% of the single-event upsets; however, that does not mean that one of the initial upsets cannot cause a reset. The reset type may also be dependent on the Van Allen Probes operation dynamics of the RAD750, which are unlikely to be the same as any of the BAE test configurations.

Dose, dose rate, and spacecraft charging phenomena are ruled out from the ERM environmental data, which did not show anything extreme and were subdued during the appropriate time frame. Only the worst-week heavy ion environment (used in Ref. 13 for conservatism) gives upset rates of approximately one every 1.5 years, comparable to the proton upset rates shown in Table 3. However, near perigee, any solar effects are suppressed by the geomagnetic field (Fig. 6), and the ERM showed no large increases in current (picoamps range) indicative of a worst-week solar disturbance (Figs. 10 and 11).

## CONCLUSION FOR THE RAD750 RESET

The most likely cause of the C&DH reset on 16 September 2014 was a single-event upset due to a high-energy trapped proton. Table 3 shows that there can be an upset due to trapped protons every 110–1100 days on the Van Allen Probes mission. The C&DH RAD750 on spacecraft B experienced a reset on mission day 748 after almost 2000 orbits and 4000 traversals of the proton environment near perigee. The alignment of the orbit with the geomagnetic field increased the flux of high-energy protons and a heavy ion fragment (e.g., magnesium) from the proton–silicon nucleus collision deposited its energy in a sensitive region of the RAD750.

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