Twenty-Years of Radiation Measurements in Low Earth Orbit: What Have We Learned?

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Radiation Measurements During Manned Missions—What Can We Learn?

• Efforts under way to improve and/or develop new trapped radiation models
  ◦ NASA’s “Living With a Star” (LWS) program
  ◦ USAF Phillips Lab
  ◦ ESA’s TREND program
• On-going trapped radiation modeling activity include empirical, semi-empirical, and physics-based approaches
• Space missions being planned to answer important trapped radiation belt science questions
  ◦ NASA’s LWS “Geospace Mission” effort
• Until new data sets available, modelers and theoreticians continuously looking for existing data
• What can be learned from radiation measurements during the past 20 years of Shuttle, Mir, and ISS missions to improve the understanding or models of the trapped radiation environment
Trapped Radiation Belt Monitoring During Manned Space Flight--Synopsis

- Since the advent of manned space flight 40 years ago, scientists and health physicists have monitored the local low-Earth orbit (LEO) space radiation environment inside and outside the spacecraft in order to understand and quantify the exposure received by human crews.
- First 25 years, monitoring typically performed with simple omni-directional, integrating passive radiation absorbed dose detectors similar to those used for radiation protection monitoring of radiation protection workers.
- Past 15 years, more advanced active instruments have been introduced which provide time-resolved measurements, some information about the physical properties of the radiation, and in some cases improved directionality information.
- Measurement periods in a particular LEO region range from relative “snapshots” of just a few days to 1.5 solar cycles.
- These measurements comprise an important database of the LEO space radiation environment:
  - Covering nearly 9,000 days in orbit
  - More than three solar cycles
  - 200-600 km
  - Magnetic latitudes up to approximately 75°.
Trapped Radiation Belt Monitoring During Manned Space Flight—What Can We Learn?

- While this is an abundant set of data, much of it cannot be used directly to study or model the geomagnetically trapped radiation belts in the atmospheric cutoff region
  - Measurements frequently do not include enough physical information (e.g., energy, particle type, arrival direction) or appropriate correlative measurements (e.g., local magnetic field strength and orientation, atmospheric density, plasma waves etc.)
  - Location and orientation of the detectors/instrument, as well as the orbital parameters, launch date and mission duration, are driven by considerations other than monitoring the space radiation environment

- What can we learn about the physics of the trapped radiation belts in the atmospheric cutoff region from these measurements?
  - Temporal changes in the location of the geomagnetic trapping region (i.e., SAA)
  - Formation and decay of additional pseudo-stable trapping regions
  - Local anisotropy in direction of trapped proton flux
  - Control of trapped proton flux by the Earth’s tenuous atmosphere
Temporal Changes in the Location of the South Atlantic Anomaly (SAA)

SAA: Protons > 30 MeV
Temporal Changes in the Location of the South Atlantic Anomaly

Drift Rate of the South Atlantic Anomaly

- RME-III–Shuttle (flux rate)
- RME-III–Shuttle (dose rate)
- TEPC–Shuttle (Badhwar et. al. 1996, 1997)
- TEPC–Mir (Badhwar 1997)
Temporal Decay of Pseudo-stable Additional Radiation Belts

STS-39
RME-III Measured Dose Rate
(uGy / min.)
28 Apr – 06 May 1991

Inclination = 57 deg.
Altitude ~ 258 km.

Golightly, et. al. (1994)
Temporal Decay of Pseudo-stable Additional Radiation Belts

UoSAT-3 CREDO Monthly Average Count Rate
Counts Above Background (98.7° / 800 km)
Trapped Proton Dose Rate—Impact of Flux Anisotropy

Trapped Proton East/West Ratio
STS-60 SAA Pass Data—Descending Node

- Longitude (°E)
- TEPC Dose Rate (nGy/m)
- Dose Rate Ratio

YC3 Pass (Badhwar et. al. 1996)
YC4 Pass (Badhwar et. al. 1996)
YC Pass' E/W Ratio
Avg 'YC Pass' E/W Ratio
## Summary of Trapped Proton East-West Ratio Data

<table>
<thead>
<tr>
<th>East/West Ratio</th>
<th>Mission/Spacecraft</th>
<th>Epoch/Date</th>
<th>Average Altitude (km)</th>
<th>Inclination (°)</th>
<th>Instrument &amp; Location</th>
<th>Omni/Directional</th>
<th>Directional Absorber/Shield</th>
<th>Parameter Measured</th>
<th>Energy Range</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>1.85 ± 0.09</td>
<td>STS-60</td>
<td>07-Feb-94</td>
<td>352</td>
<td>57.0</td>
<td>TEPC--Shuttle DLOC 2</td>
<td>omni</td>
<td>airlock shadowing of DLOC 2 location</td>
<td>SAA absorbed dose rate corrected for GCR</td>
<td>&gt;30 MeV, 56 MeVeff</td>
<td>Golightly, Badhwar et. al. 1997</td>
</tr>
<tr>
<td>1.9</td>
<td>STS-65</td>
<td>16-Jul-94</td>
<td>296</td>
<td>28.5</td>
<td>TLD--Shuttle DLOC 5/6 TLD--Shuttle DLOC 2/3</td>
<td>omni</td>
<td>opposite side of symmetrically shielded vehicle</td>
<td>absorbed dose, GCR corrected</td>
<td>&gt;32 MeV, 58 MeVeff</td>
<td>Badhwar et. al. 1998</td>
</tr>
<tr>
<td>~1.6</td>
<td>STS-63</td>
<td>07-Feb-95</td>
<td>394</td>
<td>51.6</td>
<td>TEPC--Shuttle DLOC 2</td>
<td>omni</td>
<td>airlock shadowing of DLOC 2 location</td>
<td>absorbed dose</td>
<td>Badhwar et. al. 1997</td>
<td></td>
</tr>
<tr>
<td>~1.86</td>
<td>STS-84</td>
<td>19-May-97</td>
<td>341</td>
<td>51.6</td>
<td>RRMD--SpaceHab Ceiling</td>
<td>directional</td>
<td>N/A</td>
<td>particle flux rate vs magnetic azimuth</td>
<td>8.4~27 MeV</td>
<td>Golightly, Sakaguchi et. al. 1999</td>
</tr>
<tr>
<td>2.7</td>
<td>STS-94</td>
<td>09-Jul-97</td>
<td>341</td>
<td>28.5</td>
<td>TEPC--Shuttle DLOC 2</td>
<td>omni</td>
<td>airlock shadowing of DLOC 2 location</td>
<td>absorbed dose rate</td>
<td>Badhwar 2000</td>
<td></td>
</tr>
<tr>
<td>2.18</td>
<td>ISS</td>
<td>08 Mar-13 Jun 2001</td>
<td>394</td>
<td>51.6</td>
<td>R-16 ИР2S detector, Service Module panel 327</td>
<td>omni</td>
<td>Mir intrinsic shielding (XPOP:LVLH attitude)</td>
<td>accumulated absorbed dose, GCR corrected</td>
<td>Golightly</td>
<td></td>
</tr>
<tr>
<td>1.68</td>
<td>ISS</td>
<td>08 Mar-13 Jun 2001</td>
<td>394</td>
<td>51.6</td>
<td>R-16 ИР2S detector, Service Module panel 327</td>
<td>omni</td>
<td>Mir intrinsic shielding (XPOP:LVLH attitude)</td>
<td>accumulated absorbed dose, GCR corrected</td>
<td>Golightly</td>
<td></td>
</tr>
<tr>
<td>0.09-16.66</td>
<td>Mir</td>
<td>late 1994-1996</td>
<td>400</td>
<td>51.6</td>
<td>REM--external surface of Mir</td>
<td>2π</td>
<td>Mir core module</td>
<td>particle flux/32 s</td>
<td>&gt;30 MeV</td>
<td>Buhler et. al. 1996</td>
</tr>
</tbody>
</table>
Trapped Proton East-West Ratio—Variation with Altitude

SAA Trapped Proton East-West Effect

Altitude (km)

East/West Ratio

- Badhwar et. al. 1997 (data only)
- Badhwar et. al. 1997
- Badhwar et. al. 1998
- Sakaguchi et. al. (data only)
- Badhwar 2000
- Buhler et. al. 1996 (>30 MeV)
- Golightly
Temporal Decay of Pseudostable Additional Radiation Belts

- Mar 1991 Event—Characterization from UoSAT-3 Data
  - 98.7° inclination / 800 km altitude
  - CREDO background count rate—count rate corrected for nominal contributions from SAA and GCR
  - Fit to background count rate $2.2 < L < 2.4$ data
    - $J(2.2 < L < 2.4) = 1761 e^{-t/5.1}$
    - $(DF \ adj \ r^2 = 0.8027)$
    - $t =$ months since belt formation
    - $J =$ counts/day
  - Flux rate $e$-folding time = 5.1 months
  - Flux rate enhancement ($t = 0$) relative to background = $x \ 10.5$
  - Flux rate enhancement ($t = 0$) relative to nominal SAA flux = 21.4%
Trapped Proton Flux in Low-Earth Orbit—A Function of Atmospheric Density

Golightly, et. al. (1994)
Trapped Proton Flux in Low-Earth Orbit—A Function of Atmospheric Density

- Trapped proton exposure inside the Space Shuttle derived from TLD measurements over 1.5 solar cycles
  - TLD absorbed dose at fixed monitoring locations corrected for GCR background
  - Atmospheric density computed for flux-weighted average altitude through SAA
- Trapped proton exposure well modeled as a power-law function of atmospheric density: \( \text{Daily Dose Rate (} \mu\text{Gy} \cdot \text{d}^{-1} \text{)} = e^{a} \cdot \rho^{b} \)

Table 1: Fit parameters and degree-of-freedom adjusted \( r^2 \) for trapped proton dose rate at four locations inside the Space Shuttle for 28.5° inclination missions. Thermospheric temperature capped at 938°K.

<table>
<thead>
<tr>
<th>PRD 1</th>
<th>PRDs 2 &amp; 3 AVERAGED</th>
<th>PRD 4</th>
<th>PRDs 5 &amp; 6 AVERAGED</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF ADJ ( r^2 )</td>
<td>( a )</td>
<td>( b )</td>
<td>DF ADJ ( r^2 )</td>
</tr>
<tr>
<td>0.8890</td>
<td>-14.26</td>
<td>-0.7220</td>
<td>0.9359</td>
</tr>
<tr>
<td>MOST HEAVILY SHIELDED</td>
<td>LEAST SHIELDED</td>
<td>AVERAGE ATTITUDE EFFECT</td>
<td>MEDIUM SHIELDED</td>
</tr>
</tbody>
</table>

Table 2: Fit parameters and degree-of-freedom adjusted \( r^2 \) for trapped proton dose rate at four locations inside the Space Shuttle for 57° inclination missions. Thermospheric temperature capped at 975°K.

<table>
<thead>
<tr>
<th>PRD 1</th>
<th>PRDs 2 &amp; 3 AVERAGED</th>
<th>PRD 4</th>
<th>PRDs 5 &amp; 6 AVERAGED</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF ADJ ( r^2 )</td>
<td>( a )</td>
<td>( b )</td>
<td>DF ADJ ( r^2 )</td>
</tr>
<tr>
<td>0.8915</td>
<td>-16.26</td>
<td>-0.7964</td>
<td>0.9192</td>
</tr>
<tr>
<td>MOST HEAVILY SHIELDED</td>
<td>LEAST SHIELDED</td>
<td>AVERAGE ATTITUDE EFFECT</td>
<td>MEDIUM SHIELDED</td>
</tr>
</tbody>
</table>
Solar Cycle Modulation of Trapped Proton Flux in Low Earth Orbit

UoSAT-3 Daily Accumulated CREDO Channel 1 Counts in SAA Region

- UoSAT-3 CREDO Channel 1 (Dyer 1998)
- Fourier Data Fit
Solar Cycle Modulation of Trapped Proton Flux in Low Earth Orbit

- Solar Cycle Modulation of Low-Altitude Trapped Proton Flux—Characterization from UoSAT-3 Data
  - 98.7° inclination / 800 km altitude
  - CREDO channel 1 (low-LET particles)
  - Count rate from SAA trapped protons
    - corrected for GCR
    - \( J(\text{channel 1}) = 9477 - 937\cos(t) - 979\sin(t) \)
      
      \( (DF \ adj \ r^2 = 0.7698) \)
    - \( t = \) date (year)
    - \( J = \) counts/day
  - Maximum flux (solar minimum): Jun 1997
  - Solar cycle modulation (ratio of solar maximum to minimum flux): 1.33
  - Solar cycle phase lag
    - smoothed monthly international sunspot index (RI)
    - Solar cycle 22 activity maximum: Jul 1989 \( \Rightarrow + 2.3 \) y to SAA flux minimum
    - Solar cycle 23 activity minimum: Oct 1996 \( \Rightarrow + 0.67 \) y to SAA flux maximum
AP-8/JSC Model Comparison

Trapped Proton Dose Ratio (Solar Min/Solar Max)

Altitude/(km)

DLOC 1

28.5° Inclination

57° Inclination

DLOC 2&3 Avg

28.5° Inclination

57° Inclination

AP-8/IGRF65 or USGS70

JSC

Parsignault & Holeman
1964/1969 55-MeV Flux Ratio

Parsignault & Holeman
1976/1969 55-MeV Flux Ratio
Radiation Measurements During Manned Missions—Impact on Exposure Modeling

Crew Exposure Projection Accuracy

<table>
<thead>
<tr>
<th>Time</th>
<th>Exposure Projection Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981-1986</td>
<td>23 missions</td>
</tr>
<tr>
<td>1987-1991</td>
<td>18 missions</td>
</tr>
<tr>
<td>1992-1996</td>
<td>35 missions</td>
</tr>
<tr>
<td>1997-2001</td>
<td>23 missions</td>
</tr>
</tbody>
</table>

Solar Maximum

Solar Minimum
Radiation Measurements During Manned Missions—What Have We Learned?

- The location of the South Atlantic Anomaly is drifting in the geocentric coordinate system
  - approximately 0.33°/y westward drift
  - evidence for a 0.07°/y northward drift component
- Observation of the formation and decay of a pseudo-stable additional radiation belt following the March 1991 solar particle event and geomagnetic storm
  - estimated decay e-folding time of approximately 5 months
- Observation of a local geomagnetic east-west trapped proton exposure anisotropy
  - altitude-dependent east-west flux ratio
  - estimated to be in the range of 1.6-3.3
- Trapped proton exposure in low-Earth orbit can be reasonably modeled as a power-law function of atmospheric density in the SAA region
  - best correlations obtained when the exospheric temperature dependence saturates at 938-975°K
- Actual modulation of trapped proton exposure in LEO is less than predicted by the AP8 model.
Many more individuals than can be listed here have contributed over the past 2 decades to the success of radiation measurements aboard U.S. manned space missions. Among the more deserving of recognition include

- Omar Baltaji
- Lorraine Benevides
- Mark Bowman
- Dr. Les Braby
- Terry Byers
- Bernard Cash
- Dr. Tom Conroy
- Alan Dickey
- Robert Dunn
- Joel Flanders
- Frank Gibbons
- Alva Hardy
- Ken Hardy
- Dr. William Quam,
- Dr. Vladislav Petrov (IBMP),
- Robert Richmond
- Fadi Riman.


References (cont.)


