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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

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- 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?

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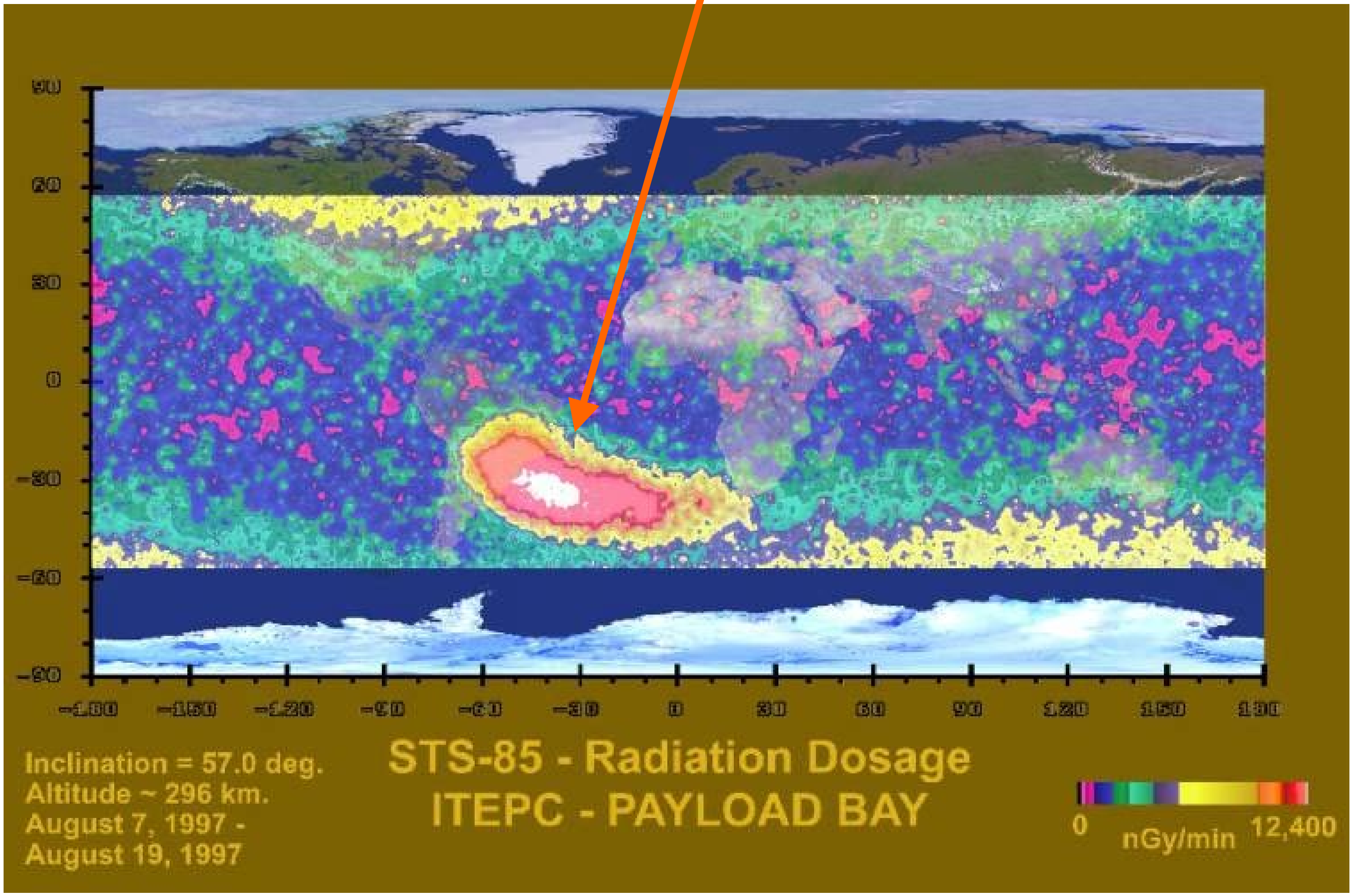
- While this is an abundant set of data, much of it cannot be used directly to study or model the geomagnetically trapped radiation belts in the atmospheric cutoff region
  - Measurements frequently do not include enough physical information (e.g., energy, particle type, arrival direction) or appropriate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



Badhwar

Temporal Changes in the Location of the South Atlantic Anomaly

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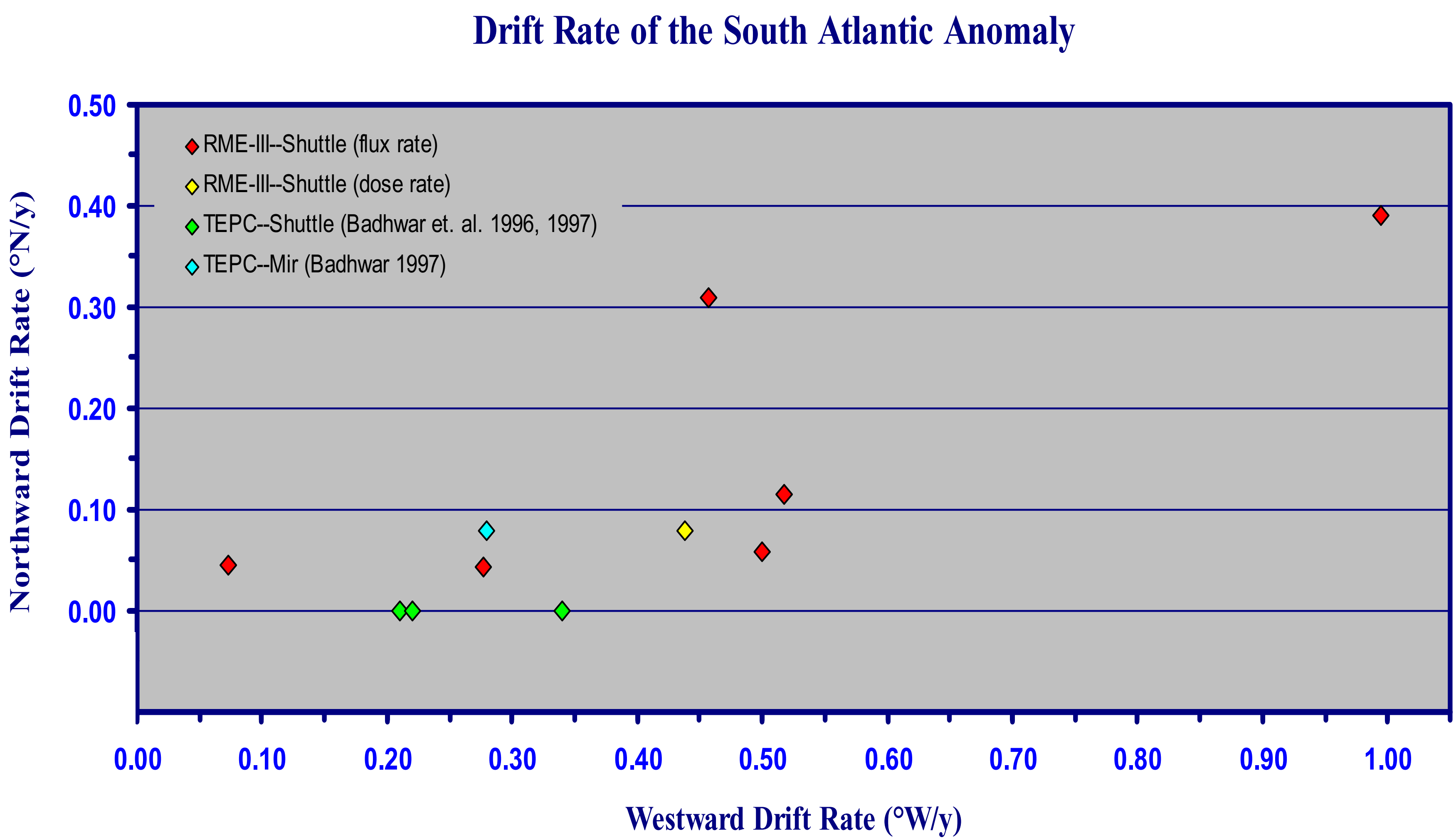
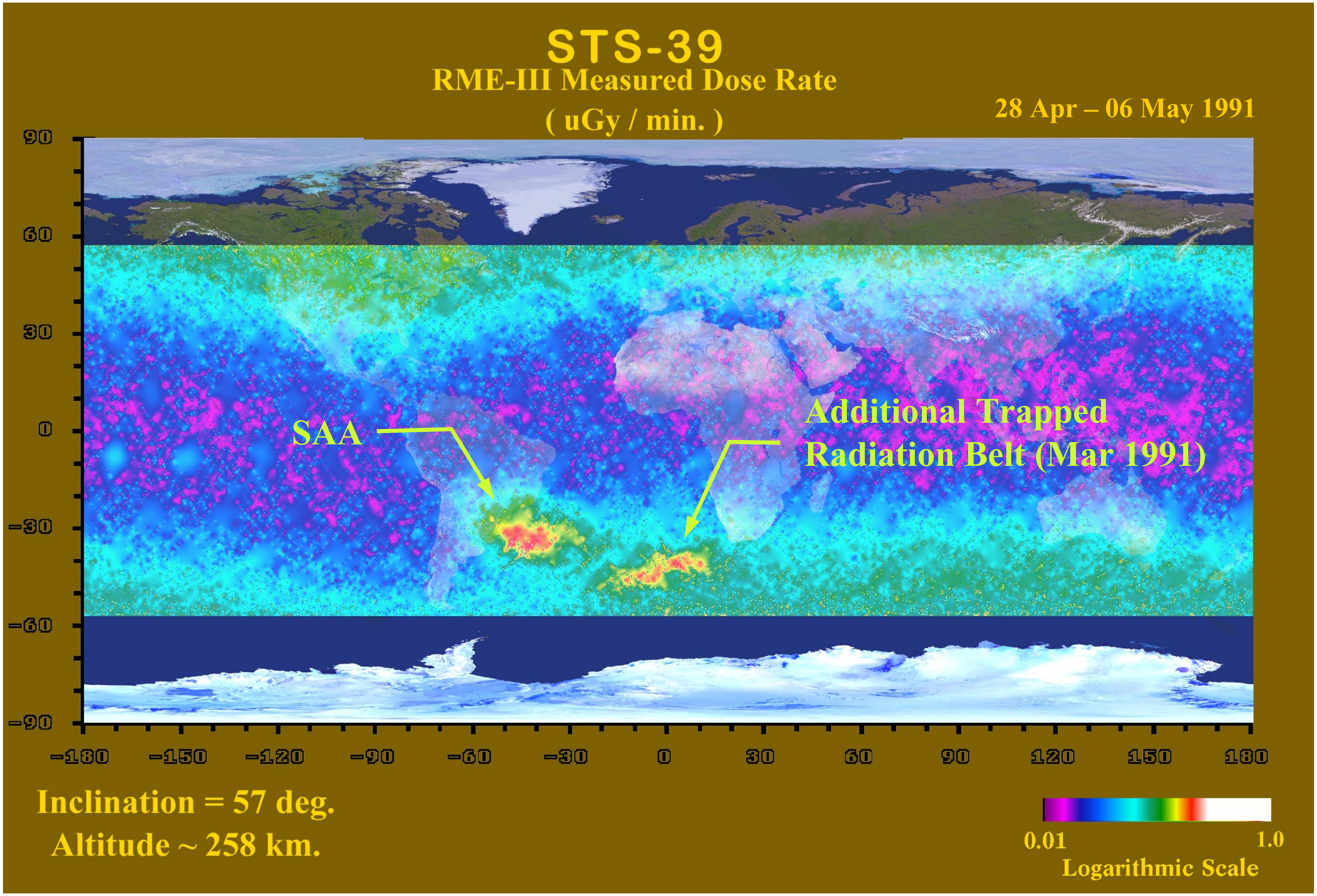


Temporal Decay of Pseudo-stable Additional Radiation Belts



Golightly, *et. al.* (1994)

Temporal Decay of Pseudo-stable Additional Radiation Belts

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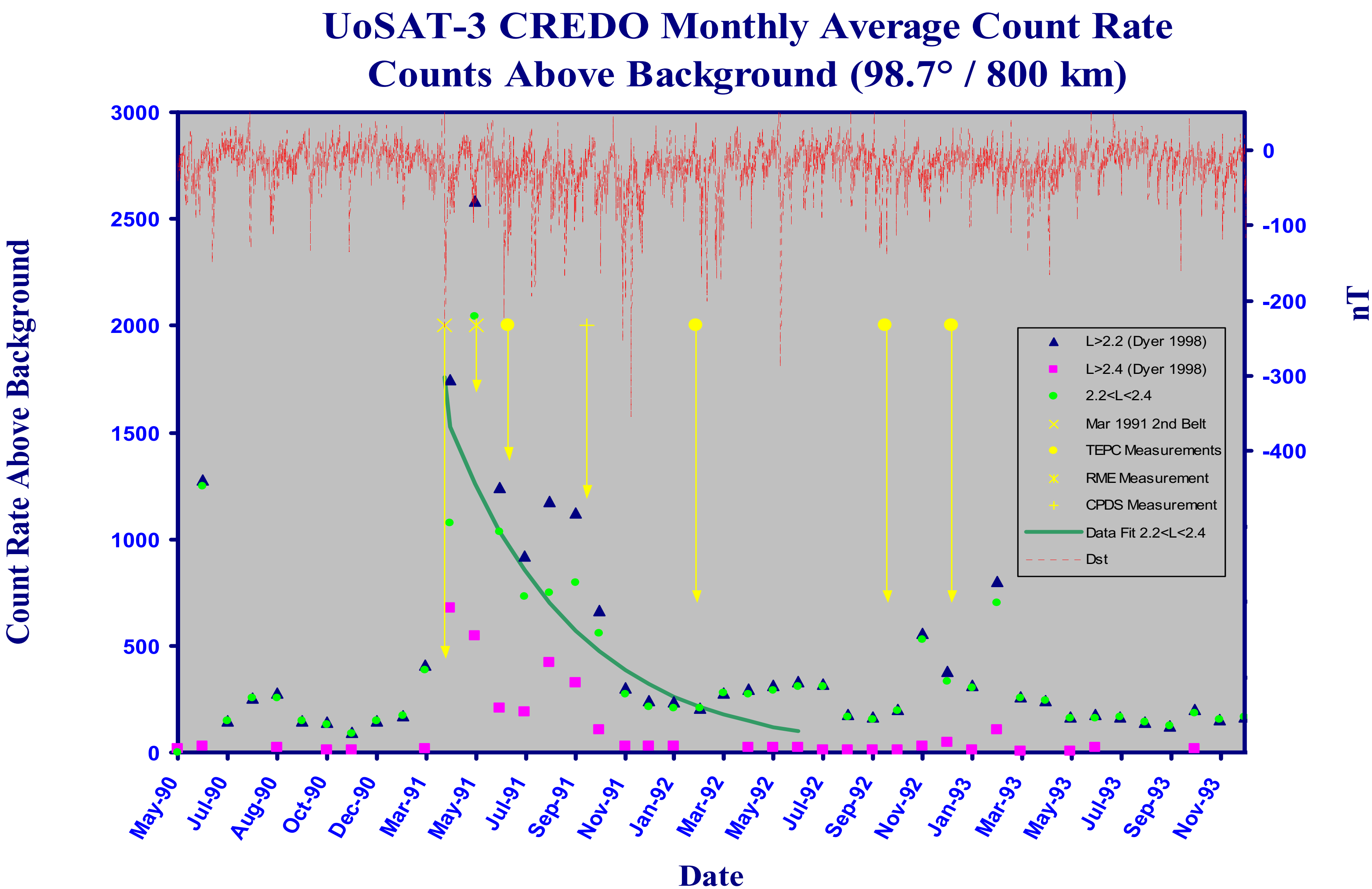
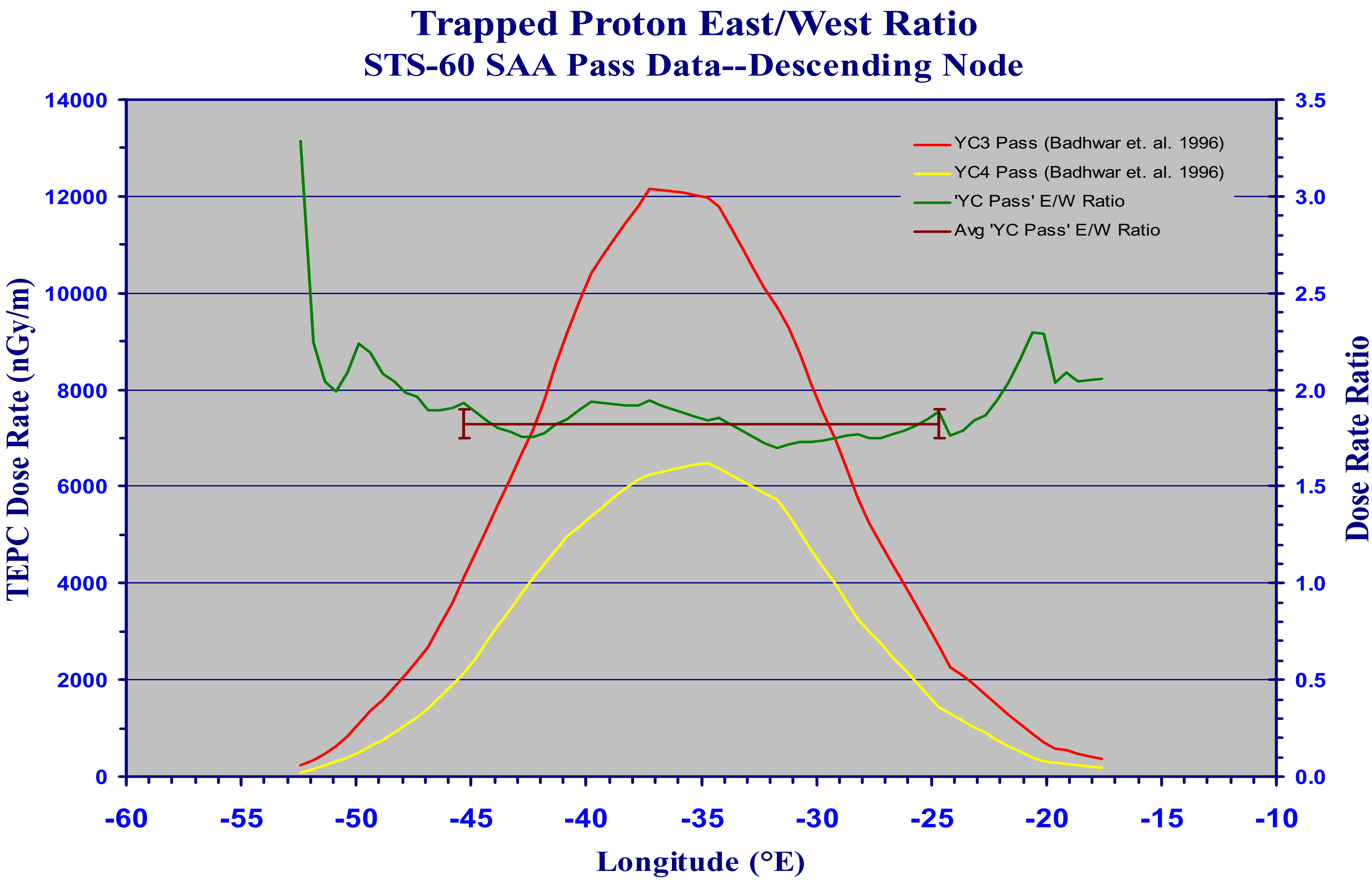


Trapped Proton Dose Rate—Impact of Flux Anisotropy



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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 *et. al.* 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 *et. al*. 1998
~1.6	STS-63	07-Feb-95	394	51.6	TEPC--Shuttle DLOC 2		airlock shadowing of DLOC 2 location	absorbed dose		Badhwar *et. al.* 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 *et. al.* 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 ИP2S 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 et. al. 1996

Trapped Proton East-West Ratio—Variation with Altitude

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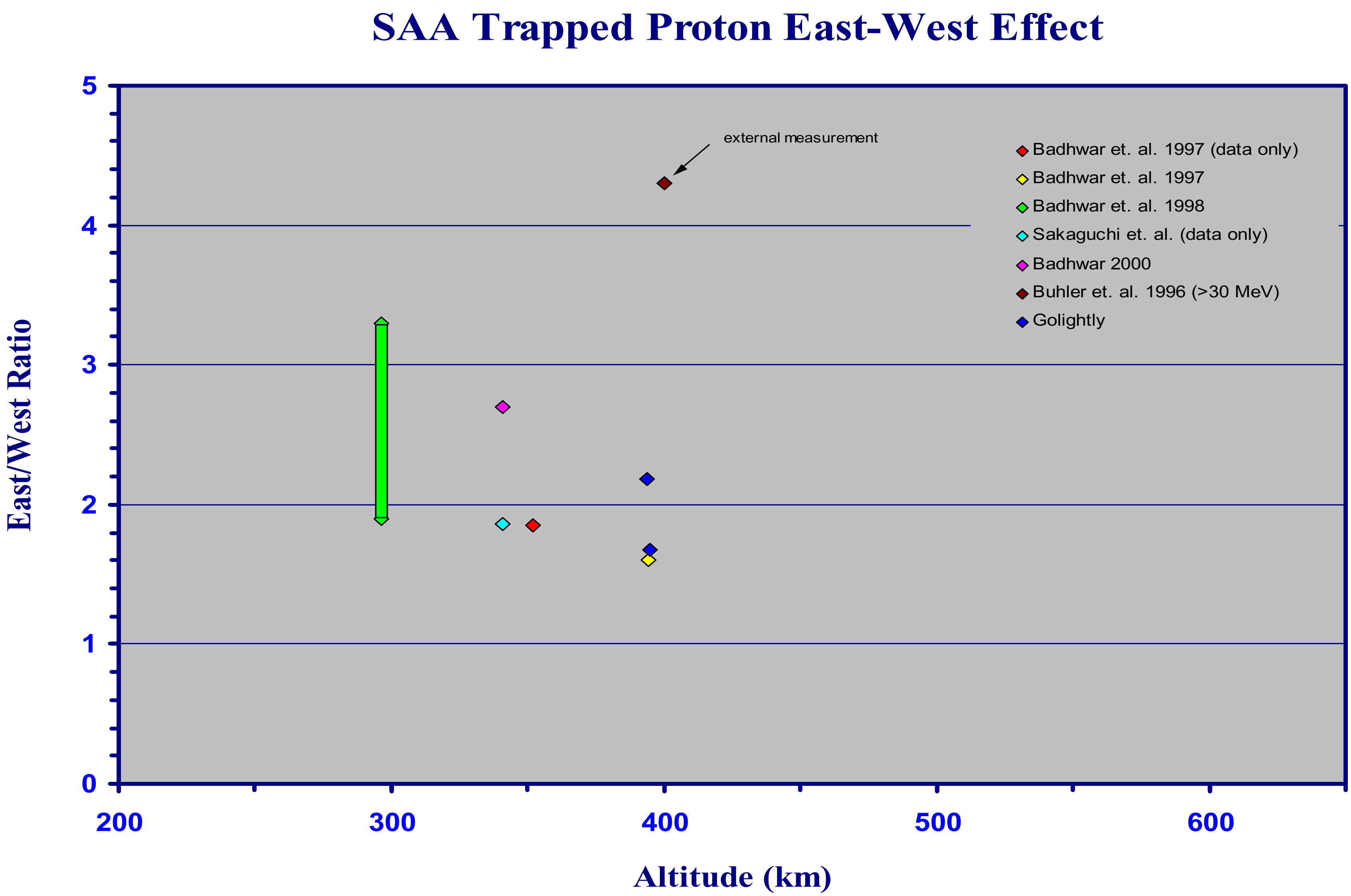

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Temporal Decay of Pseudostable Additional Radiation Belts

- 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 = 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

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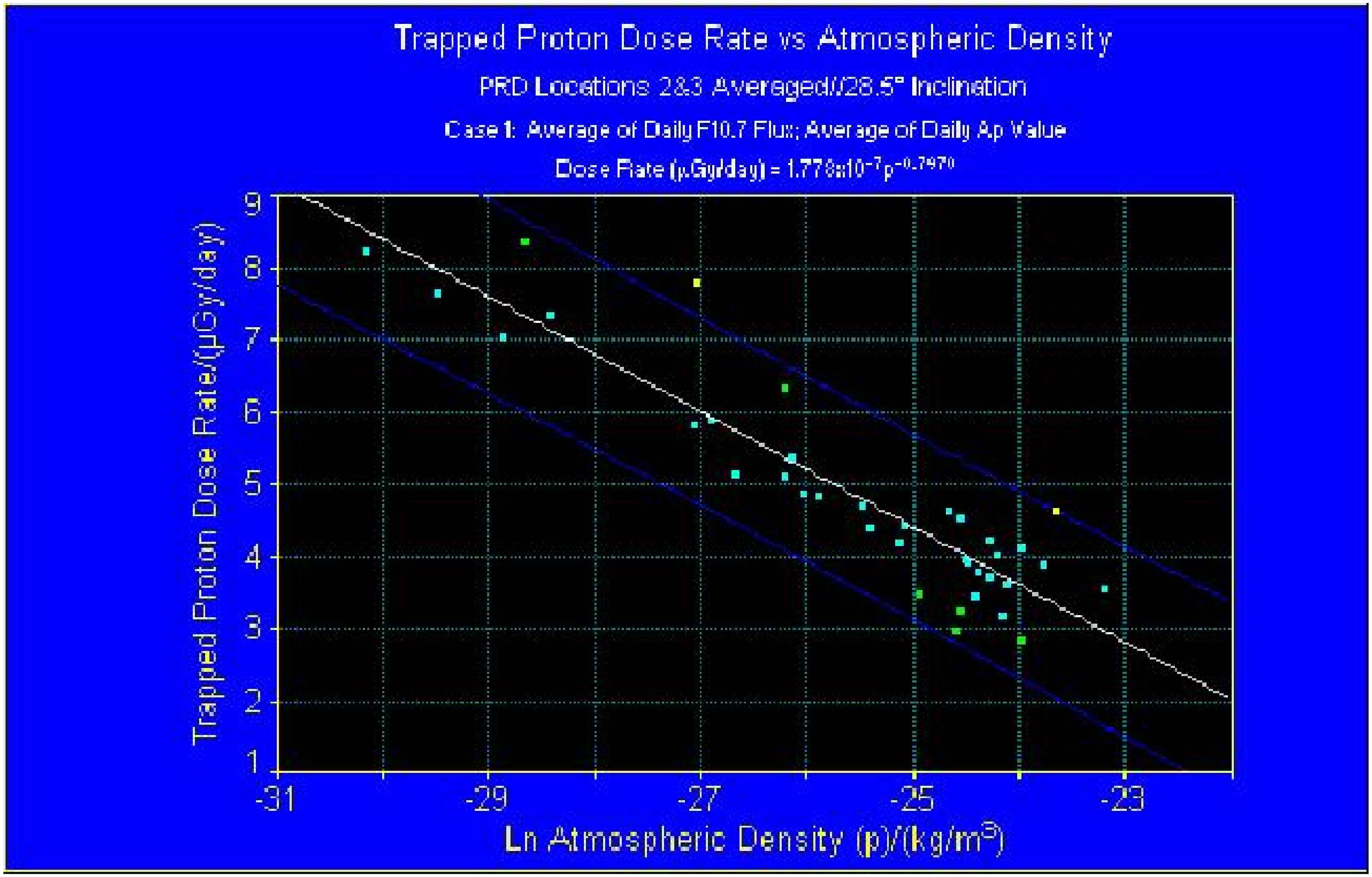

Golightly, *et. al.* (1994)

Trapped Proton Flux in Low-Earth Orbit—A Function of Atmospheric Density

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- 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: $\textit{Daily Dose Rate}\ (\mu Gy \bullet d^{-1}) = e^{a} * \rho^{b}$

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

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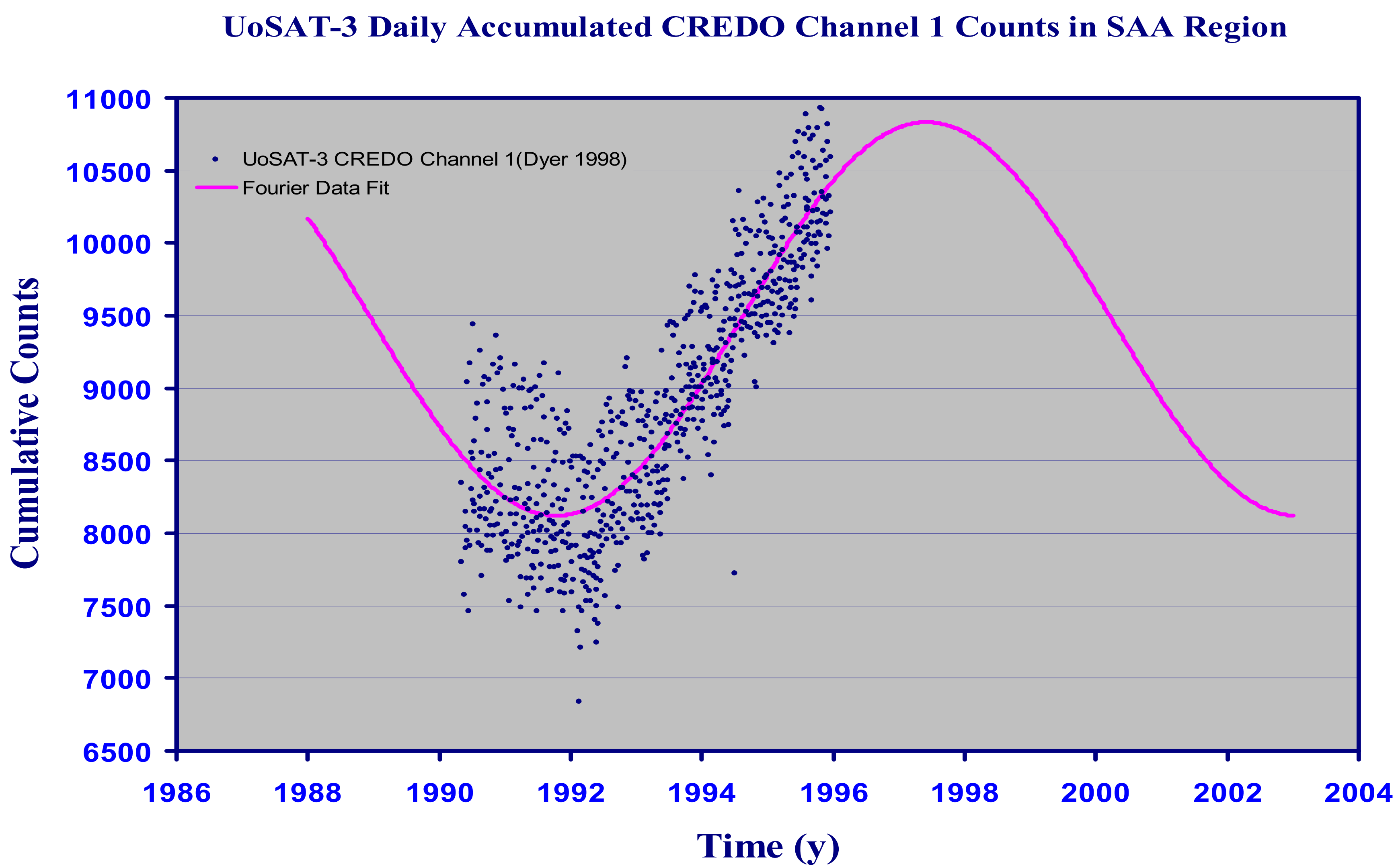

Solar Cycle Modulation of Trapped Proton Flux in Low Earth Orbit

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- 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(channel 1) = 9477 - 937cos(t) - 979sin(t)

      (*DF adj* r^2 = 0. 0.7698)

      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 ⇒ + 2.3 y to SAA flux minimum
    - Solar cycle 23 activity minimum: Oct 1996 ⇒ + 0.67 y to SAA flux maximum

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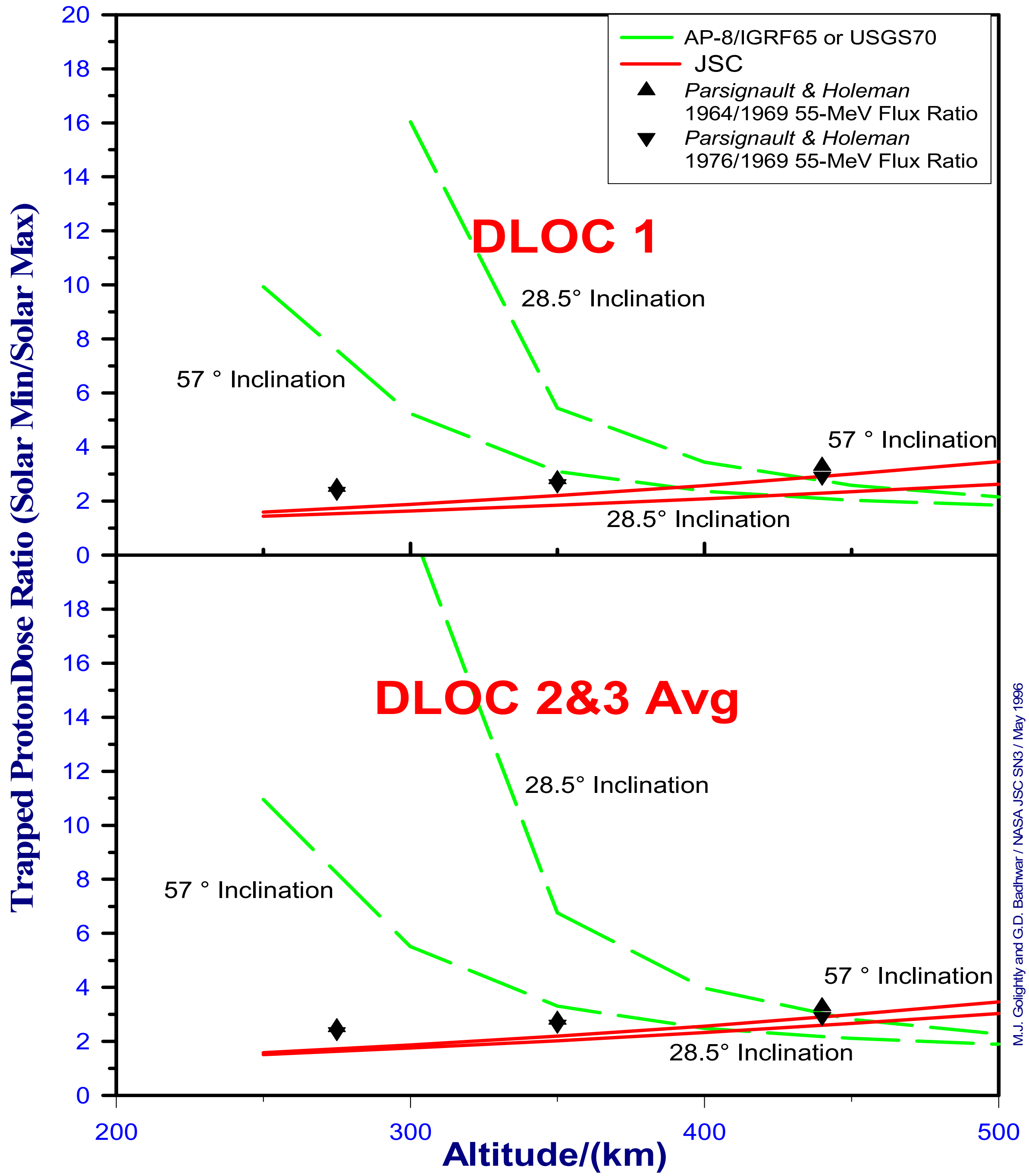
AP-8/JSC Model Comparison



Radiation Measurements During Manned Missions—Impact on Exposure Modeling

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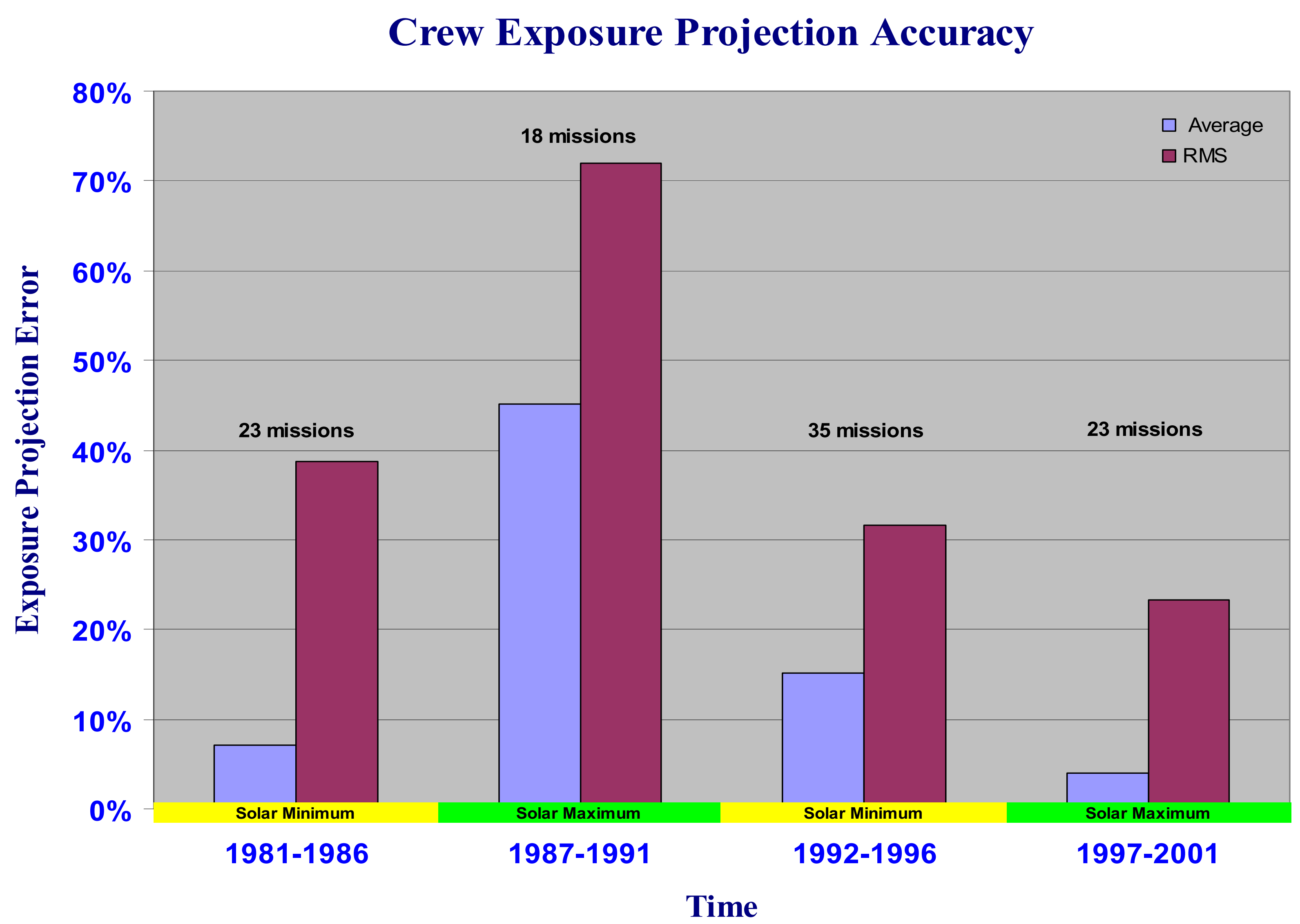

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Radiation Measurements During Manned Missions—What Have We Learned?

- The location of the South Atlantic Anomaly is drifting in the geocentric coordinate system
  - approximately 0.33°/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 938-975ºK
- Actual modulation of trapped proton exposure in LEO is less than predicted by the AP8 model.

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