

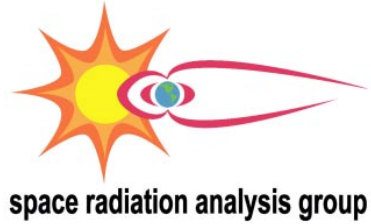
Twenty-Years of Radiation Measurements in Low Earth Orbit: What Have We Learned?

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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



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Trapped Radiation Belt Monitoring During Manned Space Flight--Synopsis

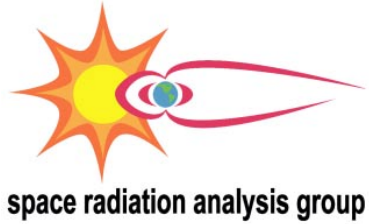
- Since the advent of manned space flight 40 years ago, scientists and health physicists have monitored the local low-Earth orbit (LEO) space radiation environment inside and outside the spacecraft in order to understand and quantify the exposure received by human crews
- First 25 years, monitoring typically 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°.



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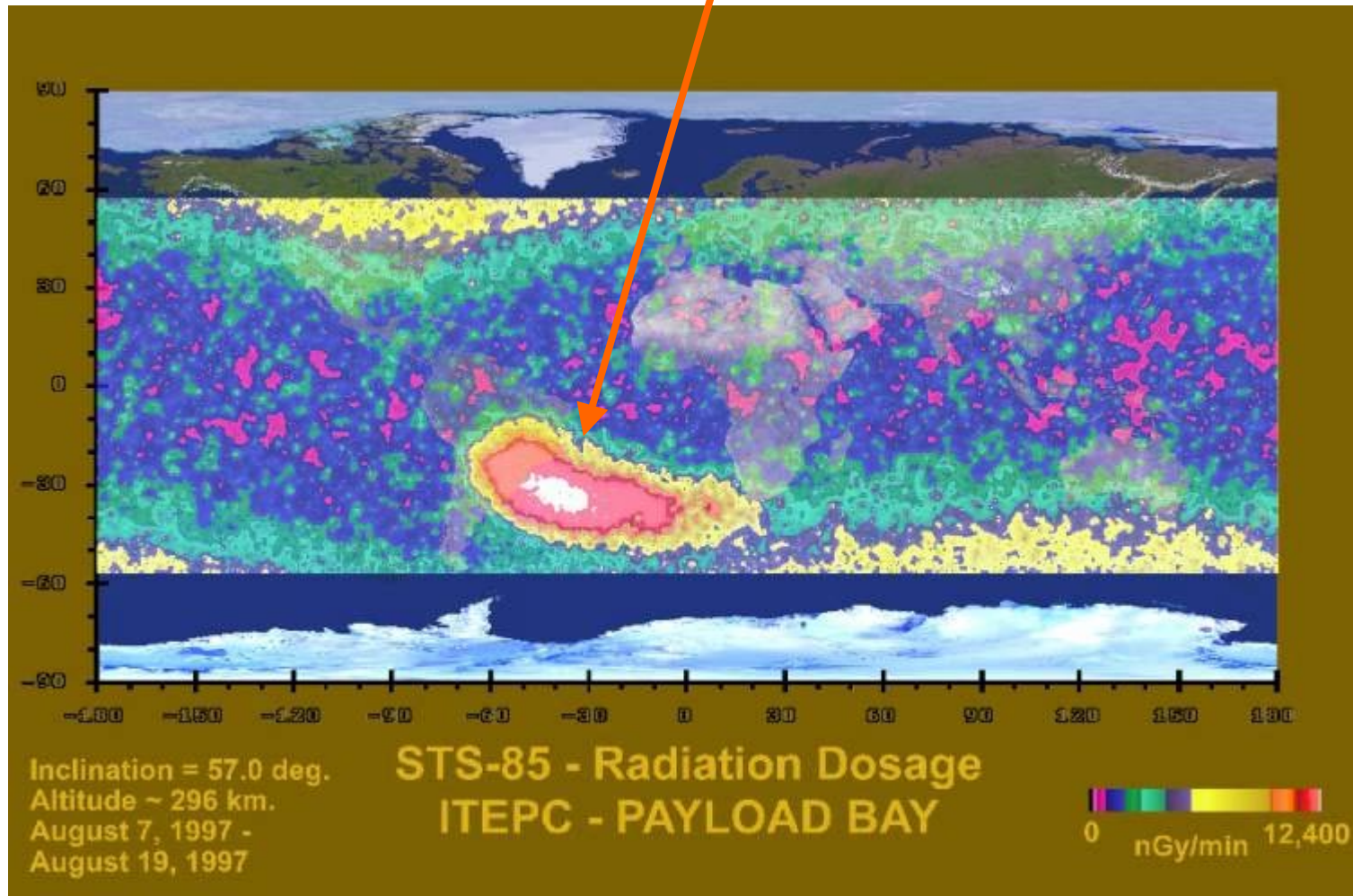
Trapped Radiation Belt Monitoring During Manned Space Flight—What Can We Learn?

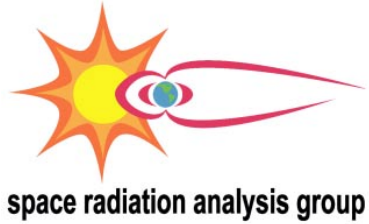
- While this is an abundant set of data, much of it cannot be used directly to study or model the geomagnetically trapped radiation belts in the atmospheric cutoff region
 - < Measurements frequently do not include enough physical information (e.g., energy, particle type, arrival direction) or appropriate 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)

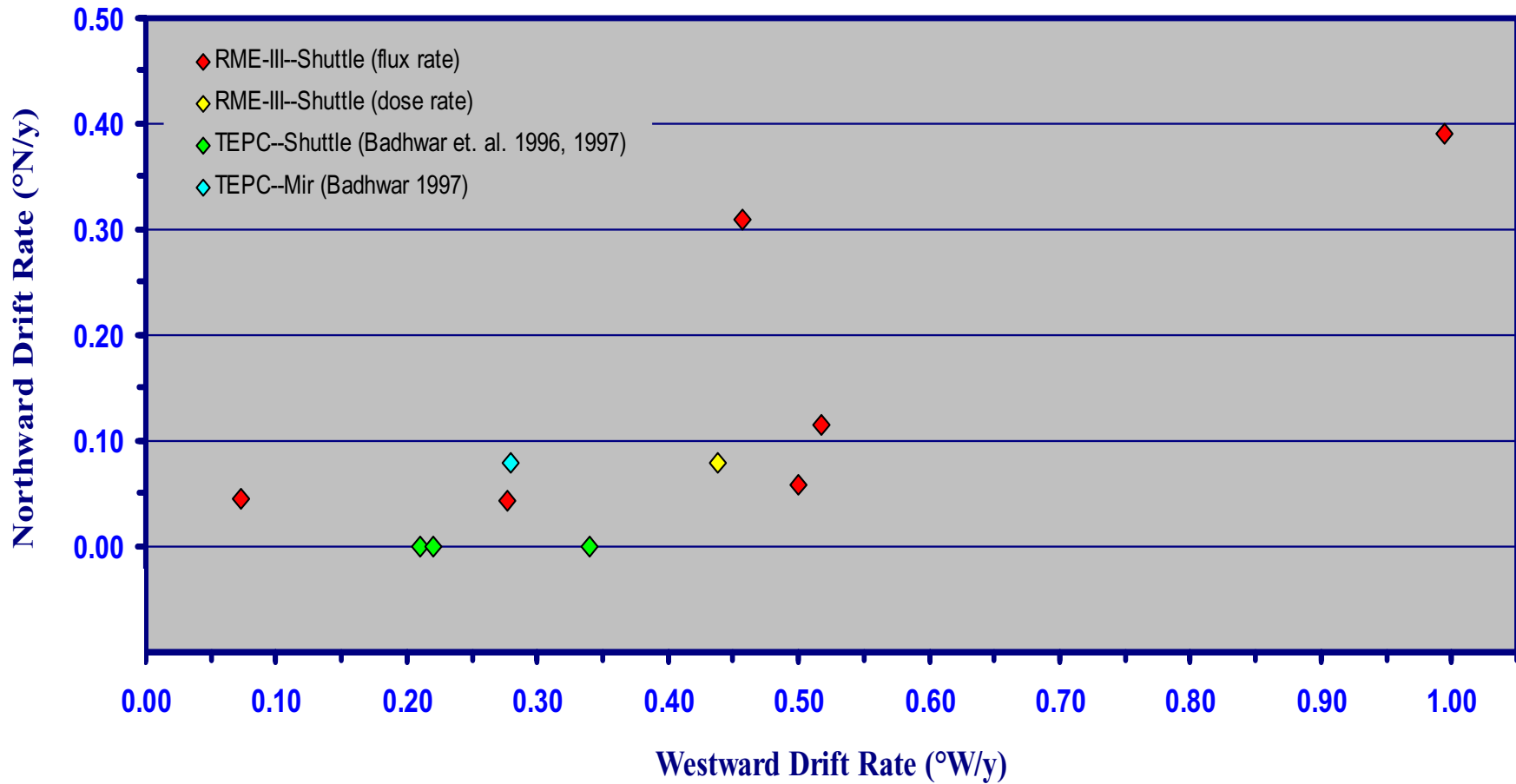
SAA: Protons > 30 MeV

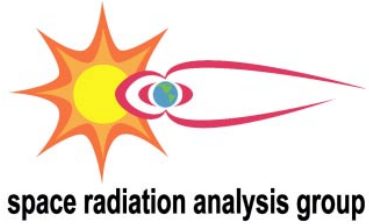




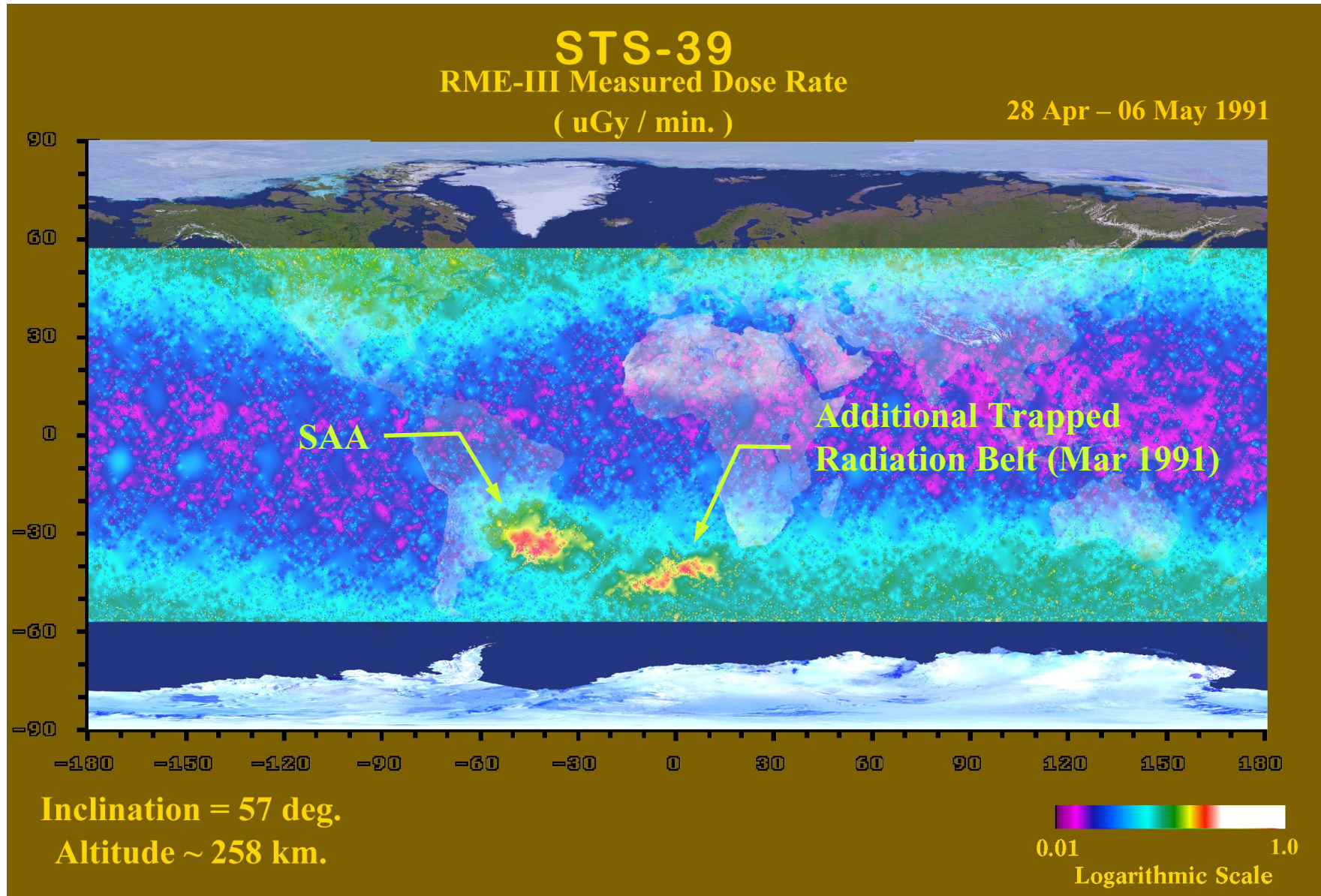
Temporal Changes in the Location of the South Atlantic Anomaly

Drift Rate of the South Atlantic Anomaly

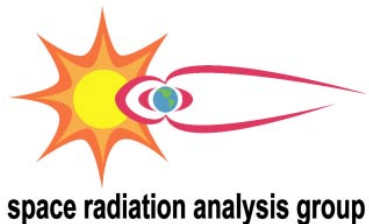




Temporal Decay of Pseudo-stable Additional Radiation Belts

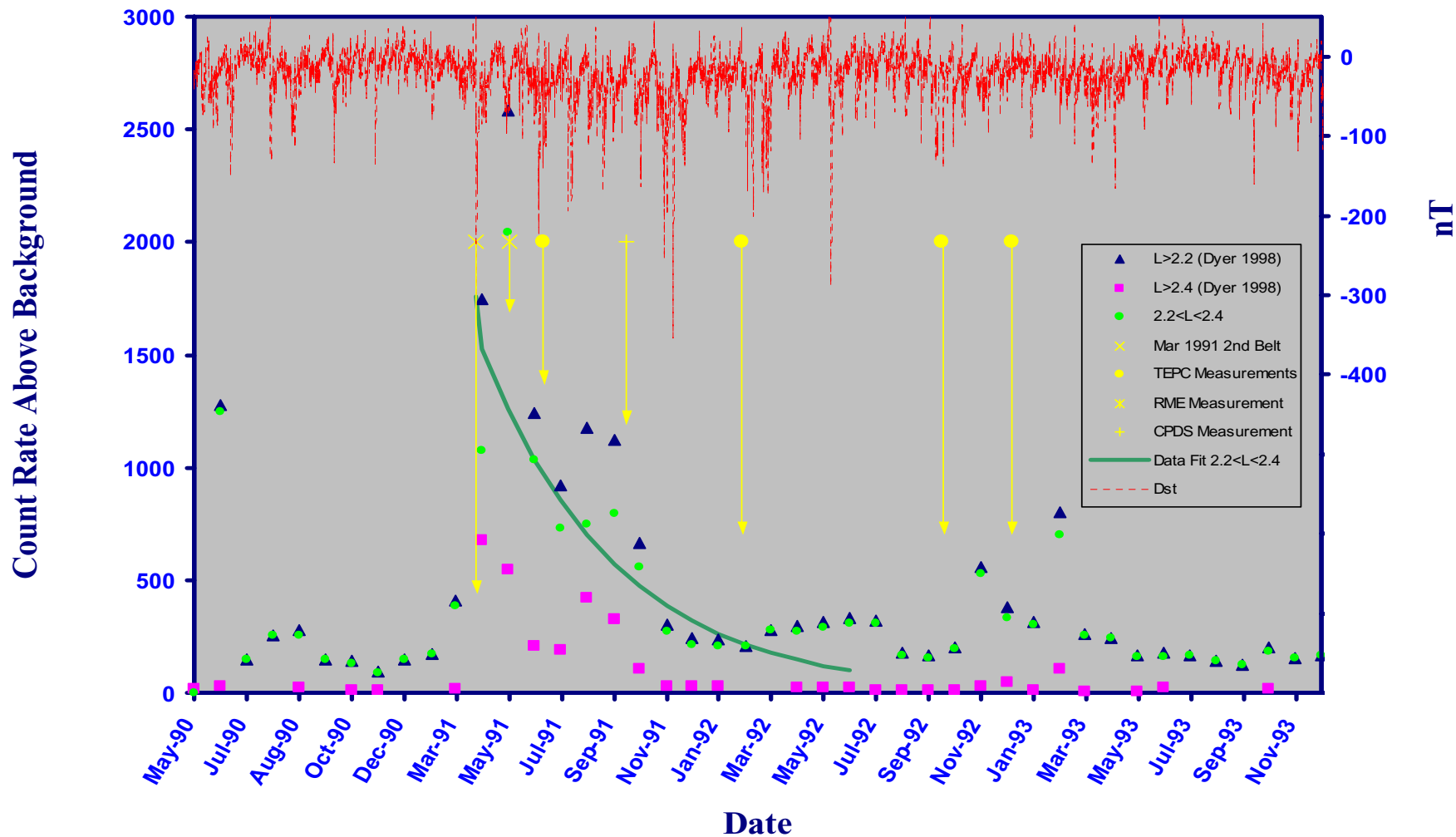


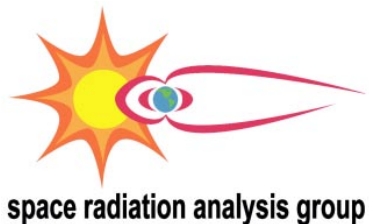
Golightly, et. al. (1994)



Temporal Decay of Pseudo-stable Additional Radiation Belts

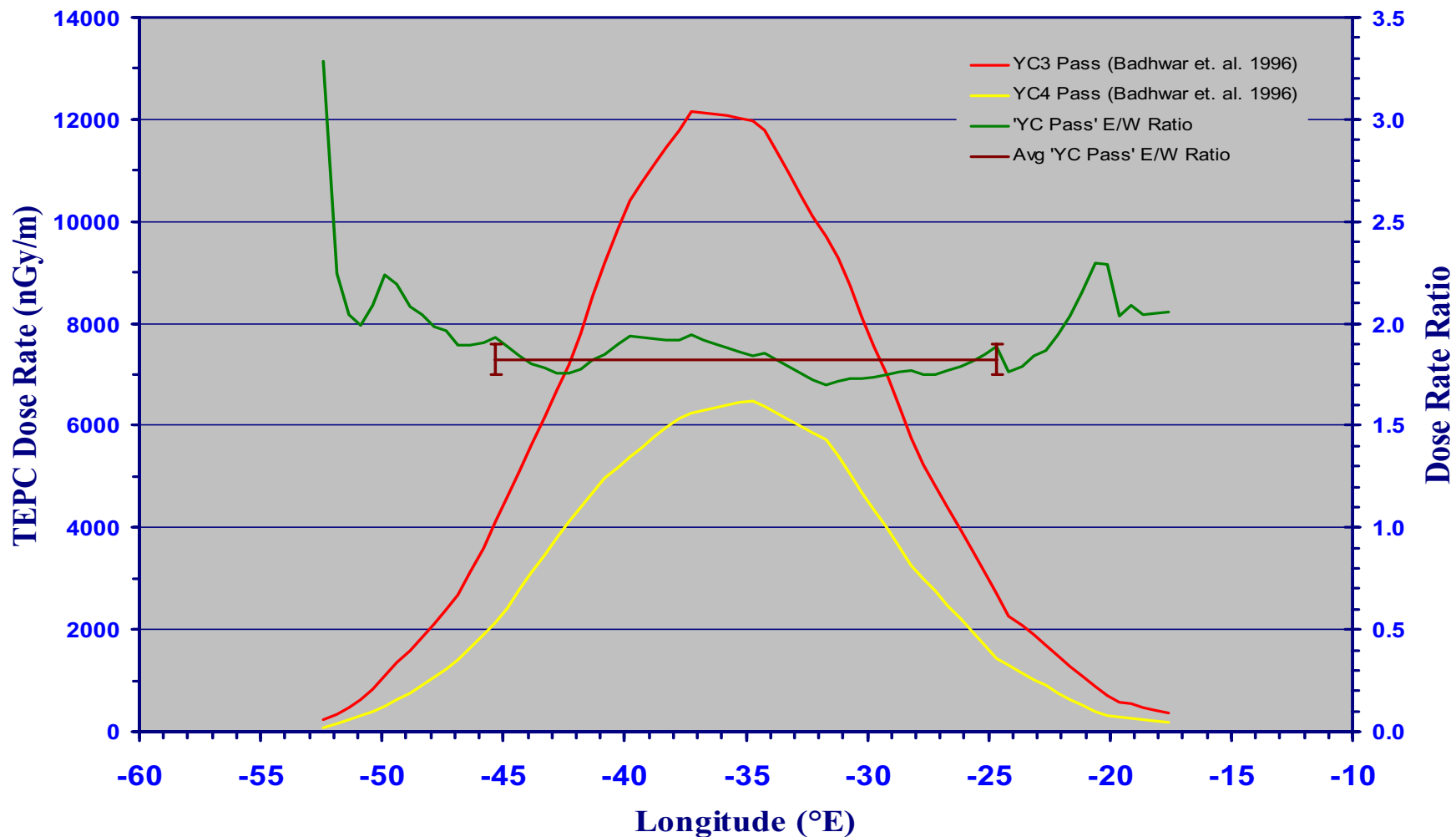
UoSAT-3 CREDO Monthly Average Count Rate Counts Above Background (98.7° / 800 km)





Trapped Proton Dose Rate—Impact of Flux Anisotropy

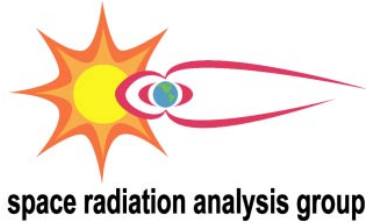
Trapped Proton East/West Ratio STS-60 SAA Pass Data--Descending Node





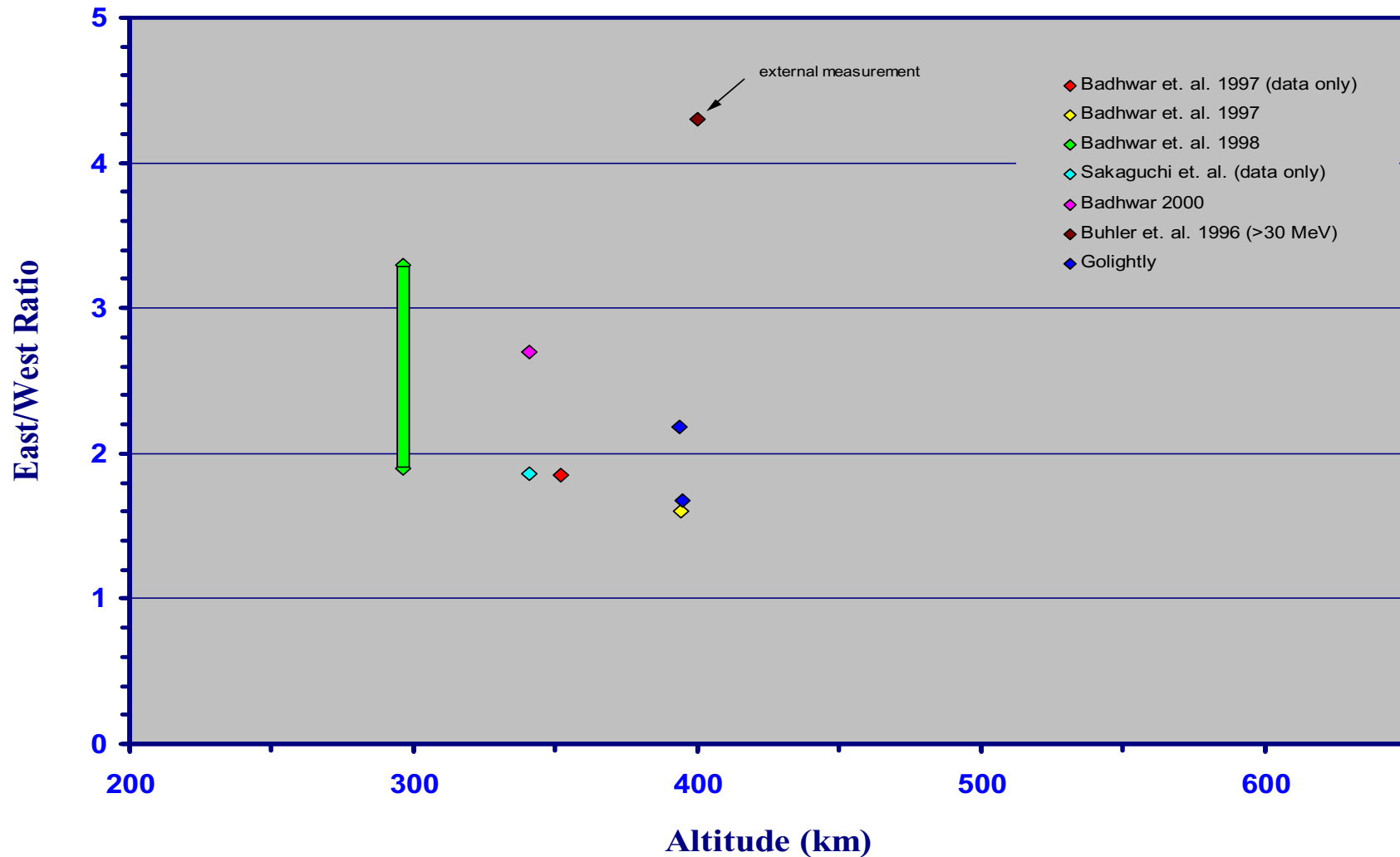
Summary of Trapped Proton East-West Ratio Data

East/West Ratio	Mission/Spacecraft	Epoch/Date	Average Altitude (km)	Inclination (°)	Instrument & Location	Omni/Directional	Directional Absorber/Shield	Parameter Measured	Energy Range	Reference
1.85 ± 0.09	STS-60	07-Feb-94	352	57.0	TEPC--Shuttle DLOC 2	omni	airlock shadowing of DLOC 2 location	SAA absorbed dose rate corrected for GCR		Golightly, Badhwar <i>et. al.</i> 1997
1.9 ----- 3.3	STS-65	16-Jul-94	296	28.5	TLD--Shuttle DLOC 5/6 ----- TLD--Shuttle DLOC 2/3	omni	opposite side of symmetrically shielded vehicle	absorbed dose, GCR corrected	>30 MeV, 56 MeVeff ----- >32 MeV, 58 MeVeff	Badhwar <i>et. al.</i> 1998
~1.6	STS-63	07-Feb-95	394	51.6	TEPC--Shuttle DLOC 2		airlock shadowing of DLOC 2 location	absorbed dose		Badhwar <i>et. al.</i> 1997
~1.86	STS-84	19-May-97	341	51.6	RRMD--SpaceHab Ceiling	directional	N/A	particle flux rate vs magnetic azimuth	8.4-~27 MeV	Golightly, Sakaguchi <i>et. al.</i> 1999
2.7	STS-94	09-Jul-97	341	28.5	TEPC--Shuttle DLOC 2	omni	airlock shadowing of DLOC 2 location	absorbed dose rate		Badhwar 2000
2.18 ----- 1.68	ISS	08 Mar-13 Jun 2001 ----- 23 May-06 Jul 2001	394 ----- 395	51.6	R-16 IP2S detector, Service Module panel 327	omni	Mir intrinsic shielding (XPOP:LVLH attitude)	accumulated absorbed dose, GCR corrected		Golightly
0.09-16.66	Mir	late 1994-1996	400	51.6	REM--external surface of Mir	2π	Mir core module	particle flux/32 s	>30 MeV	Buhler <i>et. al.</i> 1996



Trapped Proton East-West Ratio— Variation with Altitude

SAA Trapped Proton East-West Effect

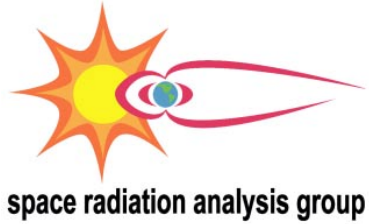




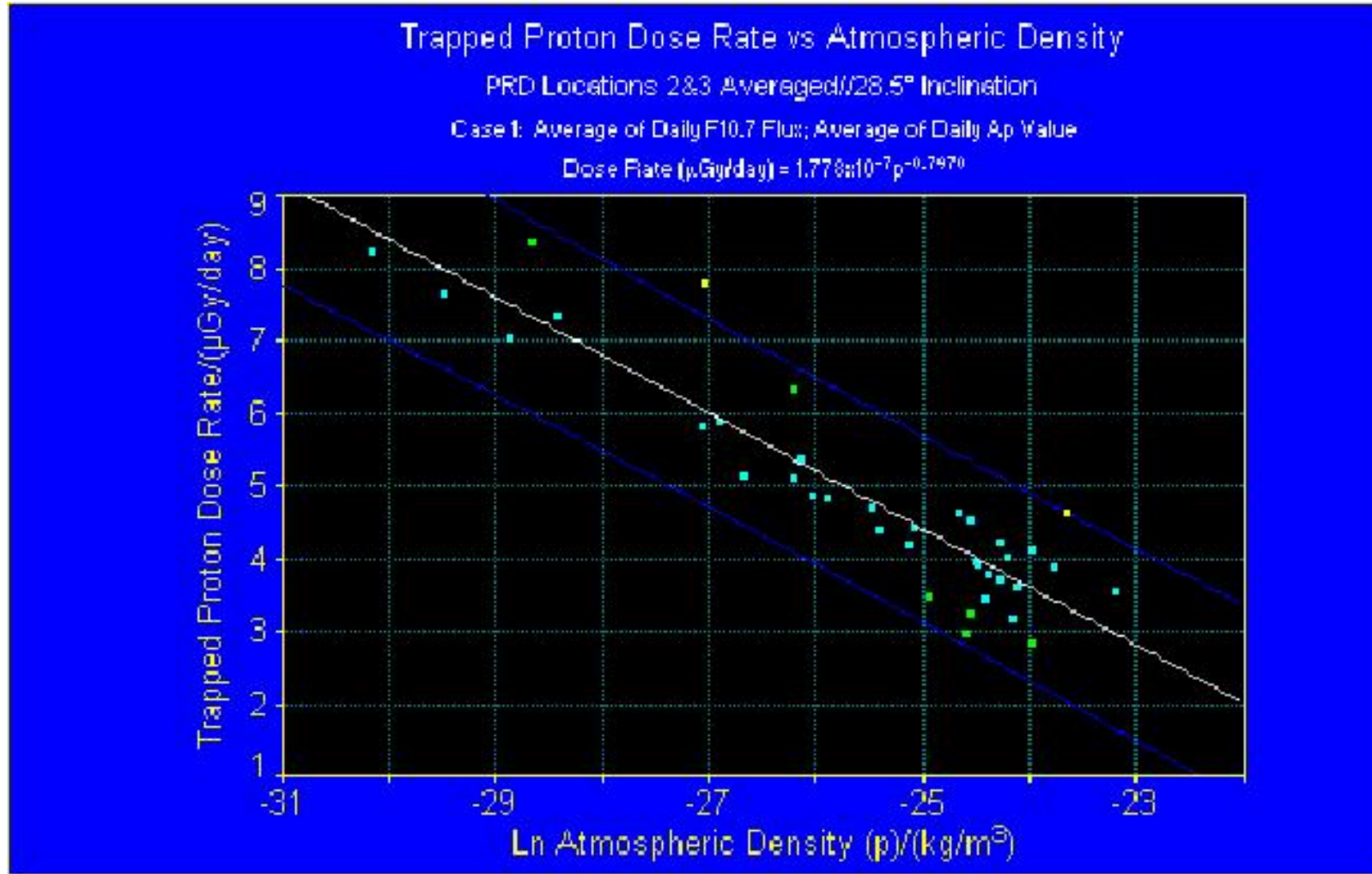
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Temporal Decay of Pseudostable Additional Radiation Belts

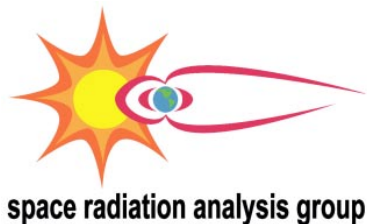
- Mar 1991 Event—Characterization from UoSAT-3 Data
 - < 98.7° inclination / 800 km altitude
 - < CREDO background count rate—count rate corrected for nominal contributions from SAA and GCR
 - < Fit to background count rate $2.2 < L < 2.4$ data
 - $J(2.2 < L < 2.4) = 1761e^{-t/5.1}$
(*DF adj* $r^2 = 0.8027$)
t = months since belt formation
J = counts/day
 - < Flux rate *e*-folding time = 5.1 months
 - < Flux rate enhancement (t = 0) relative to background = $\times 10.5$
 - < 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

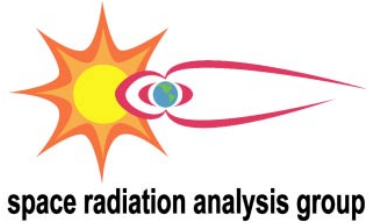
- Trapped proton exposure inside the Space Shuttle derived from TLD measurements over 1.5 solar cycles
 - ◁ TLD absorbed dose at fixed monitoring locations corrected for GCR background
 - ◁ Atmospheric density computed for flux-weighted average altitude through SAA
- Trapped proton exposure well modeled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

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.

PRD 1			PRDs 2 & 3 AVERAGED			PRD 4			PRDs 5 & 6 AVERAGED		
DF ADJ r^2	a	b	DF ADJ r^2	a	b	DF ADJ r^2	a	b	DF ADJ r^2	a	b
0.8890	-14.26	-0.7220	0.9359	-16.76	-0.8328	0.9125	-15.25	-0.7668	0.9250	-15.85	-0.7970
MOST HEAVILY SHIELDED			LEAST SHIELDED AVERAGE ATTITUDE EFFECT			MEDIUM SHIELDING			LEAST SHIELDED AVERAGE ATTITUDE EFFECT		

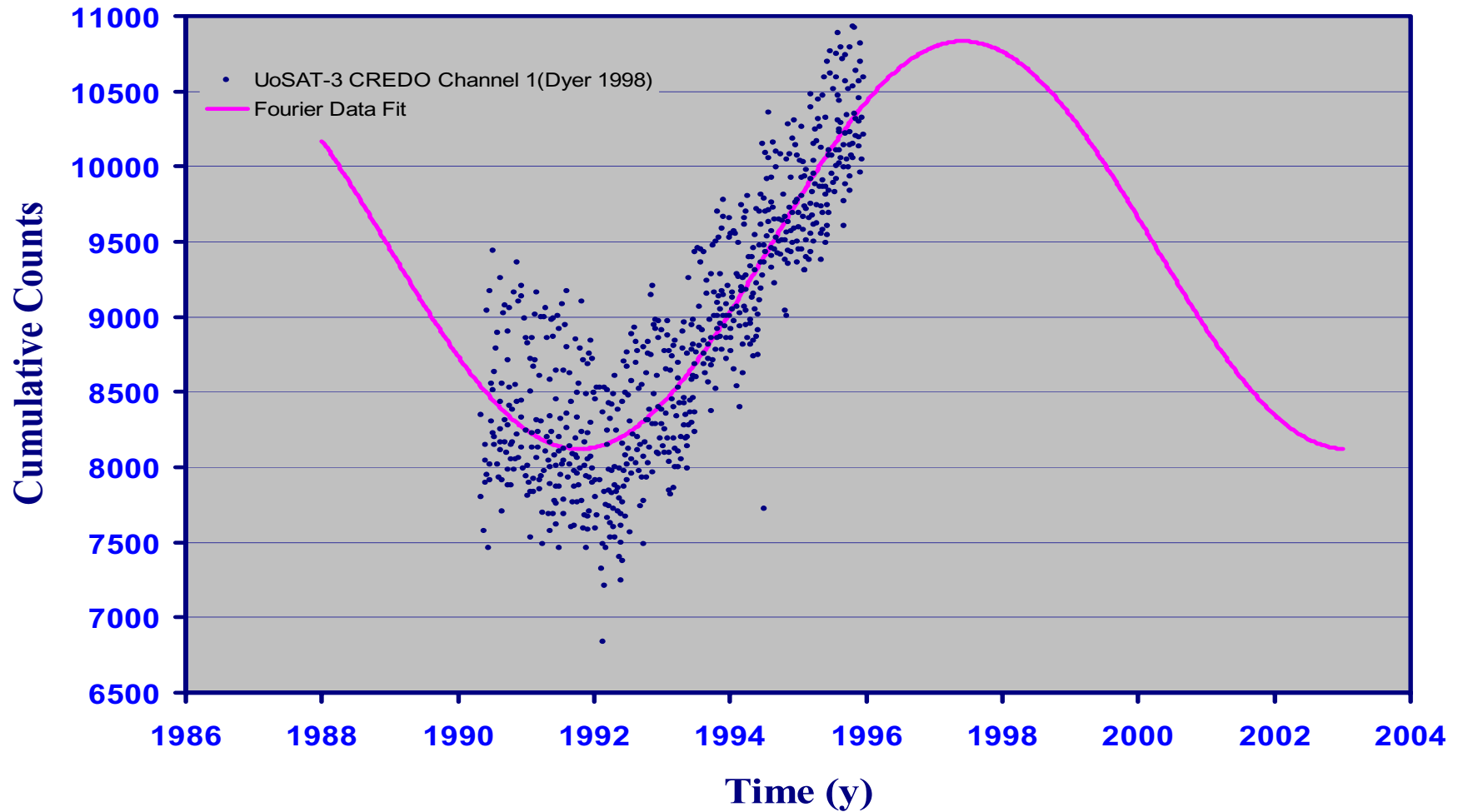
Table 2: Fit parameters and degree-of-freedom adjusted r^2 for trapped proton dose rate at four locations inside the Space Shuttle for 57° inclination missions. Thermospheric temperature capped at 975°K.

PRD 1			PRDs 2 & 3 AVERAGED			PRD 4			PRDs 5 & 6 AVERAGED		
DF ADJ r^2	a	b	DF ADJ r^2	a	b	DF ADJ r^2	a	b	DF ADJ r^2	a	b
0.6915	-16.26	-0.7964	0.9192	-15.48	-0.7964	0.8496	-15.30	-0.7722	0.9185	-16.16	-0.8141
MOST HEAVILY SHIELDED			LEAST SHIELDED AVERAGE ATTITUDE EFFECT			MEDIUM SHIELDING			LEAST SHIELDED AVERAGE ATTITUDE EFFECT		



Solar Cycle Modulation of Trapped Proton Flux in Low Earth Orbit

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

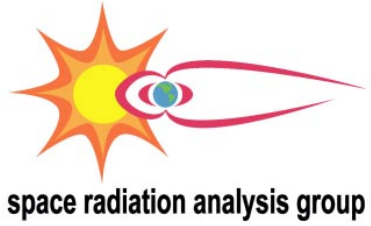




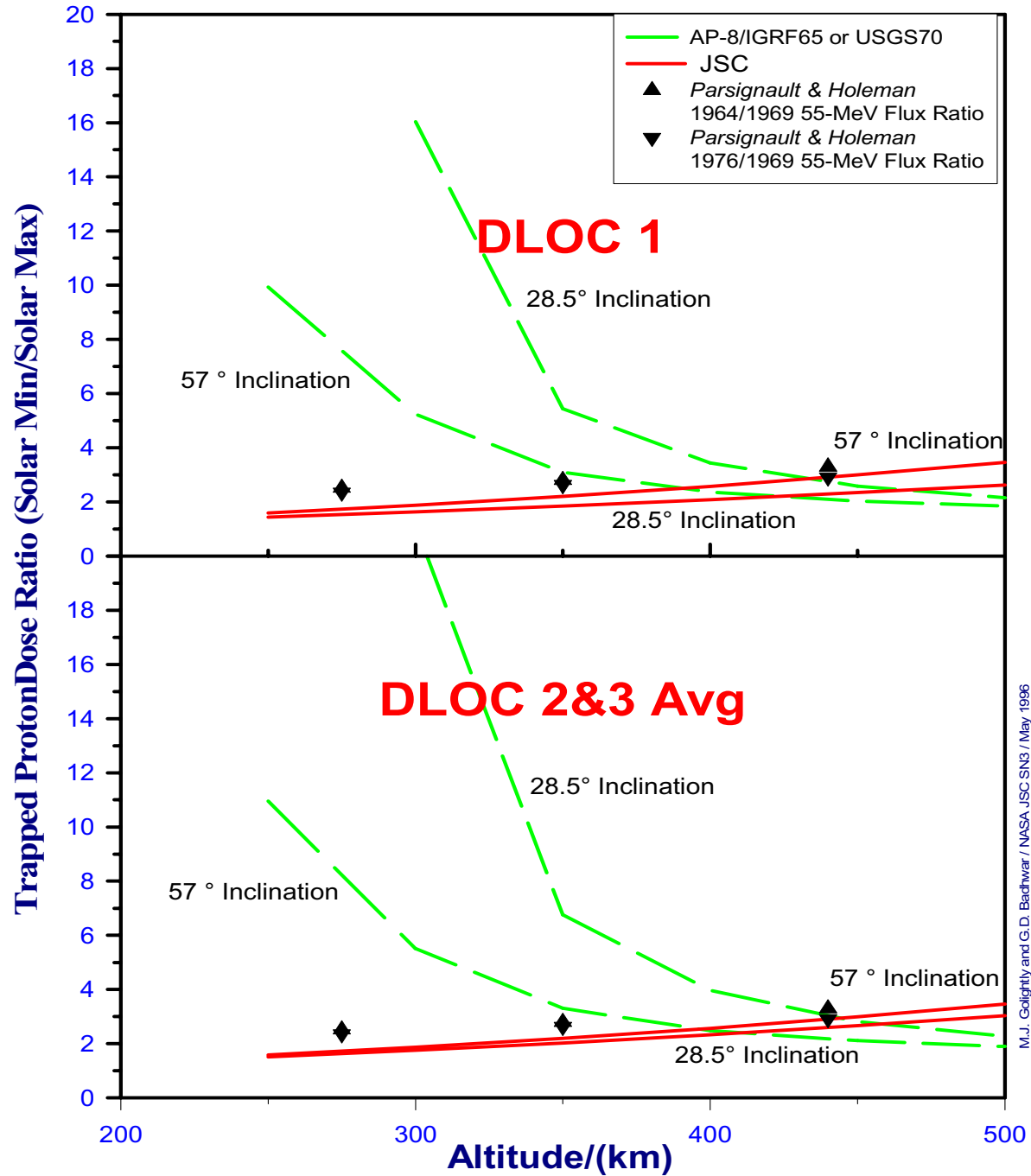
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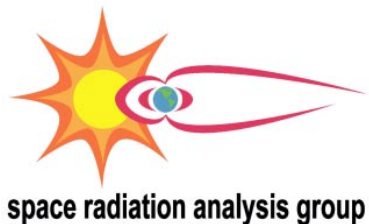
Solar Cycle Modulation of Trapped Proton Flux in Low Earth Orbit

- 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
 - $J(\text{channel 1}) = 9477 - 937\cos(t) - 979\sin(t)$
($DF \text{ adj } r^2 = 0.07698$)
t = date (year)
J = counts/day
 - < Minimum flux (solar maximum): Oct 1991
 - < 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



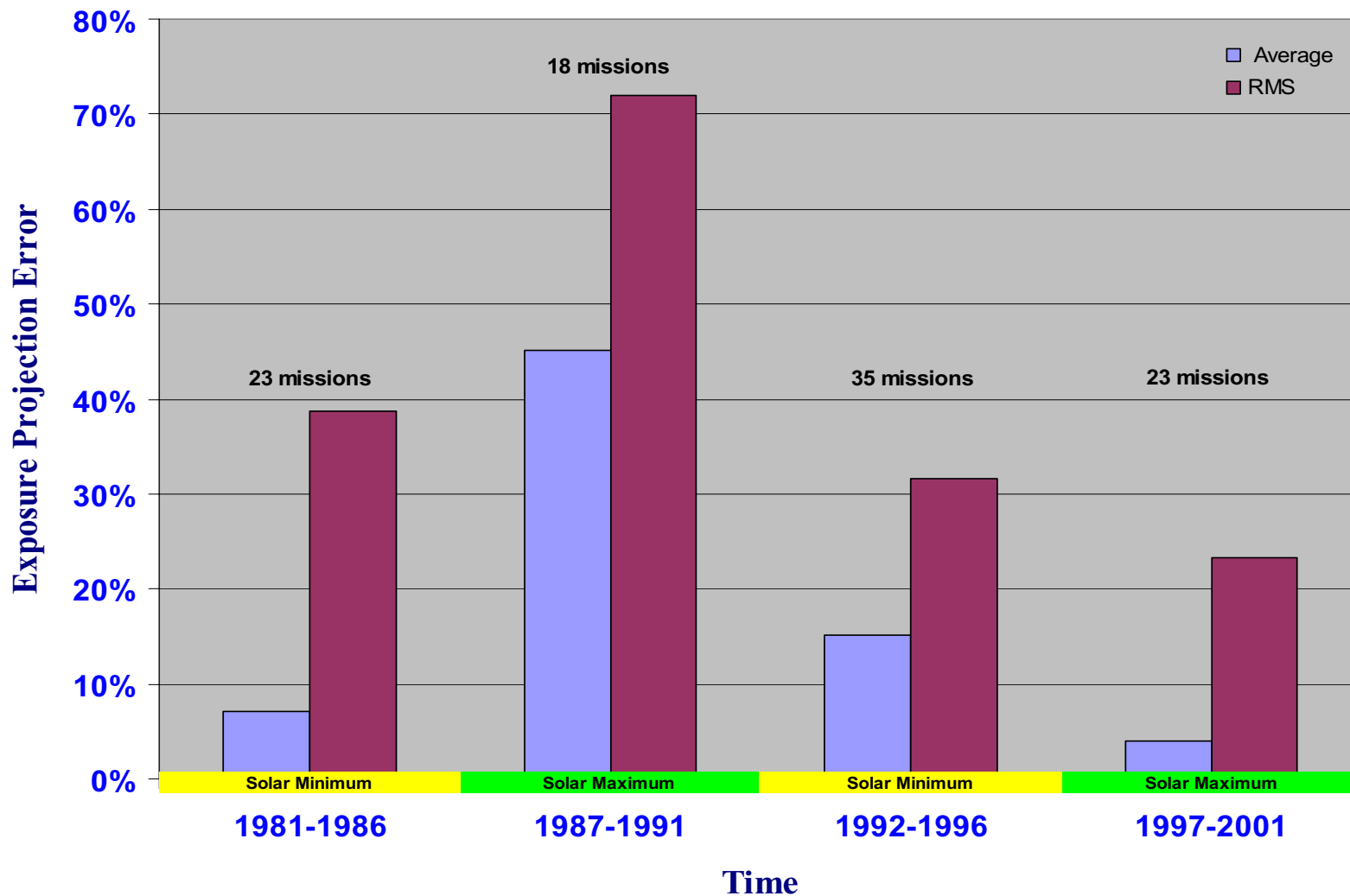
AP-8/JSC Model Comparison





Radiation Measurements During Manned Missions—Impact on Exposure Modeling

Crew Exposure Projection Accuracy





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Radiation Measurements During Manned Missions—What Have We Learned?

- The location of the South Atlantic Anomaly is drifting in the geocentric coordinate system
 - < approximately $0.33^\circ/\text{y}$ westward drift
 - < evidence for a $0.07^\circ/\text{y}$ 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.



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Acknowledgements

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