AP-9/AE-9: New Radiation Specification Models

Update

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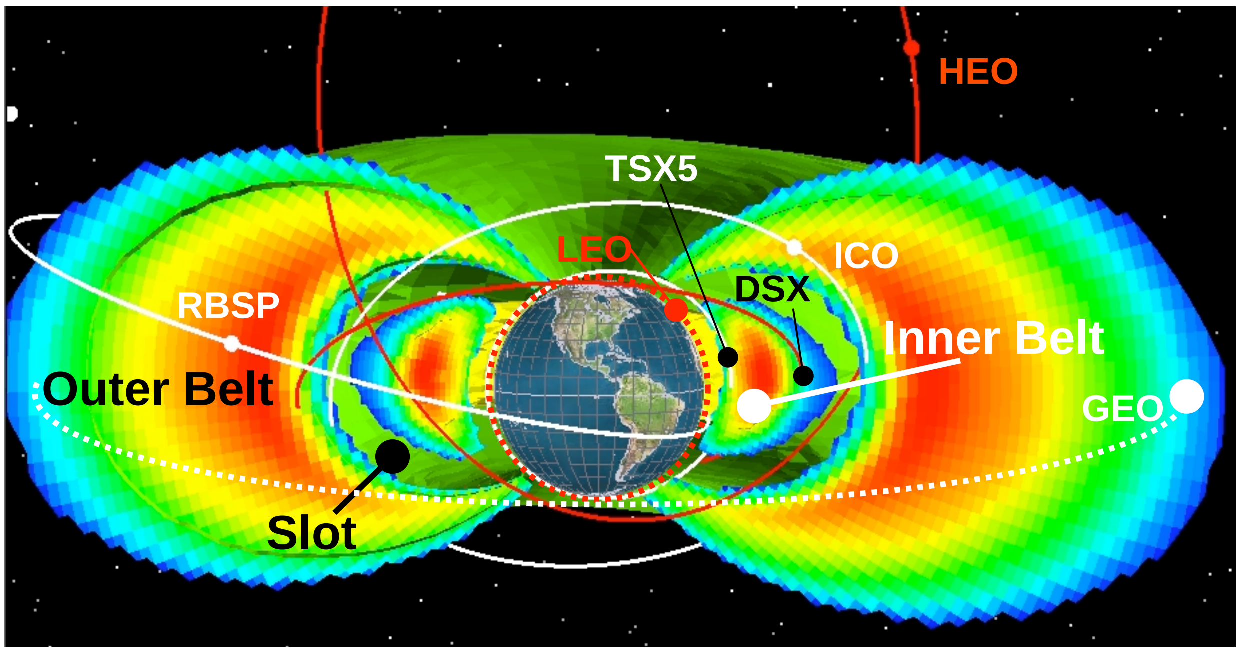
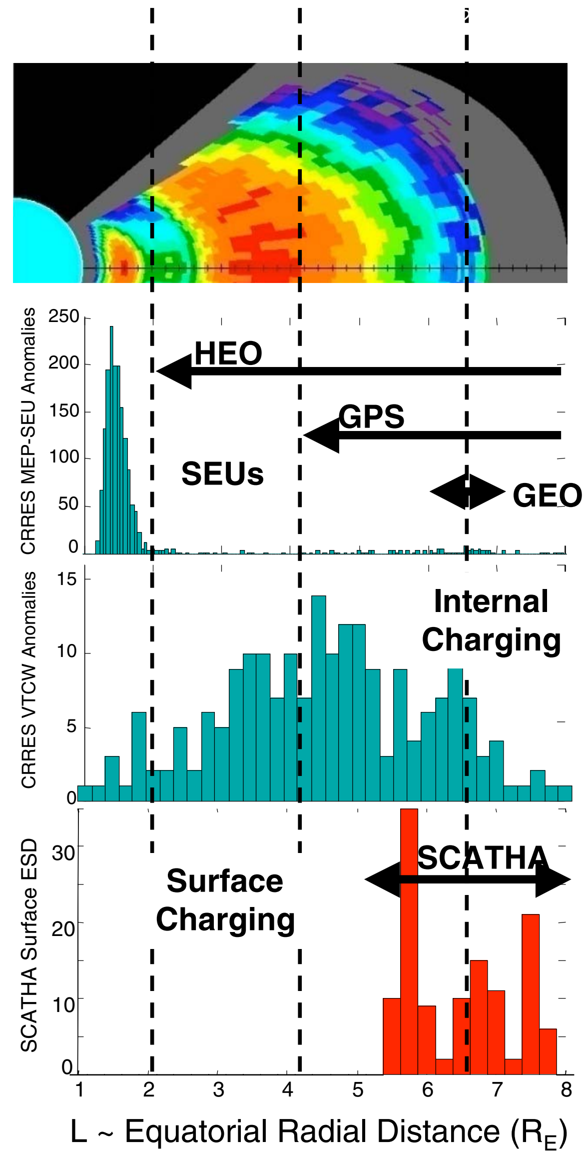
G. P. Ginet, AFRL/RVBX
T. P. O'Brien, Aerospace

AP-9/AE-9
Objective

Provide satellite designers with a definitive model of the trapped energetic particle and plasma environment to include:

- **Quantitative accuracy**
- **Indications of uncertainty**
- **Flux probability of occurance and worst cases for different exposure periods**
- **Broad energy ranges including hot plasma & very energetic protons**
- **Complete spatial coverage**

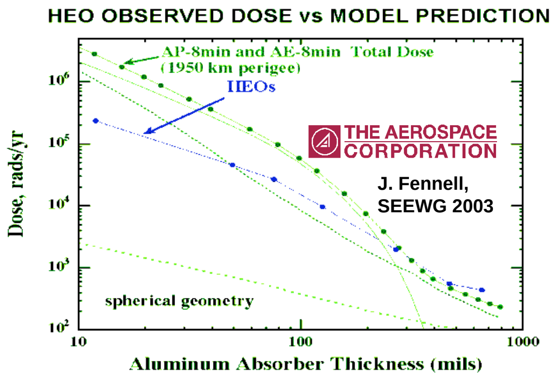




AP-9/AE-9

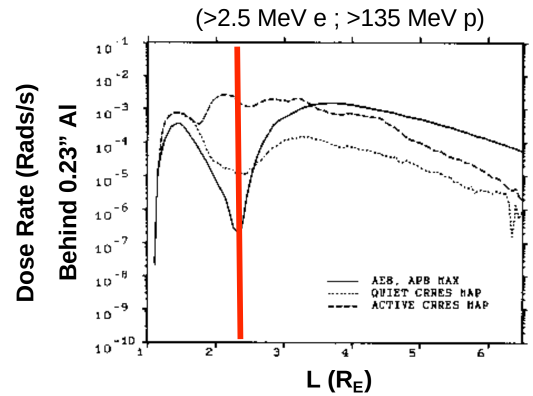
AP-8/AE-8 Deficiencies

Example: Highly Elliptic Orbit (HEO)



HEO dose measurements show that current radiation models (AE8 & AP8) over estimate the dose for thinner shielding

Example: Medium-Earth Orbit (MEO)

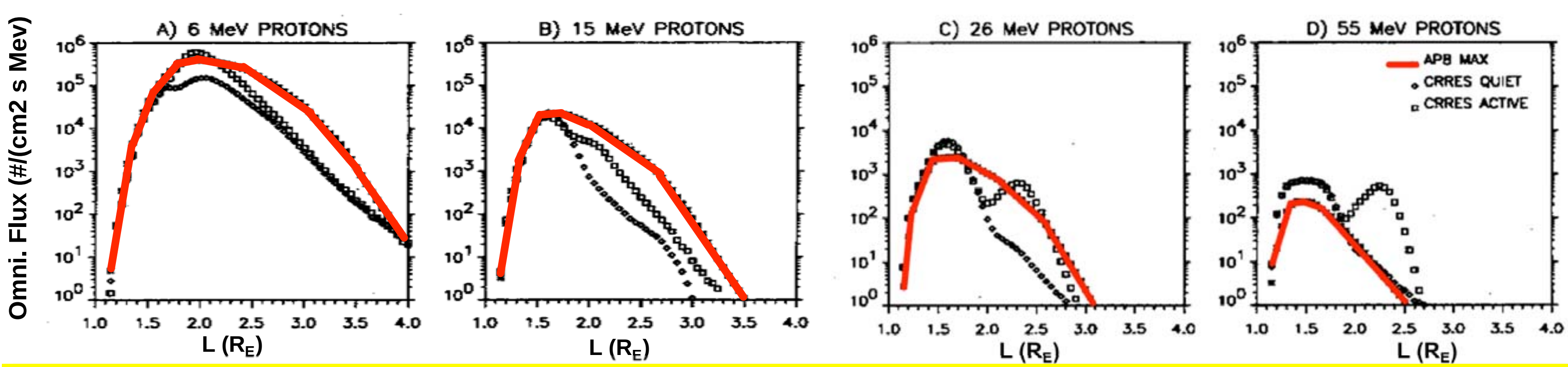


For MEO orbit (L=2.2), #years to reach 100 kRad:

- Quiet conditions (NASA AP8, AE8) : 88 yrs
- Active conditions (CRRES active) : 1.1 yrs

AE8 & AP8 under estimate the dose for 0.23'' shielding

Model differences depend on energy:



AP-8/AE-8 inadequate for modern spacecraft design and mission planning

AP-9 /AE-9
Requirements

Summary of SEEWG, NASA workshop & AE(P)-9 outreach efforts:

Priority	Species	Energy	Location	Time Variation	Effects
1	Protons	>10 MeV (> 80 MeV)	LEO & MEO	Mission statistics (i.e. % thresholds)	Dose, SEE, DD, nuclear activation
2	Electrons	> 1 MeV	LEO, MEO & GEO	5 min, 1 hr, 1 day, 1 week, & mission	Dose, internal charging
3	Plasma	30 eV – 100 keV (30 eV – 5 keV)	LEO, MEO & GEO	5 min, 1 hr, 1 day, 1 week, & mission	Surface charging & dose
4	Electrons	100 keV – 1 MeV	MEO & GEO	5 min, 1 hr, 1 day, 1 week, & mission	Internal charging, dose
5	Protons	1 MeV – 10 MeV (5 – 10 MeV)	LEO, MEO & GEO	Mission statistics	Dose (e.g. solar cells)

(indicates especially desired or deficient region of current models)

Model output: distribution of median, 75th and 90th percentile confidence levels for particle fluxes averaged over several “exposure” periods for arbitrary Earth-orbit parameters and mission duration (and uncertainties in those levels).

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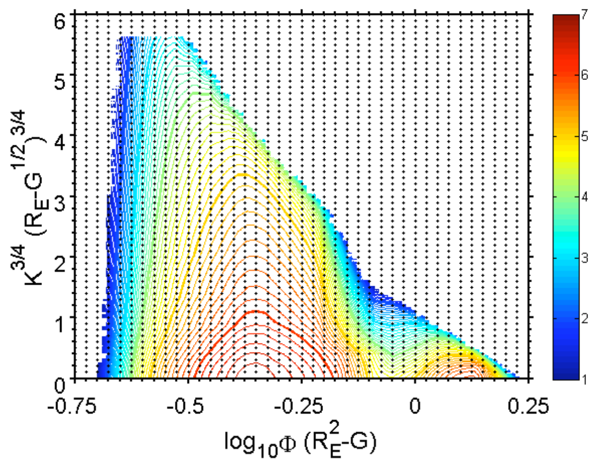
Beta Version

Satellite data



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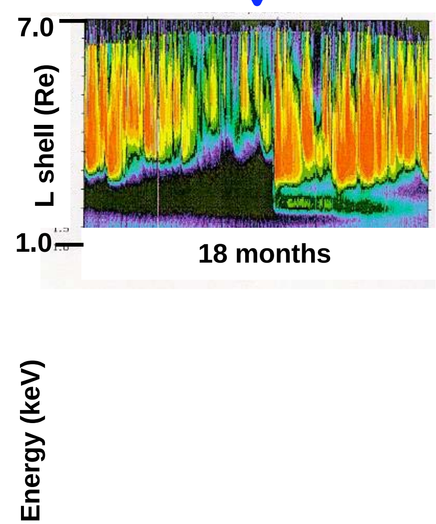
Satellite data & physics-based models



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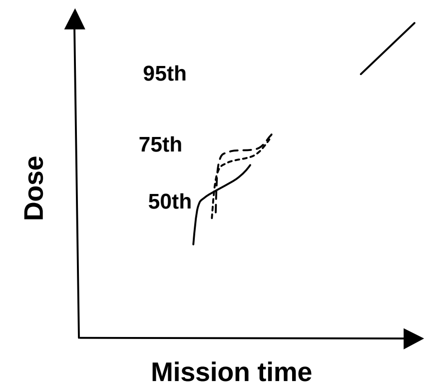
User's orbit & Monte-Carlo simulations



Flux maps

- Median, 75th and 90th percentile of distribution function
- Derived from empirical data
- Interpolation algorithms needed to fill in the gaps

Space/time covariance

- Correlate data in space and time
  - From data, if enough (electrons, plasma)
  - From physics-based models when not enough (protons)
  - Fixed sampling time scale (one day)

User application

- Flux or dose vs time
- Median, 75th and 90th confidence levels
- Confidence levels come with uncertainty estimates

AP-9/AE-9 beta scheduled for completion at end of CY2009

AP-9/AE-9

Summary of Primary Results

- Gathered requirements from satellite engineering & design community
  - Presentations & discussions at SEEWG, GOMAC, NOAA SWx, IEEE NSREC workshops & meetings
  - Detailed communication with "short list" of industry experts
- Beta version architecture defined
- Completed first spiral of cross-calibration of proton detectors with "standard sensor"
  - Proton data sets for beta version: HEO-1 (MEO), HEO-3(MEO), ICO(MEO), TSX-5/CEASE(LEO), SAMPEX(LEO), CRRES/PROTEL(GTO)
  - Calibration standard sensor = GOES – 7,8,11
- Developed & implemented algorithms for proton spectral inversion
  - Required to derive spectrum from broad channel responses of dosimeters/telescopes on HEOs, ICO & TSX-5/CEASE
- Completed initial version of Trapped Electron Model -1
  - Flux maps & spatial/temporal covariance matrices derived from CRRES/HEEF/MEA and S3-3/MSS data
  - Full Monte-Carlo dose estimate algorithm demonstrated for GEO
- Processed GPS data for inclusion into beta AE-9
  - Simple spectral inversion algorithms developed for BDD-I, BDD-II and BDD-IIR sensors (8 satellites total)
  - Validation with Polar and GEO satellite data ongoing
  - Ready enough for inclusion into AE-9 beta flux maps

Data Sets for Spiral 1

Data Set	Orbit/Duration	Measurements
HEO-1	Molniya, L>2, high alt., little coverage L<4, 1994 onward	p+: >80, >160, >320 keV, >20, >40, >55, >66 MeV e- : >130, >230 keV, >1.5, >4, >6.5, >8.5 MeV
HEO-3	Molniya, L>2, high altitude, 1997 onward	p+: >80, >160, >320 keV, >5, 8.5-35, 16-40, 27-45 MeV e- : >130, >230, >450, >630 keV, >1.5, >3.0 MeV
ICO	45°, circular, L>2.5, high altitude, 2001 onward	p+: >15, >24, >33, >44, >54 MeV e- : >1.2, >2.2, >4, >6, >8 MeV
TSX-5	67° LEO, 400 x 1700 km, June 2000- Jul 2006	CEASE (dosimeter & telescope) p+: 20 – 100 MeV, 4 integral channel e- : 0.06 – 4 MeV, 5 integral channels
DSP-21	GEO Aug 2001 onward	CEASE (dosimeter & telescope) p+: 20 – 100 MeV, 4 integral channel e- : 0.06 – 4 MeV, 5 integral channels
GPS	54° MEO, L>4.2, 20000 km, Jan 1990 onwards	BDD/CXD p+: 5/9 – 60 MeV e- : 0.1/0.2 – 10 MeV
CRRES	GTO, L>2, high altitude, little coverage L<4, 1994-	PROTEL(p+): 1 – 100 MeV, 22 channels HEEF(e-): 0.6 – 6 Mev, 10 channels MEA(e-): 0.1 – 1.0 MeV LEPA(p+ & e-): 100 ev – 50 KeV
S3-3	97.5° MEO, 236 x 8048 km, 1976-1979	p+: 80 keV – 15.5 MeV (5 ch), > 60 MeV (no GF) e- : 12 keV – 1.6 MeV (12 ch)
SAMPEX	LEO (500 km) 1992.5 onward	PET p+: up to 400 MeV e- : >0.5, >1, 1-6, 3-16, 10-20 MeV
LANL	GEO 1985 onwards	MPA/CPA/ESP/SOPA p+: 0.1 keV – 200 Mev e- : 0.1 keV - > 10 MeV

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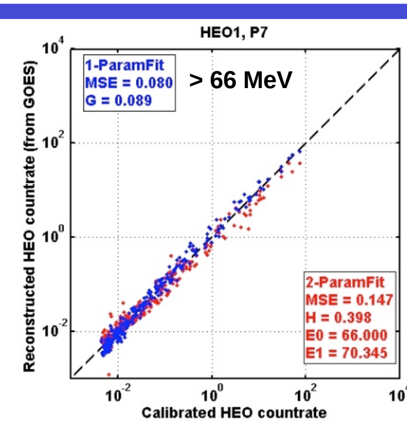
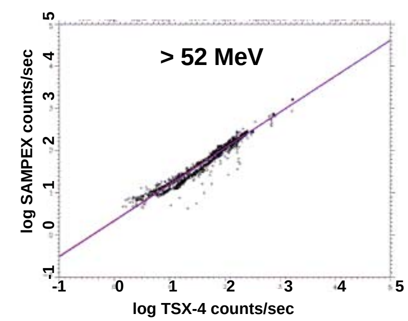
Results: Proton Cross-Calibration

- Cross-calibration vital for determining overall error bar
  - Difficult to determine absolute error bars for every detector
  - Well-studied GOES channels chosen as “standard candle”
- Compare the following:
  - TSX-5/CEASE to DSP-21/CEASE [Done]
  - DSP-21/CEASE to GOES-8/SEM [Done]
  - TSX-5/CEASE to SAMPEX/PET [Done]
  - TSX-5/CEASE to GOES-8/SEM [Working]
  - CRRES/PROTEL to GOES-7/SEM [Working]
  - GOES-7/SEM to GOES-8/SEM [Working]
  - SAMPEX/PET to GOES-8/SEM [Done]
  - HEO/Doismeter to GOES-7,8,11/SEM [Done]
  - ICO/Dosimeter to GOES-7,8,11/SEM [Done]
- Use energy-dependent SPEs as defined by GOES data
  - For non-GEO satellites compare at high latitudes

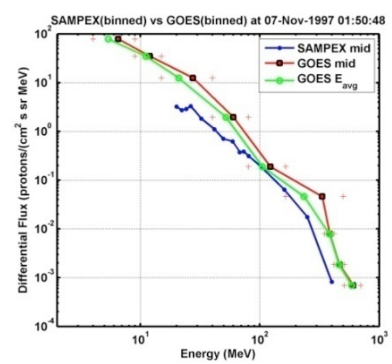
Next steps:
- Complete all satellite pairs
- Determine final set of standard candle error bars



HEO-1 vs. GOES



TSX-5 vs. SAMPEX



SAMPEX vs. GOES (spectrum)

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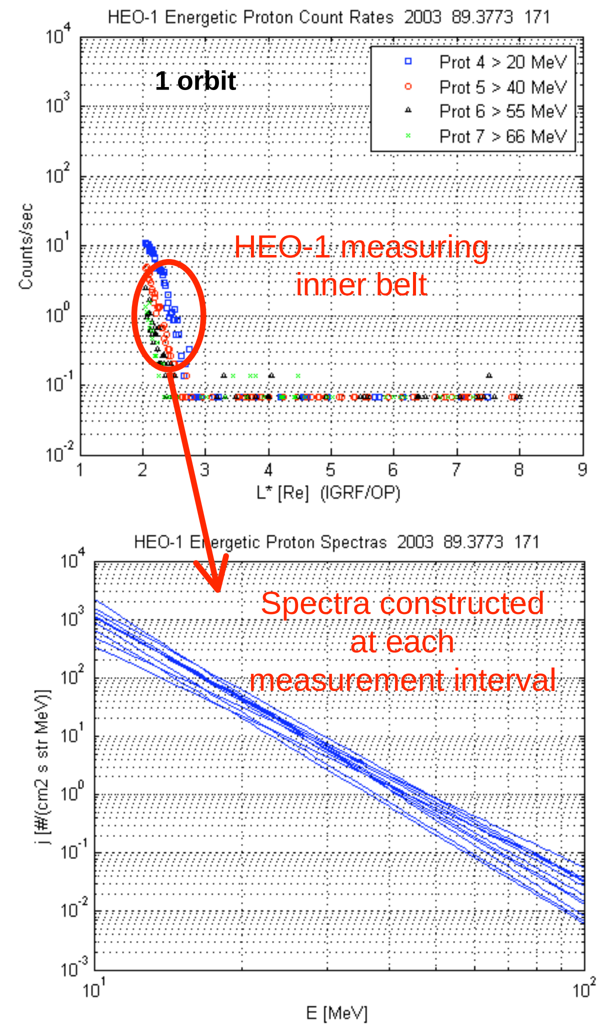
Results: Proton Spectral Inversion

- Dosimeters and telescopes on HEO-1, HEO-3, ICO and TSX-5 satellites have wide spatial and temporal coverage of LEO and MEO
- However… they are relatively simple instruments requiring inversion algorithms & statistical analysis to pull out spectral data useful for models
- Protons are relatively straightforward:
  - Power law behavior is a reasonable approximation between 10 – 100 MeV
  - Assume exponential tail for E > 100 MeV with fixed e-folding time derived from Selesnick model
- Inversion algorithms developed for above detectors
- Preliminary inversion completed for:
  - TSX-5/CEASE (6 year data set)
  - HEO-1 (13 year data set)

HEO-1 spectral inversion



Next steps:
- Validation
- Complete for all data sets
- Bin into flux maps

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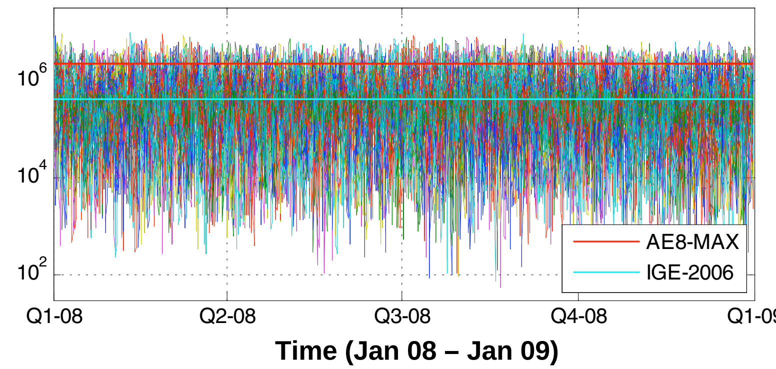
Result: Trapped Electron Model (TEM)- 1

- TEM-1 is the pathfinder for the AP-9/AE-9 beta version
- Implements statistical algorithms to compute spatial and temporal covariance matrices from gridded flux maps[1]
- Applies algorithms to electrons from 50 keV to 10 MeV, inner and outer belts
- Flux maps derived from one day averages of S3-3/MES, and CRRES MEA/HEEF data, which does not cover complete spatial/energy domain
- Produces multiple monte-carlo scenarios, then flies spacecraft through them to compute flux-at-the-spacecraft
- Percentiles of fluence and worst case (over baseline 1 day exposure period) are derived from resulting statistical distributions across scenarios
- Percentiles can be produced for any quantity derived from the flux-at-the-spacecraft time series.
- The model captures our best estimates of:
  - Measurement uncertainty
  - First-order spatial and temporal correlations (affects size of error bars, extremeness of worst cases)

[1]O'Brien, T. P. (2005), A framework for next-generation radiation belt models, *Space Weather, 3*, S07B02,doi:10.1029/2005SW000151

Demo for 1 year at GEO



Energy (keV)

Next steps:
- Incorporate GPS data
- Validation

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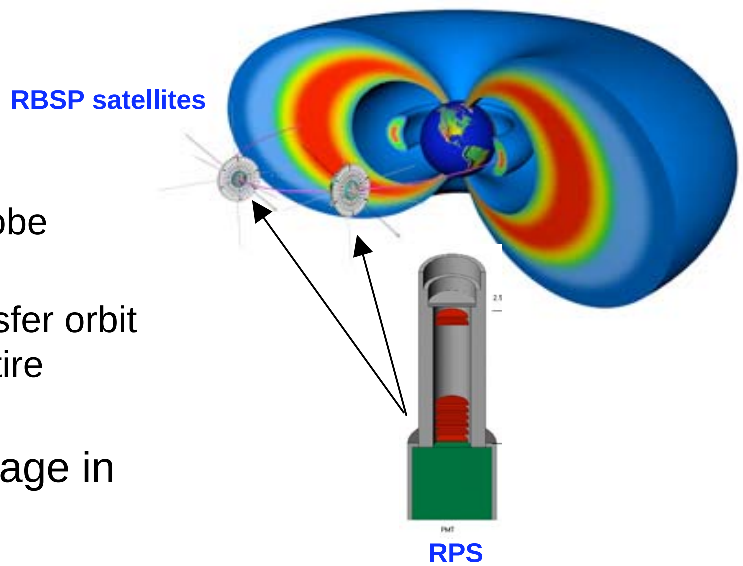
Relativistic Proton Spectrometer (RPS)

The need:

- Specification of energetic protons is the *highest* priority of satellite design community
- AP-8 has well-known under-prediction problems at higher proton energies (> 50 MeV) and in the slot region
- Inner zone protons are poorly measured ,
  - HEO-1/Dosimeter (1994 – current) – very little inner zone coverage
  - HEO-3/Dosimeter (1997 – current) – little inner zone coverage and contamination issues
  - ICO/Dosimeter (2001 – current) – only outside of inner zone coverage
  - CRRES/PROTEL (1990-1991) – covers the complete inner zone but has contamination

The solution:

- Relativistic Proton Spectrometer (RPS)
  - RPS measures protons 50 MeV to 2 GeV
  - Two RPS instruments will be on NASA Radiation Belt Storm Probe (RBSP) satellites (launch ~ 2012)
  - RPS & other NASA detectors on RBSP in geosynchronous transfer orbit will provide comprehensive energy & spatial coverage of the entire radiation belt regions
- AF DSX satellite also providing 10 – 480 MeV proton coverage in the slot region (launch ~ 2010)



AP-9/AE-9
Summary

- AE(P)-9 will improve AE(P)-8 to address vital needs of space system design community
  - More coverage in energy, time & location for *trapped* energetic particles & plasma
  - Includes estimates of instrument error & space weather statistical fluctuations
- Beta version due in early FY10
  - Energetic protons (> 1 MeV) and electrons (> 1 MeV) highest priority
  - Will provide median, 50th and 95th confidence levels of flux for arbitrary mission orbit and duration
  - Percentiles can be calculated for any quantity derivable from flux-vs-time values at the spacecraft (e.g. dose)
- Version 1 will include "Standard Solar Cycle"
  - Incorporate more sophisticated physics-based models to obtain median, 75th and 95th average flux values for *different* averaging periods, e.g. 5 min, 1 hour, 1 day, 1 week
  - Release ~2011

– Version 2 will include much needed new data sets
  - Relativistic Proton Spectrometer and other instruments on NASA Radiation Belt Storm Probes giving complete radiation belt coverage (launch in ~2012)
  - Instruments on DSX will provide slot region coverage (launch ~2010)

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Back-ups

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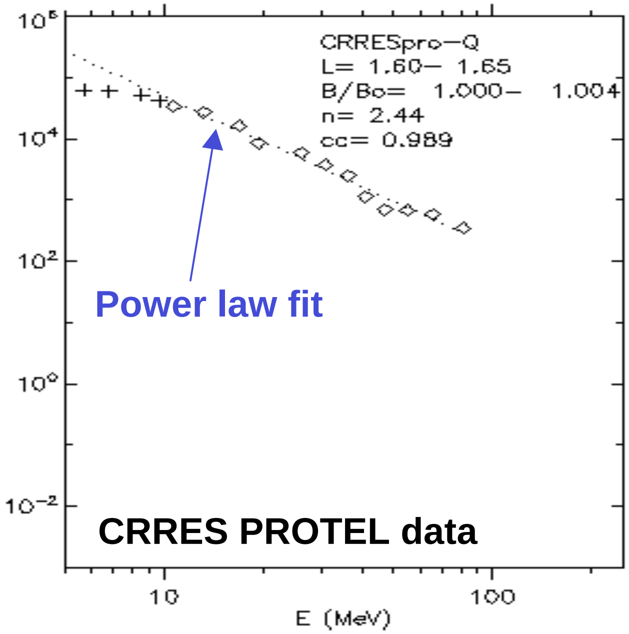
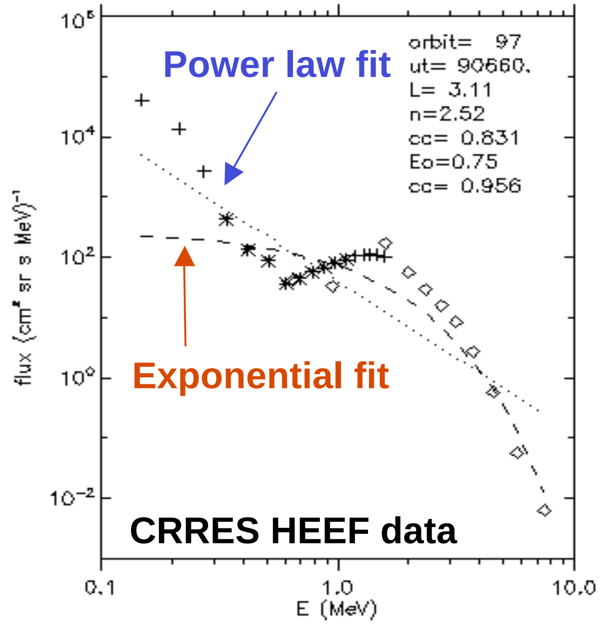
Challenges: Spectral Inversion

Protons



Electrons



Dosimeter data sets have wide spatial and temporal coverage (eg. HEO, ICO, TSX-5, GPS)… but are relatively simple instruments requiring sophisticated inversion algorithms & statistcal analysis to pull out spectra

- Protons are straight forward, power law approximation works 10 – 100 MeV: full speed ahead!
- Electrons are more complex, different functions at different locations & times: two-function approximation being developed

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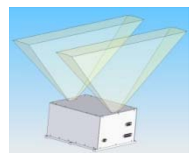
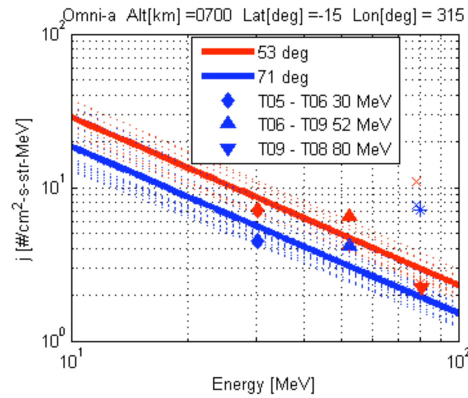
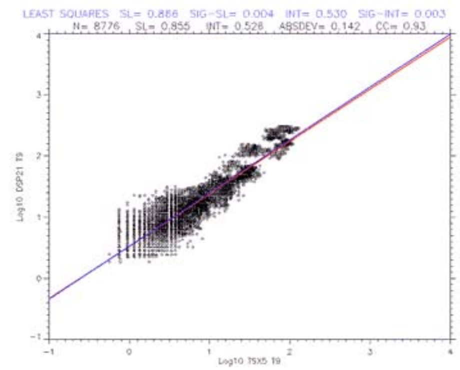
Trapped Proton Flux Map Development

1) Identify & gather data
2) Determine instrument uncertainty
   - Imperfect electronics
   - Response modeling
   - Contamination
   - Pitch-angle coverage
3) Compute spectrum (inversion)
4) Cross-calibrate
5) Bin into standard grid
6) Fill in the gaps
7) Integrate into application algorithms







Collect data → **Invert to spectrum** → **Cross-calibrate**

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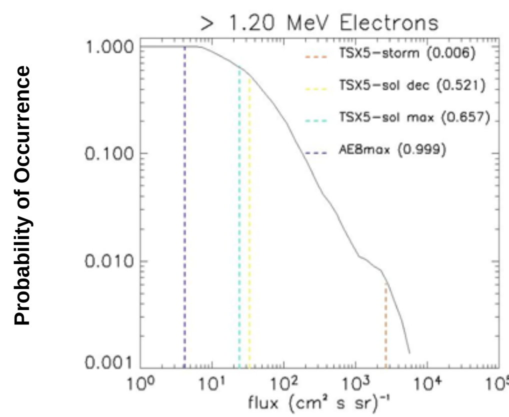
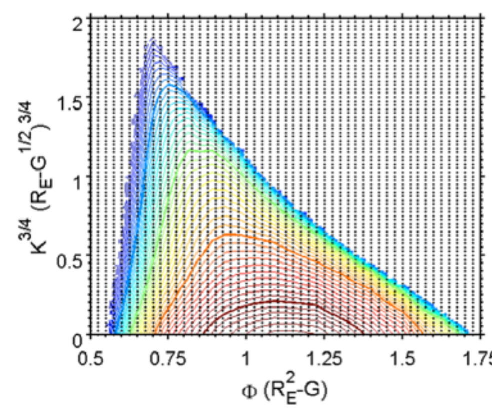
Orbit probability distribution ← **Grid & interpolate**





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Trapped Electron Model - Development

1. Intercalibrate data (50 keV – 10 Mev e-, CRRES & S3-3 sats)
2. Bin into L_m, E, α_{eq} (using IGRF/OPQ)
3. Compute daily averages & standard deviations within each bin
4. Compute 50^{th} and 95^{th} percentile log flux (m50, m95) in each bin, and a bootstrap error covariance matrix
5. Fit 50^{th} and 95^{th} percentiles with neural network in L_m, E, α_{eq} (fill in gaps)
6. Compute spatial (cov) and temporal (lagcov) covariance with daily averages
7. Fit spatial and temporal covariance to simple analytical functions (principle components)
8. Use m50 & m95 values to map the Gaussian independent variable to flux distributions, e.g. Weibull, lognormal, and vice versa

The model captures our best estimates of:

- Measurement uncertainty
- Probability spread (median, 95th percentile, shape)
- First-order spatial and temporal correlations (affects size of error bars, extremeness of worst cases)

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Trapped Electron Model – Calculating a Scenario

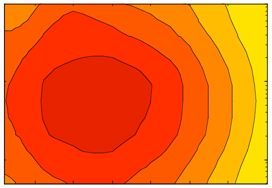
1. Evaluate m50, m95, cov and lagcov on grid
2. Compute time evolution matrices for principal components
3. Generate white noise time series
4. Generate time-space grid of gaussian independent variable using white noise time series passed through time evolution matrices

spatial & temporal covariance

Gaussian independent variable $$z_{t+\Delta t} = \Psi z_t + B\eta_{t+\Delta t}$$ **white noise**

5. Use error estimate on m50 and m95 to compute perturbed values unique to the scenario (used to convert model independent variable to fluxes and back)
6. Convert to fluxes using scenario values for m50, m95 & assumed Weibull shape
7. Project fluxes onto location of spacecraft (omni/integral spectrum at each time step)

Repeat many times (Monte – Carlo)



Principal components of Gaussian independent variable

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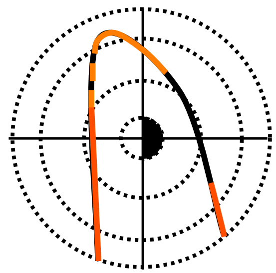
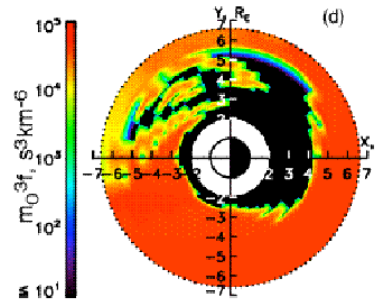
Standard Solar Cycle



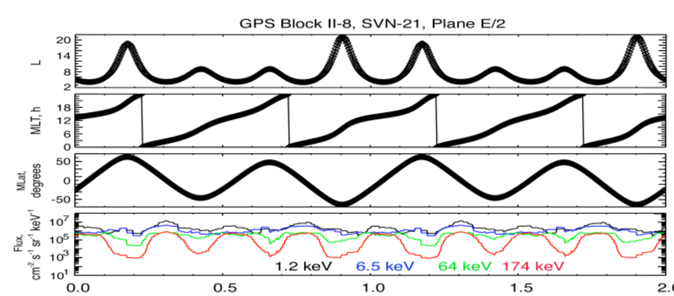
3 MeV/G (33 keV at 3 R_E) Protons

$$\frac{\partial f(\vec{X},t)}{\partial t} = \frac{1}{\Im}\sum_{ij}\frac{\partial}{\partial X_i}\left[\Im D_{X_i X_j}\frac{\partial f(\vec{X},t)}{\partial X_j}\right]$$



Sparse observations **+** **Physics-based model** **=** **Full global picture**

- A "Standard Solar Cycle" developed using re-analysis techniques can capture fully realistic spatio-temporal variation
  - Data assimilation adjusts physics-based numerical model – physics fills in the gaps
  - Reconstruct actual 11+ year interval on global grid at uniform time cadence
  - Includes realistic variability during actual storms
  - "Fly" planned mission through to accumulate average/worst case environments
- Three components:
  - Energetic protons (inner belt) - Aerospace
  - Energetic electrons (inner belt, slot, outer belt) - LANL
  - Plasmas (eV-keV e^-, H^+, O^+) - Aerospace



GPS fly-through of plasma model

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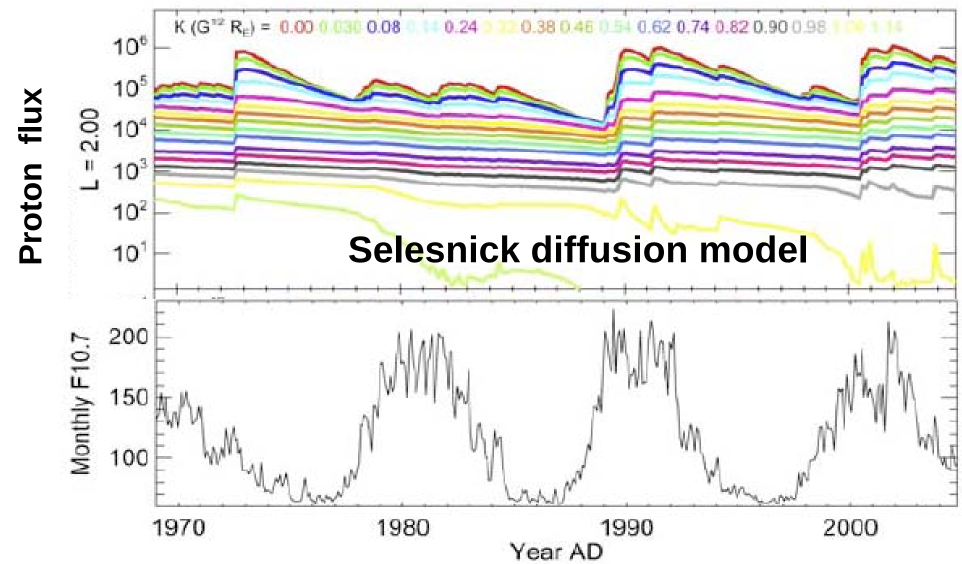
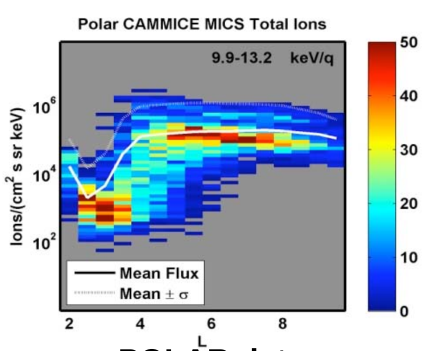
Standard Solar Cycle Component Models

- Energetic protons
  - Selesnick (2007) time-dependent diffusion model for multiple solar cycles
  - Investigating assimilation of HEO, ICO, SAMPEX & TSX-5 data
- Energetic electrons
  - LANL radial diffusion + Kalman Filter model for equatorially mirroring particles (DREAM) + Aerospace statistical model
  - Assimilation LANL-GEO at L=6.6 and GPS at L=4.2 (equatorial crossing)
- Plasma
  - Based on POLAR satellite plasma measurements (2 < L < 9)
  - Fill in gaps with Rice Convection Model





POLAR data

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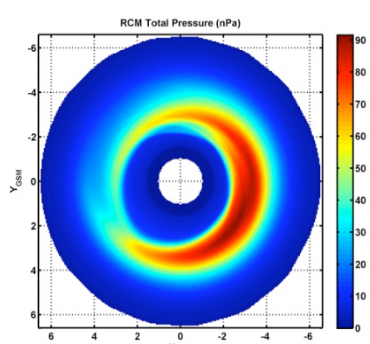
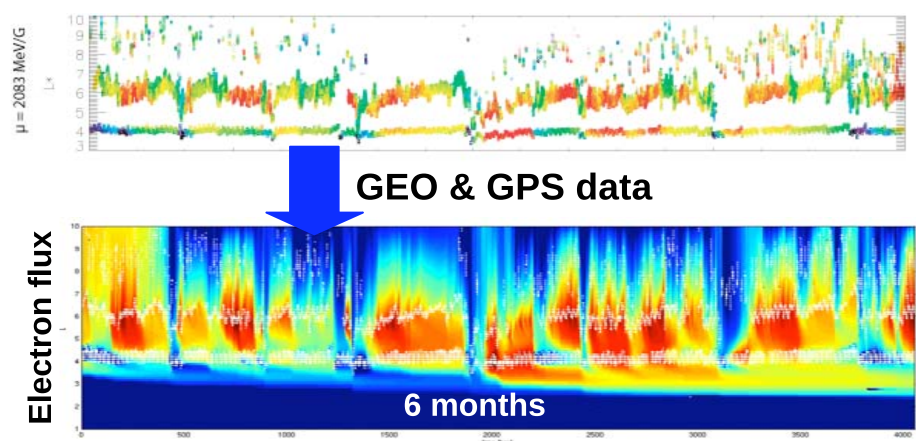


Rice Convection Model



DREAM model