Air Force Research Laboratory

AE9, AP9, and SPM: New Models for Radiation Belt and Space Plasma Specification

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Integrity ★ Service ★ Excellence

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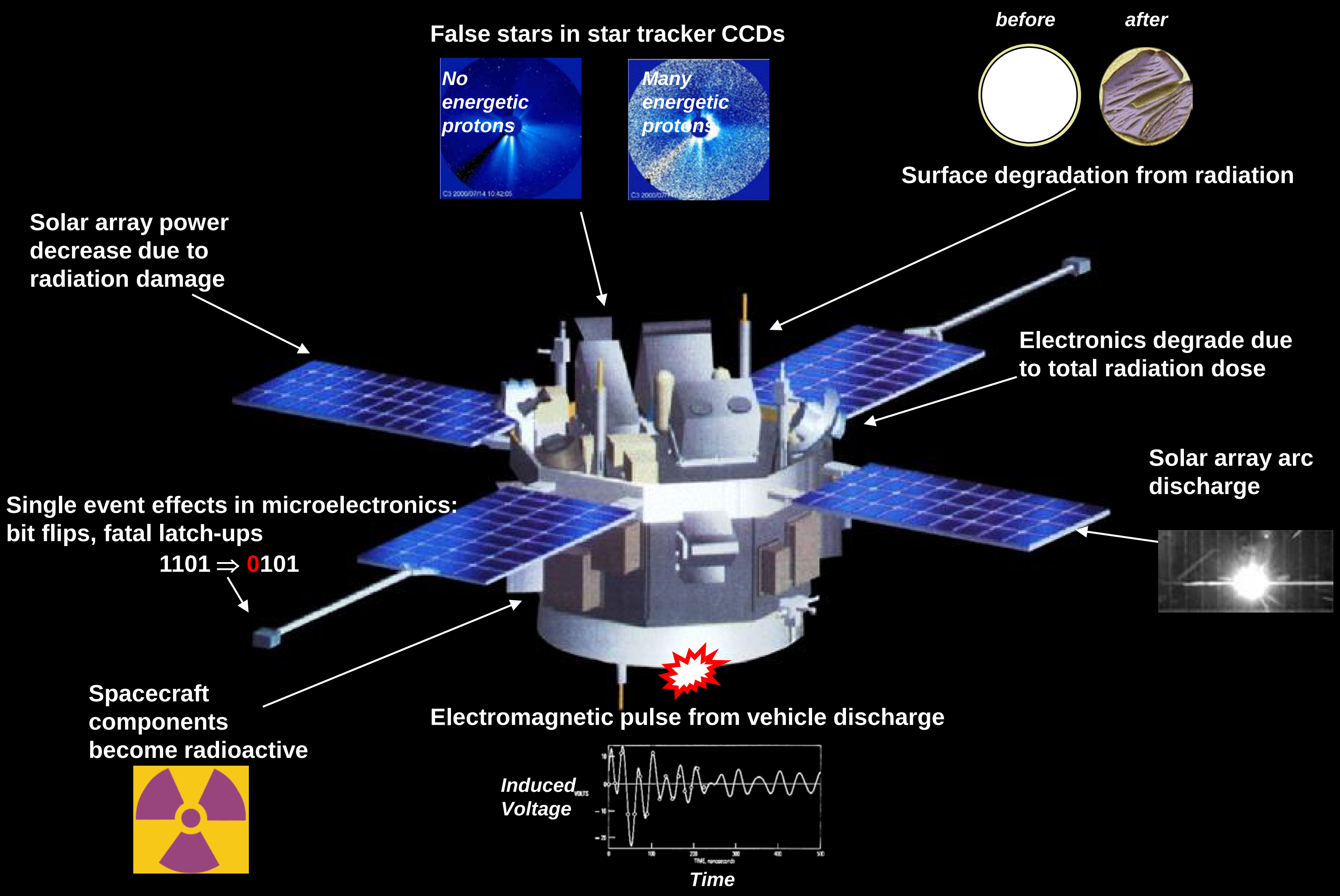
Hope to add more…

Outline

- Introduction & Background
- Architecture & Data
- Application
- Comparisons with AE8/AP8 and Data
- Future Plans
- Summary

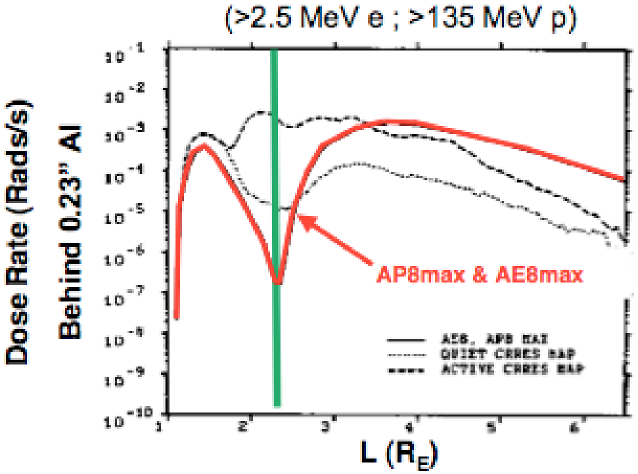
Energetic Particle & Plasma Hazards



The Need for AE9/AP9

- Prior to AE9/AP9, the industry standard models were AE8/AP8 which suffered from
  - inaccuracies and lack of indications of uncertainty leading to excess margin
  - no plasma specification with the consequence of unknown surface dose
  - no natural dynamics with the consequence of no internal charging or worst case proton single event effects environments
- AE8/AP8 lacked the ability to trade actual environmental risks like other system risks
- AE8/AP8 could never answer questions such as “how much risk can be avoided by doubling the shielding mass?”

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

System acquisition requires accurate environment specifications without unreasonable or unknown margins.

Requirements

Summary of SEEWG, NASA workshop & AE/AP-9 outreach efforts:

Priority	Species	Energy	Location	Sample Period	Effects
1	Protons	>10 MeV (> 80 MeV)	LEO & MEO	Mission	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	Dose (e.g. solar cells)

(indicates especially desired or deficient region of current models)

Inputs:

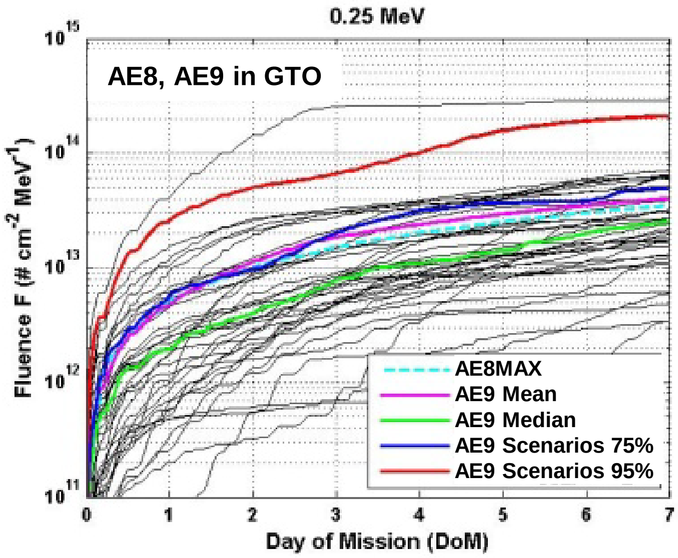
- **Orbital elements, start & end times**
- **Species & energies of concern (optional: incident direction of interest)**

Outputs:

- **Mean and percentile levels for whole mission or as a function of time for omni- or unidirectional, differential or integral particle fluxes [#/(cm^2 s) or #/(cm^2 s MeV) or #/(cm^2 s sr MeV)] aggregated over requested sample periods**

What is AE9/AP9?

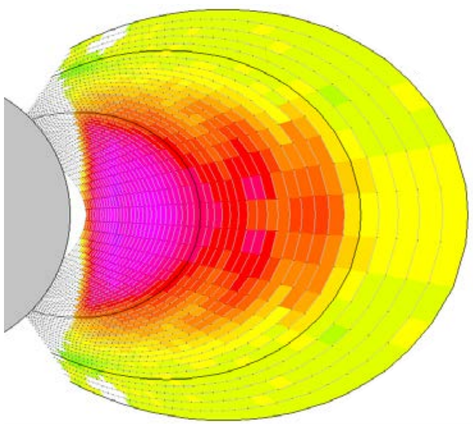
- AE9/AP9 specifies the natural trapped radiation environment for satellite design
- Its unprecedented coverage in particles and energies address the major space environmental hazards
- AE9/AP9 includes uncertainties and dynamics that have never been available for use in design
  - *The uncertainty allows users to estimate design margins (95 percentile rather than arbitrary factors)*
  - *Dynamic scenarios allow users to create worst cases for internal charging, single event effects, and assess mission life*



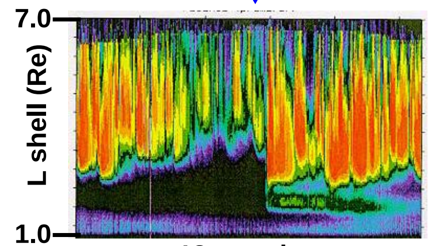
- “Turn-Key” system for ingesting new data sets ensures that the model can be updated easily
- The model architecture and its datasets are superior to AE8/AP8 in every way
- V1.0 released 20 January 2012 to US Government and Contractors
- V1.0 cleared for public release on 5 September 2012 (Current version is 1.04)

Architecture Overview

Satellite data



Satellite data & theory



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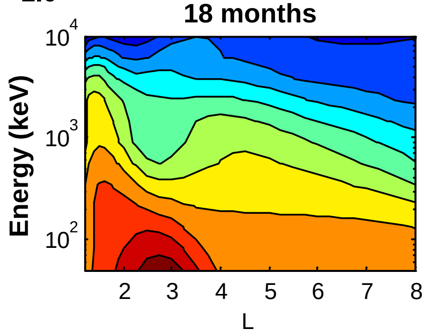

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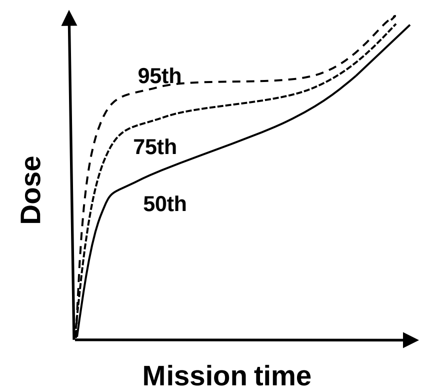
User's orbit



Flux maps

- **Derive from empirical data**
  - Systematic data cleaning applied
- **Create maps for median and 95th percentile of distribution function**
  - Maps characterize nominal and extreme environments
- **Include error maps with instrument uncertainty**
- **Apply interpolation algorithms to fill in the gaps**

Statistical Monte-Carlo Model

- **Compute spatial and temporal correlation as spatiotemporal covariance matrices**
  - From data (V 1.0)
  - Use one-day (protons) and 6 hour (electrons) sampling time (V 1.0)
- **Set up Nth-order auto-regressive system to evolve perturbed maps in time**
  - Covariance matrices give SWx dynamics
  - Flux maps perturbed with error estimate give instrument uncertainty

User application

- **Runs statistical model N times with different random seeds to get N flux profiles**
- **Computes dose rate, dose or other desired quantity derivable from flux for each scenario**
- **Aggregates N scenarios to get median, 75th and 90th confidence levels on computed quantities**

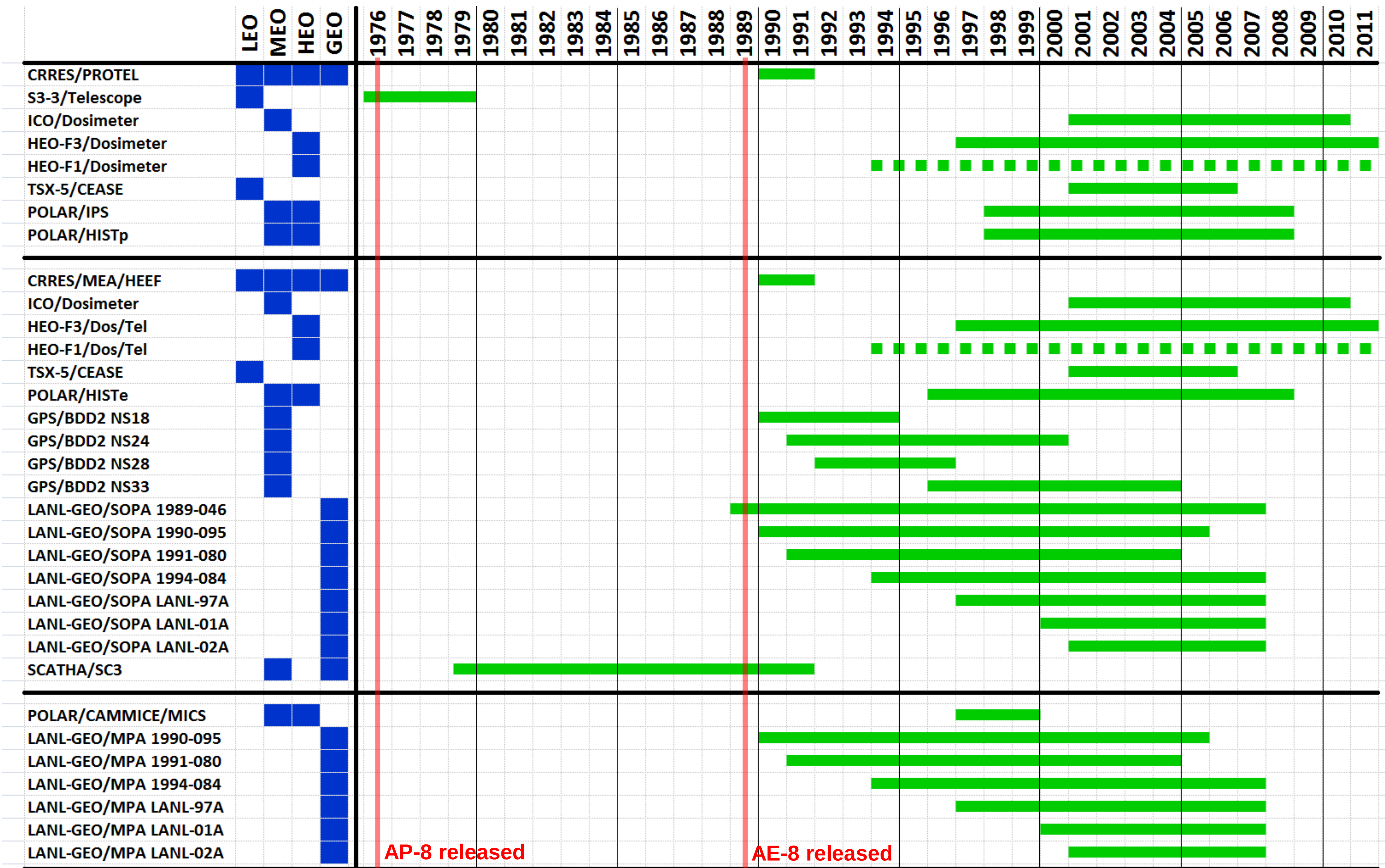
Data Sets – Energy Coverage

Protons	Orbit				Energy [MeV]																								
	LEO	MEO	HEO	GEO	0.10	0.20	0.40	0.60	0.80	1.00	2.00	4.00	6.00	8.00	10.0	15.0	20.0	30.0	50.0	60.0	80.0	100.0	150.0	200.0	300.0	400.0	700.0	1200.0	2000.0
CRRES/PROTEL	■	■	■	■							■	■	■	■	■	■	■	■	■	■	■								
S3-3/Telescope	■				■	■	■	■	■	■	■																		
ICO/Dosimeter		■													■	■	■	■	■	■	■	■	■	■	■	■			
HEO-F3/Dosimeter			■												■	■	■	■	■	■	■	■	■	■	■	■			
HEO-F1/Dosimeter			■												■	■	■	■	■	■	■	■	■	■	■	■			
TSX5/CEASE	■														■	■	■	■	■	■	■	■	■	■	■	■			
POLAR/IPS		■	■		■	■	■	■	■	■																			
POLAR/HISTp		■	■										■	■	■	■													

Electrons	Orbit				Energy [MeV]																				
	LEO	MEO	HEO	GEO	0.04	0.07	0.10	0.25	0.50	0.75	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50	7.00	8.50	10.0
CRRES/MEA/HEEF	■	■	■	■			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
ICO/Dosimeter		■									■	■	■	■	■	■	■	■	■	■	■	■	■		
HEO-F3/Dos/Tel			■						■	■	■	■	■	■	■	■	■	■	■						
HEO-F1/Dos/Tel			■									■	■	■	■	■	■	■	■	■	■	■	■	■	■
TSX5/CEASE	■					■	■	■	■	■	■	■	■	■	■										
POLAR/HISTe		■	■								■	■	■	■	■	■	■	■	■	■	■				
GPS/BDDII		■						■	■	■	■														
LANL GEO/SOPA				■		■	■	■	■	■	■	■													
SAMPEX/PET	■												■	■	■	■									
SCATHA/SC3		■		■				■	■	■	■	■	■	■	■	■	■	■							

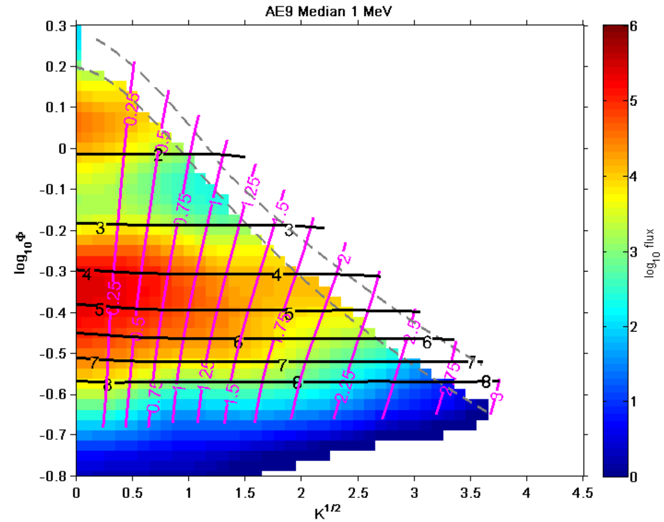
Plasma	Orbit				Energy [keV]											
	LEO	MEO	HEO	GEO	0.50	1.00	2.00	4.00	6.00	12.00	20.0	40.0	60.0	80.0	100.0	150.0
POLAR/CAMMICE/MICS		■	■			H+, He+, O+	■	■	■	■	■	■	■	■	■	■
POLAR/HYDRA		■	■			e-	■	■	■	■	■					
LANL GEO/MPA				■		He+, e-	■	■	■	■	■	■	■			

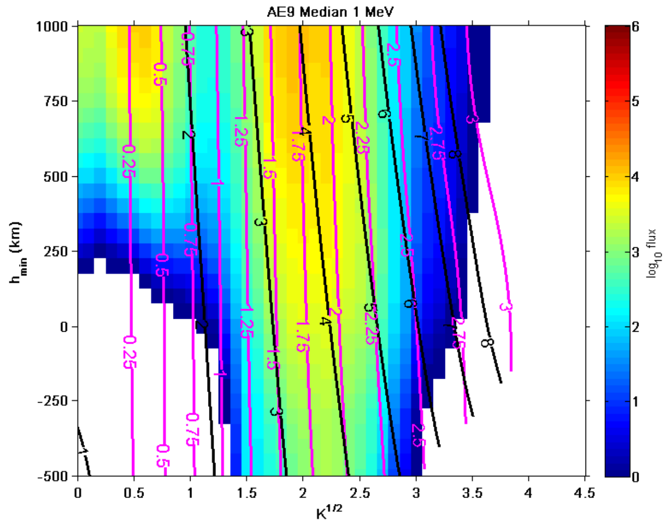
Data Sets – Temporal Coverage



Coordinate System

- **Primary coordinates are *E, K, Φ***
  - **IGRF/Olson-Pfitzer ‘77 Quiet B-field model**
  - **Minimizes variation of distribution across magnetic epochs**
- **(*K*, *Φ*) grid is inadequate for LEO**
  - **Not enough loss cone resolution**
  - **No “longitude” or “altitude” coordinate**
    - » **Invariants destroyed by altitude-dependent density effects**
    - » **Earth’s internal B field changes amplitude & moves around**
    - » **What was once out of the loss-cone may no longer be and vice-versa**
    - » **Drift loss cone electron fluxes cannot be neglected**
- **Version 1.0 splices in a LEO grid onto the *(Φ, K)* grid at 1000 km**
  - **Minimum mirror altitude coordinate h_{min} to replace *Φ***
  - **Capture quasi-trapped fluxes by allowing $h_{min} < 0$ (electron drift loss cone)**
  - **$\min(h_{min})$ set to – 500 km**

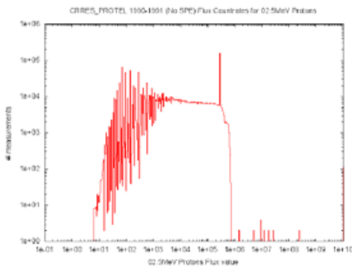


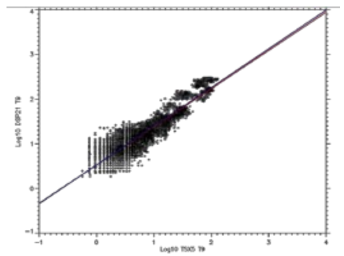


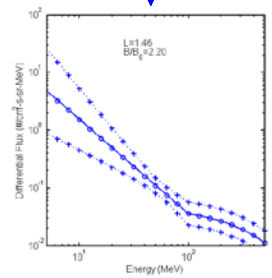
Building Flux Maps

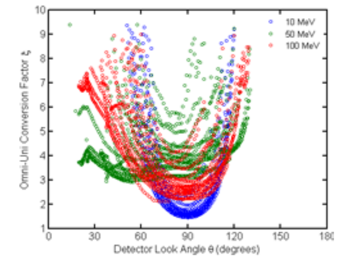
Example for a dosimeter data set

Sensor model





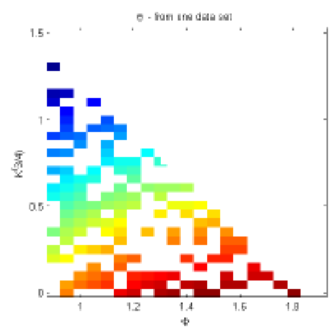


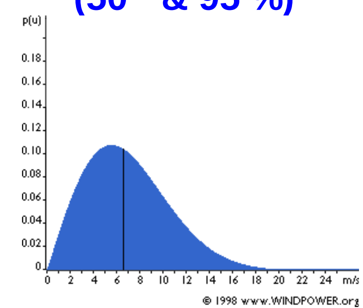


Sensor 1 data → Cleaning → Cross-calibration → Spectral inversion → Angle mapping (j_{90})

↓

Statistical reduction (50th & 95 %) → Template interpolation → Flux map – sensor 1





Flux map – sensor 1

Flux map – sensor 2

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Flux – map sensor N

Bootstrap initializing with variances

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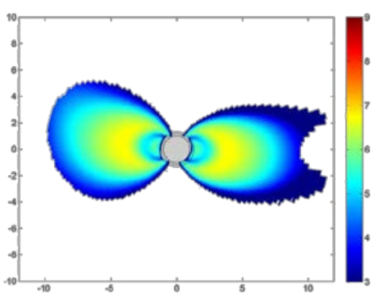
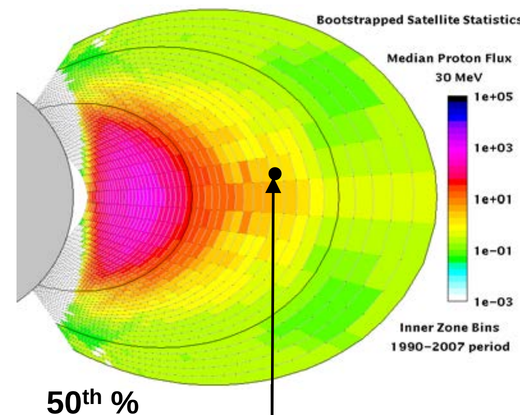
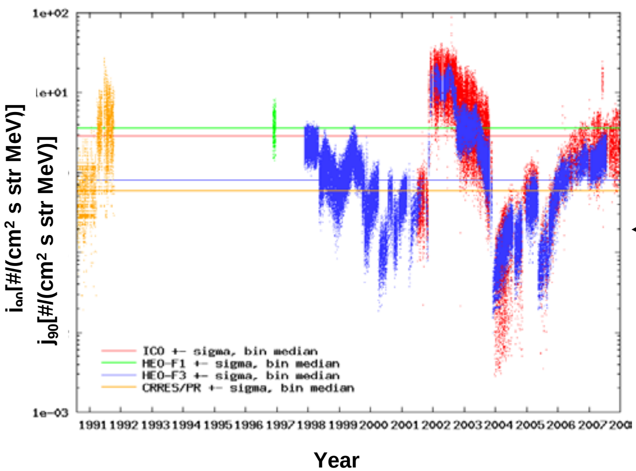
50th & 95 % Flux maps

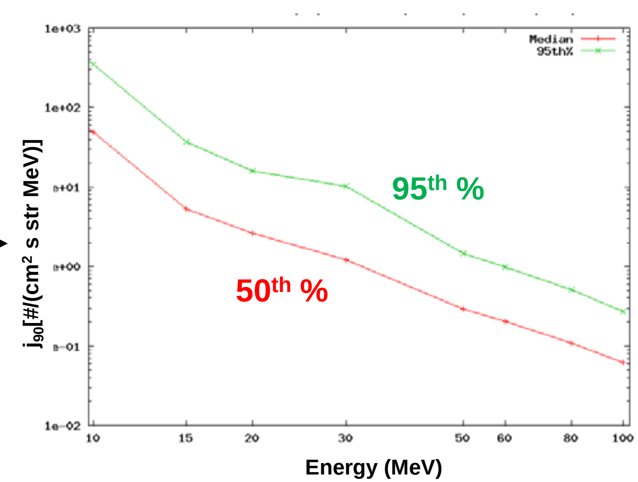


Example: Proton Flux Maps

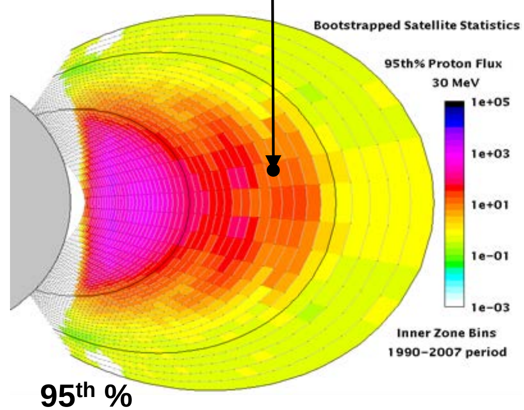




Time history data



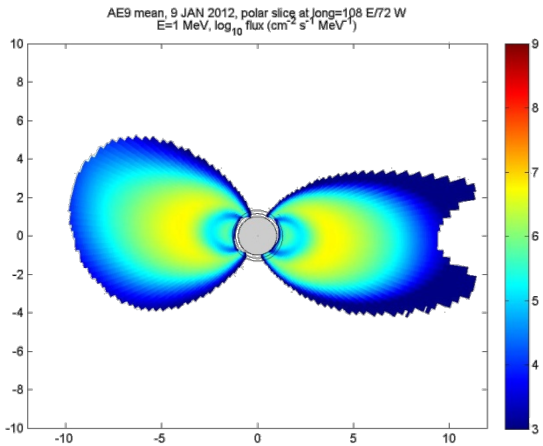
Energy spectra



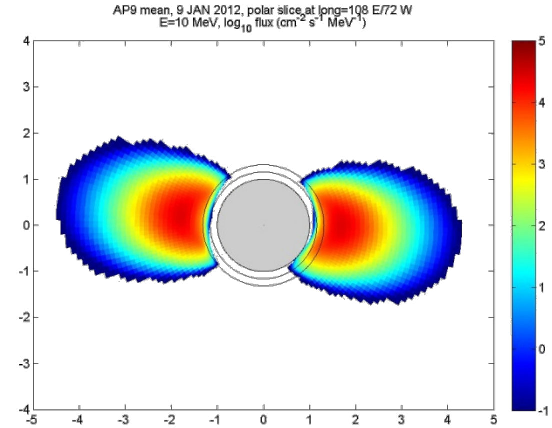
Flux maps (30 MeV)

Gallery of Mean Flux Maps

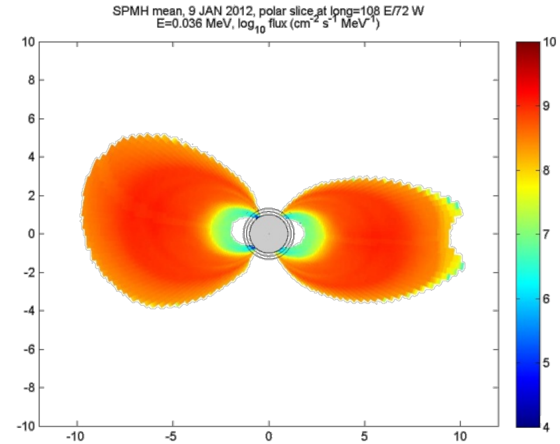
AE9 1 MeV



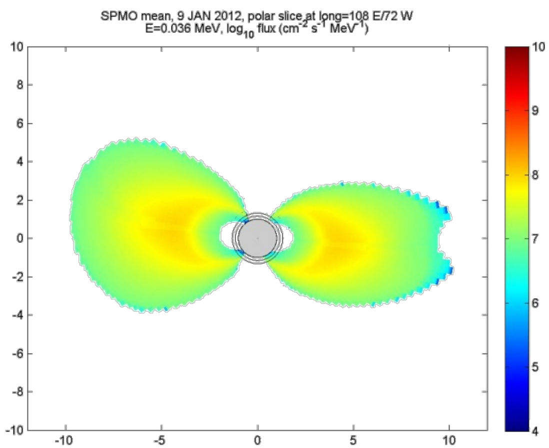
AP9 10 MeV



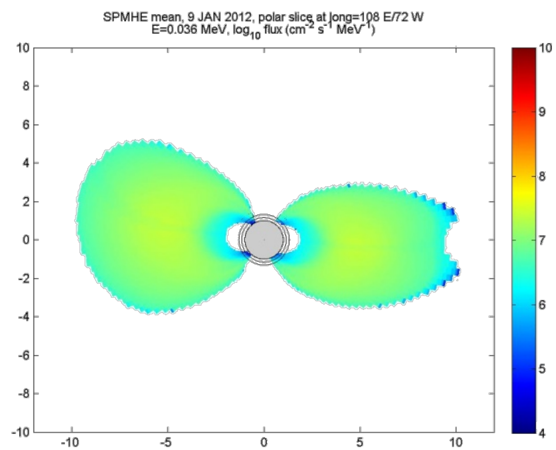
SPMH 36 keV



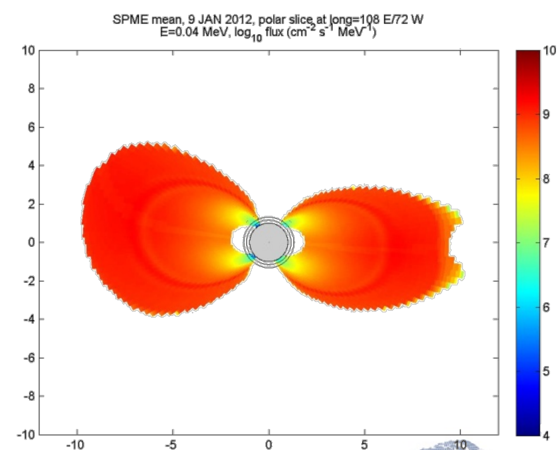
SPMO 40 keV



SPMHE 40 keV



SPME 40 keV



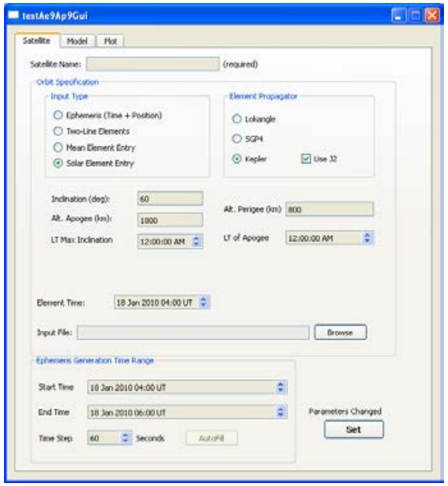
GEOC coordinates

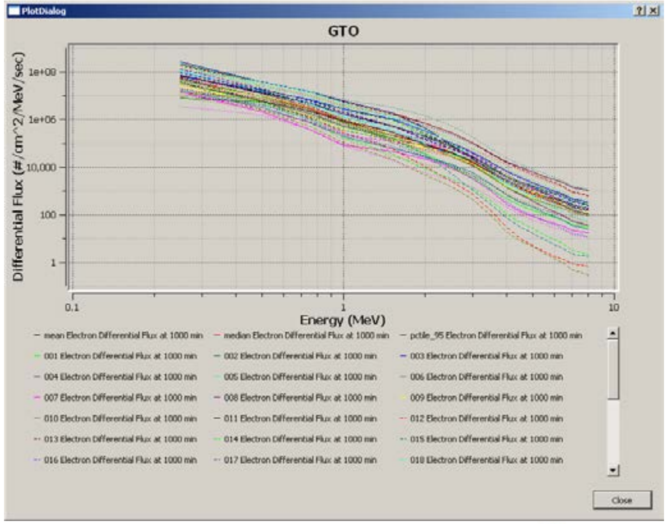
Software Applications (1)

- **Primary product: AP9/AE9 “flyin()” routine modeled after ONERA/IRBEM Library**
  - **C++ code with command line operations**
  - **Input: ephemeris**
  - **Runs *single* Monte-Carlo scenario**
  - **Output: flux values along orbit**
    - **Unidirectional or Omnidirectional**
    - **Differential or Integral**
    - **Mean (no instrument error or SWx)**
    - **Perturbed Mean (no SWx)**
    - **Full Monte-Carlo**
  - **Wrappers available for C and Fortran**
  - **Source available for other third party applications on request (pending license)**

Software Applications (2)

- **However… an application tool is provided to demonstrate completed capability**
  - **Accessible by command line or GUI interface**
  - **Contains orbit propagator, Monte-Carlo aggregator and SHIELDOSE-2 dose estimation applications**
  - **Contains historical models AE8, AP8, CRRESELE, CRRESPRO and CAMMICE/MICS**
  - **Provides simple plot and text file outputs**
- **We expect other developers to create new software tools incorporating the model**





AP9/AE9 Code Stack

GUI input and outputs

– User-friendly access to AE-9/AP-9 with nominal graphical outputs

High-level Utility Layer

– Command line C++ interface to utilities for producing mission statistics
– Provides access to orbit propagator and other models (e.g. AP8/AE8, CRRES)
– Aggregates results of many MC scenarios (flux, fluence, mean, percentiles)
– Provides dose rate and dose for user-specified thicknesses (ShieldDose-2)

Application Layer

– Simple C++ interface to single Monte-Carlo scenario “flyin()” routines

AP9/AE9 Model Layer

– Main workhorse; manages DB-access, coordinate transforms and Monte Carlo cycles; error matrix manipulations

Low-level Utility Layer

– DB-access, Magfield, GSL/Boost

Run Modes

- Static Mean/Percentile
  - Flux maps initialized to mean or percentile values
  - Flux maps remain static throughout run
  - Flux output is always the mean or selected percentile
  - Percentiles are appropriate only for comparing with measurements at a given location
- Perturbed Mean/Percentile
  - Flux maps are initialized with random perturbations
  - Flux maps remain static throughout run
  - Multiple runs provide confidence intervals based on model uncertainties
  - Appropriate for cumulative/integrated quantities (e.g., fluence, TID)
- Monte Carlo
  - Flux maps are initialized with random perturbations
  - Flux maps evolve over time
  - Multiple runs provide confidence intervals including space weather (e.g., worst-case over specified time intervals)
  - Needed for estimate of uncertainty in time-varying quantities (e.g., SEE rates, deep dielectric charging)

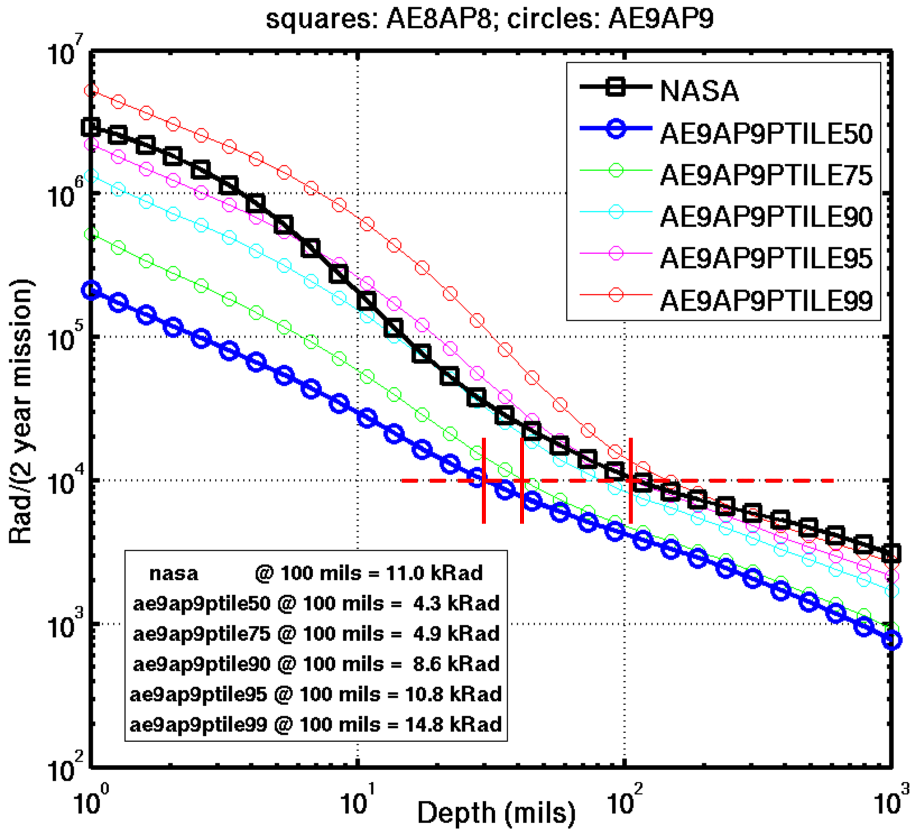
What Type of Run

Spec Type	Type of Run	Duration	Notes
Total Dose	Perturbed Mean	Several orbits or days	SPME+AE9, SPMH+AP9+Solar
Displacement Damage (proton fluence)	Perturbed Mean	Several orbits or days	AP9+Solar
Proton SEE (proton worst case)	Monte Carlo	Full Mission	AP9+Solar
Internal Charging (electron worst case)	Monte Carlo	Full Mission	AE9 (no SPME)

- Run 40 scenarios through either static Perturbed Mean or dynamic Monte Carlo
- Compute statistics by comparing results across scenarios (e.g., in what fraction of scenarios does the design succeed)
- Do not include plasma (SPM*) models in worst case runs

AE9/AP9 Use Example: LEO Dipper

- A rarely-used mission orbit (150 x 1500 km, 83º inclination) required an analysis of trades between two hazardous environments:
  - Perigee dips at ~150 km yield intense atomic oxygen erosion of exposed polymers
  - Higher apogees expose the vehicle to radiation dose and SEE hazards from the inner Van Allen belt protons
- AE9/AP9 places the mission in the context of normal (blue) or extreme (red) radiation environments



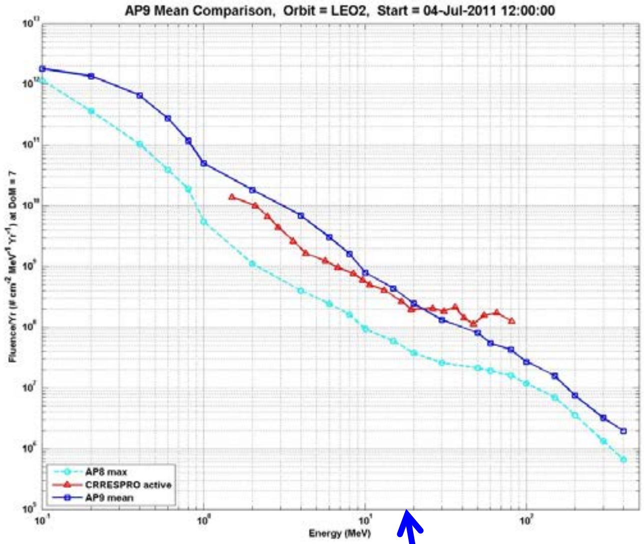
- The AE9/AP9 environment percentiles informed the program of the margin they will have for EEE parts selection

AE9/AP9 allows new concepts to trade space environment hazards against other mission constraints.

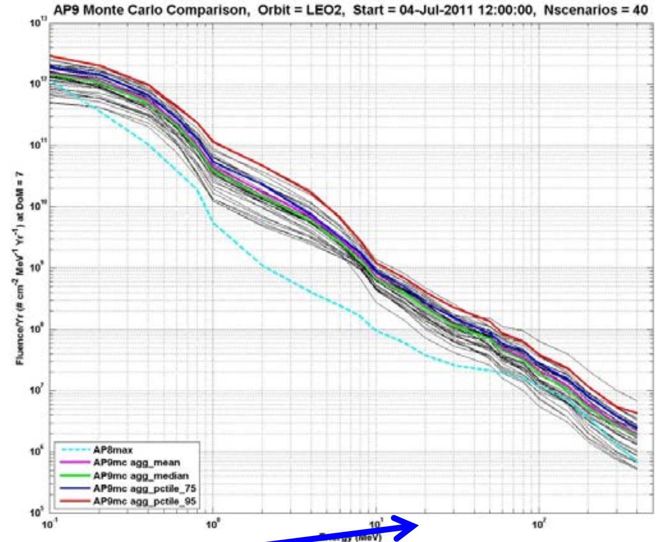
MODEL & DATA COMPARISONS

Example—AP9 in LEO

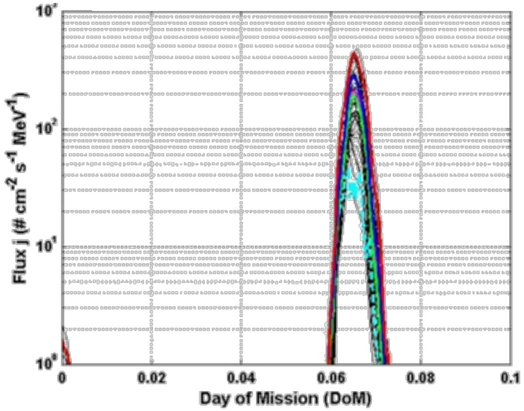
Mean Spectra



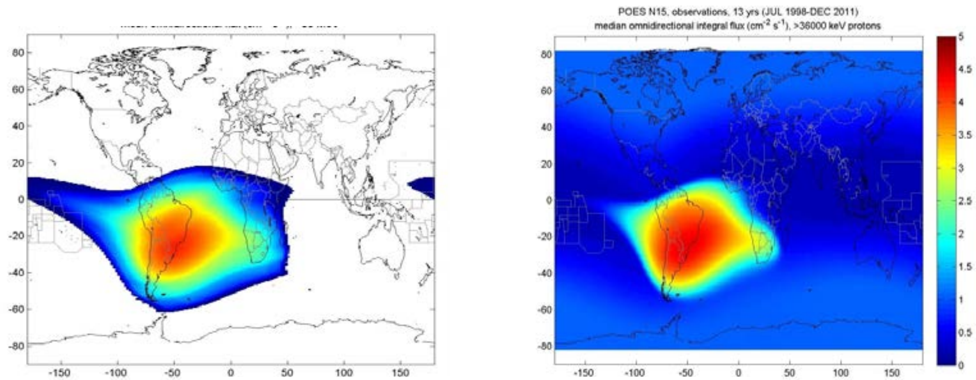
Monte Carlo Spectra



20 MeV time series



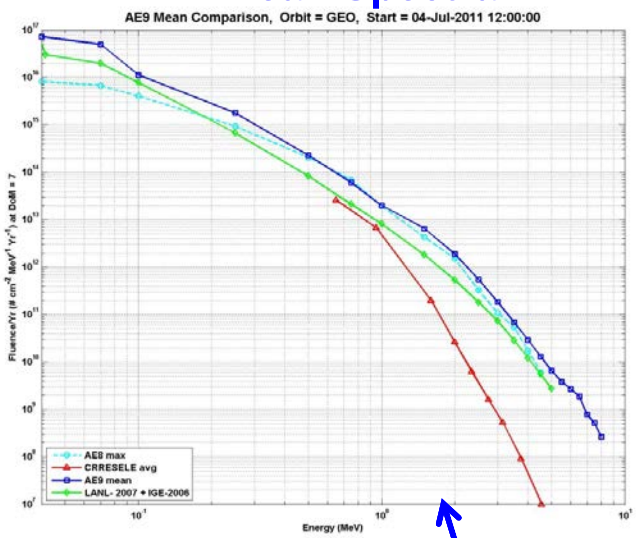
36 MeV map



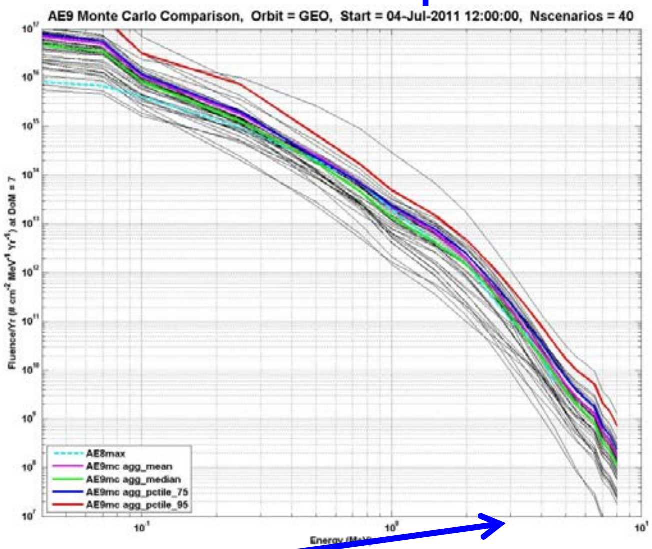
AP9 model vs. POES data

Example—AE9 in GEO

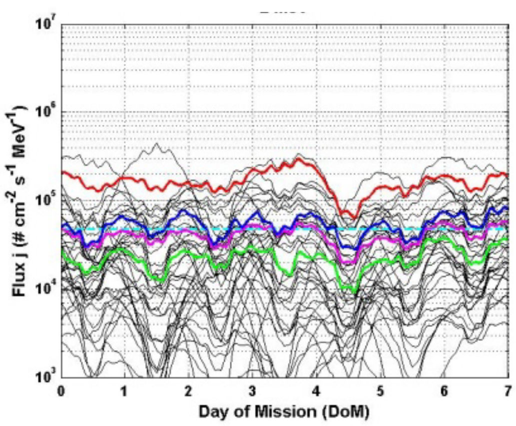
Mean Spectra

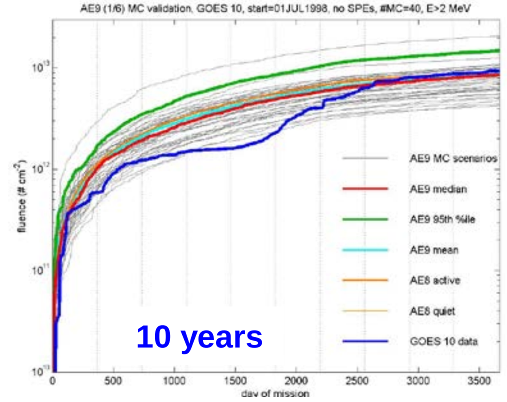


Monte Carlo Spectra



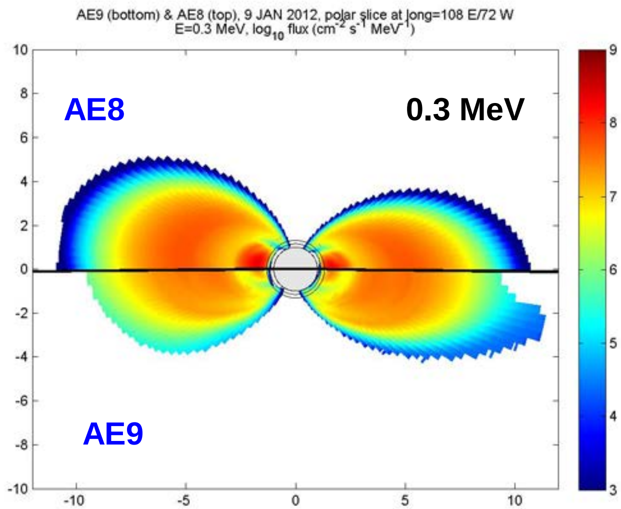
2 MeV time series

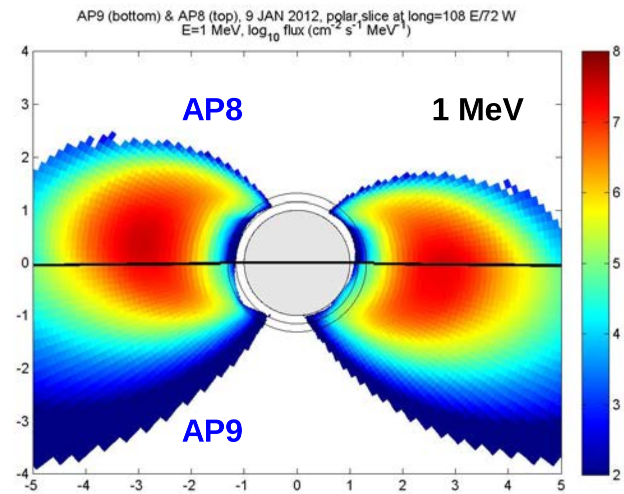


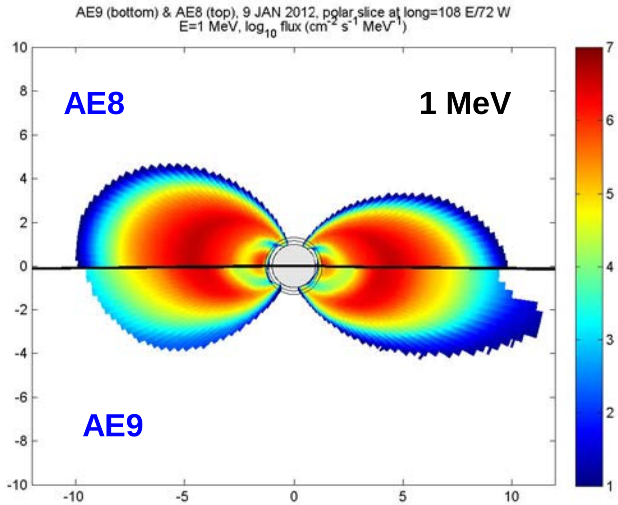


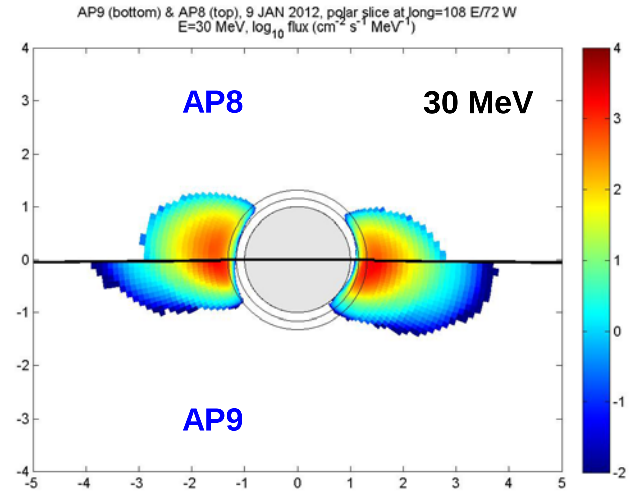
Compare to GOES >2 MeV fluence

AE9/AP9 Compared to AE8/AP8

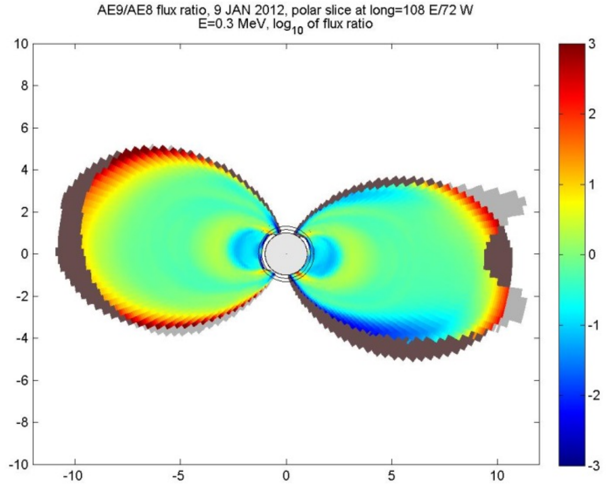


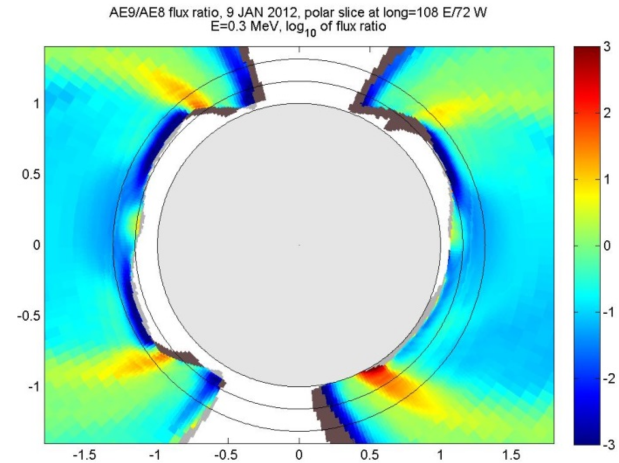




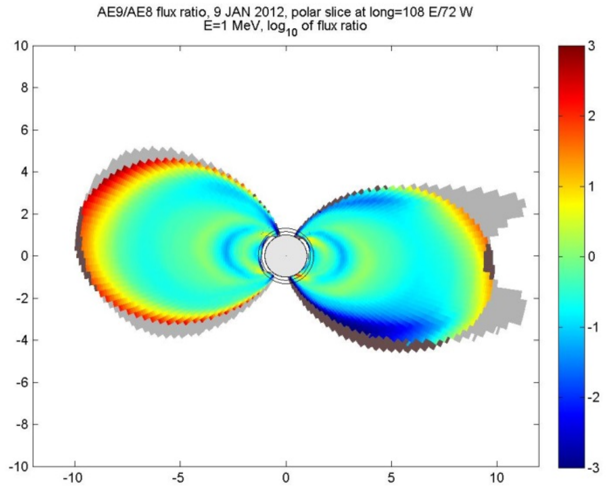


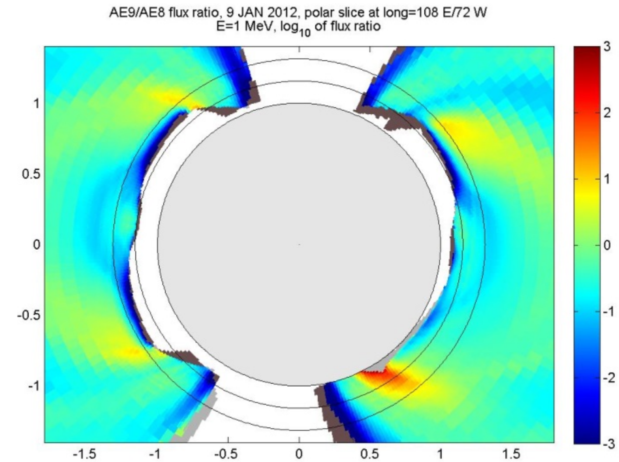
AE9-to-AE8 flux ratio





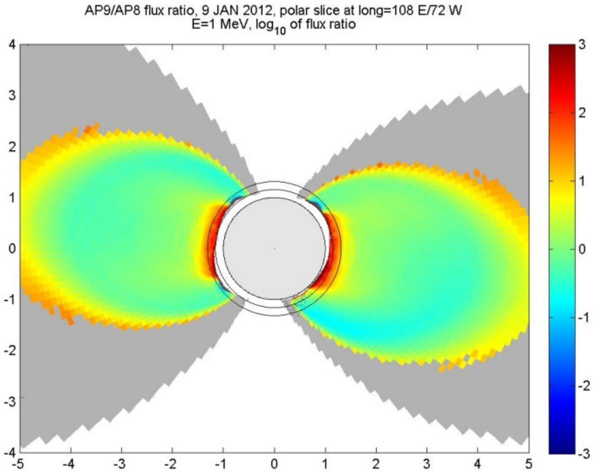
0.3 MeV

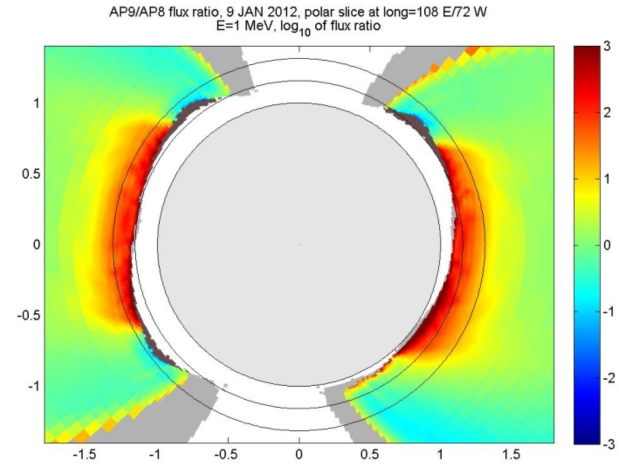




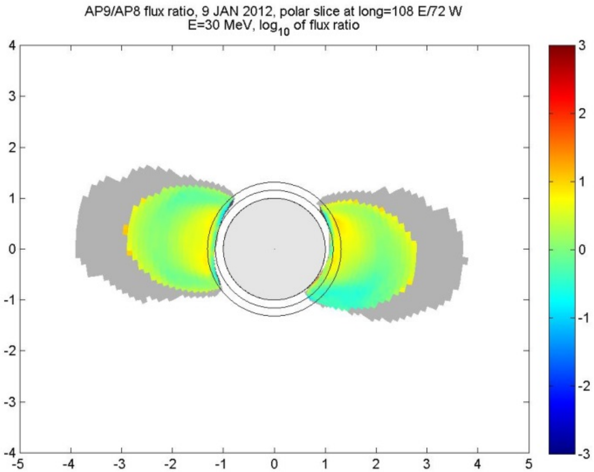
1 MeV

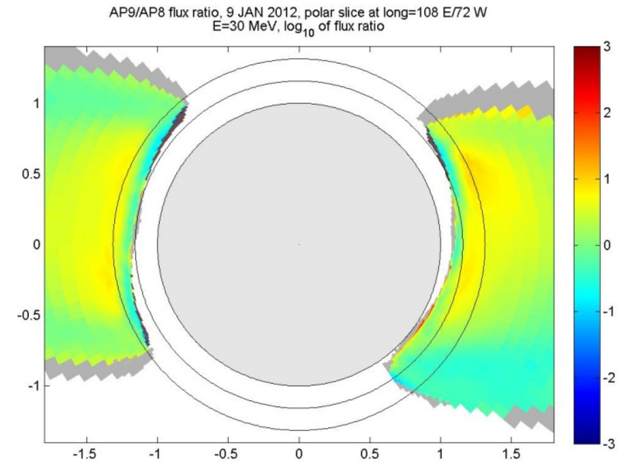
AP9-to-AP8 Flux Ratio





1 MeV





30 MeV

Known Issues—V1.0

- No reliable data for inner zone electrons at lower energy (<~ 600 keV)
  - Spectral and spatial extrapolation can lead to large deviations (e.g., comparison to POES and DEMETER data)
  - No worse than AE8
- No data for high energy protons (> 200 MeV)
  - No data – spectra are extrapolated based on physical models
  - The primary reason for flying the Relativistic Proton Spectrometer (RPS) on the Van Allen Probes
- SPMO (plasma oxygen) and SPME (plasma electron) have small errors which do not reflect the uncertainty in the measurements
  - Not much data (one instrument) with uncorrelated errors
  - Spectral smoothness was imposed at the expense of clamping the error bar
- Error in the primary variables θ_1 (log 50^{th} percentile) and θ_2 (log 95^{th}-50^{th} percentile) capped at factor of 100 (electrons) and 10 (protons)
  - Large variations in these quantities can quickly lead to obviously unrealistic variations in fluxes derived from our assumed non-Gaussian distributions
  - Does not limit representation of space weather variation which is captured in θ_2 (95^{th} %)

RBSP/Van Allen Probe data will be incorporated into V2.0 and should address many of the V1.0 deficiencies.

International Collaboration

- Boulder workshop October 2012
  - Proposed AE9/AP9/SPM as an ISO standard
  - Initiated participation from ESA, Russia, Japan
- Santorini Workshop June 2013
- Azur data
  - Obtained data set from Daniel Heynderickx
  - Will be incorporated into next release
- SPENVIS
- We invite additional collaboration
  - New data sets
  - Additional applications & functionality
- International collaboration on updates after V2.0, (as with IGRF, IRI)
- A new name:
  - **IRENE** -- **I**nternational **R**adiation **E**nvironment **N**ear **E**arth
  - Will gradually replace "AE9/AP9" as international involvement increases

Recent AE9/AP9 Improvements

CmdLineAe9Ap9 Program

- Support more SHIELDOSE2 options
- Improved Linux compiler optimization settings
- Documented command-line options
- Multiple file limit resolved
- MJD conversion fixed

User's Guide Document

- Additional information provided for
  - SHIELDOSE2 model parameters
  - Legacy model 'advanced' options
  - Model performance tuning
  - Orbit definition parameters
  - Coordinate system details
  - Modified Julian Date conversions

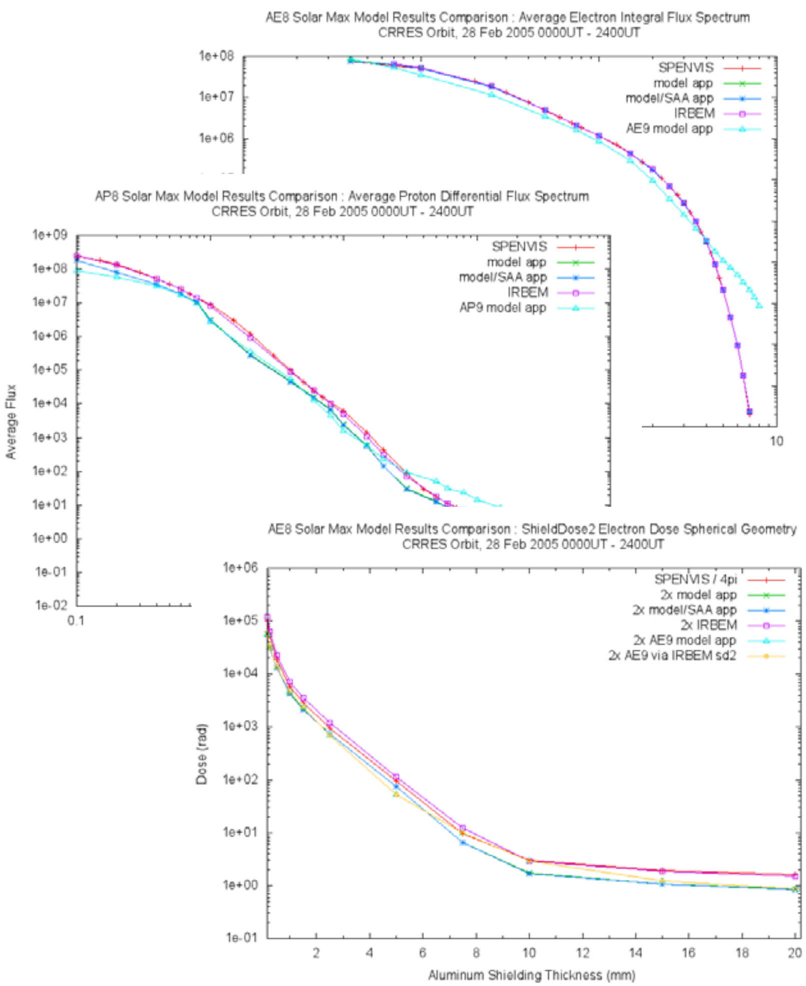
Graphical User Interface

- Clarified labels & error messages
- Added more 'tooltip' information
- Various GUI behavior fixes

New Utility Programs

- PlasmaIntegral
  - Adjusts Plasma integral flux calculations (for non-GUI runs)
- CoordsAe9Ap9
  - Calculates 'Adiabatic Invariant' coordinates from satellite ephemeris

Comparison of AE8/AP8 (Legacy) Models to External Implementations



Model Run Parameters

- Ax8 in CmdlineAe9Ap9, IRBEM and SPENVIS
- CRRES satellite orbit (GTO)
- Fixed Epoch & Shift SAA options 'on'
- 28 Feb 2005 (arbitrary), 24 hours, Δt=120 sec

Comparison Results

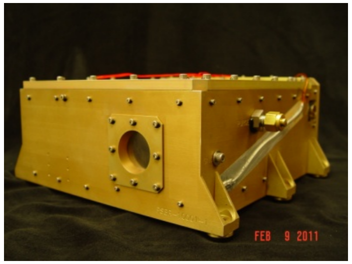
- Most model results *nearly* matching
  - Different magnetic field models used
- Integral Flux results match
- Differential Flux results near match
  - Differences due to calculation method
- SHIELDOSE2 results mostly match
  - Slight offset due to Diff Flux differences

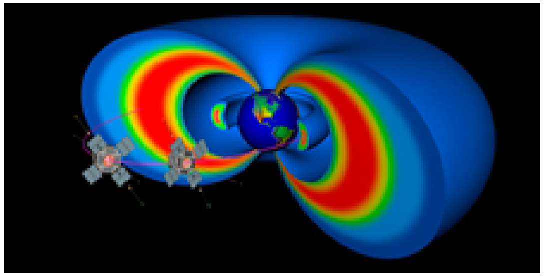
Full report documents all findings

Future Versions

- One major pitfall of AE8/AP8 was the cessation of updates derived from new space environment data and industry feedback
- To insure that AE9/AP9 remains up to date and responsive to program evolution, the following actions must occur in 2013 to 2015:
  1. Complete full documentation of V1.0 and release underlying database
  2. Add these industry-requested capabilities: solar cycle dependence of LEO protons; a “sample solar cycle”; local time dependence of plasmas; longitude dependence of LEO electrons
  3. Ensure ongoing collection of new data to fill holes, improve accuracy, and reduce uncertainty (e.g., Van Allen Probes, with emphasis on inner belt protons; AFRL/DSX; TacSat-4, foreign and domestic environment datasets)
  4. Establish mechanism for annual updates to result in V2 in 2015
- NOAA/NGDC has offered to coordinate 5-year updates after 2015
  – NGDC hosted an international collaboration workshop for AE9/AP9 in October 2012

Relativistic Proton Spectrometer





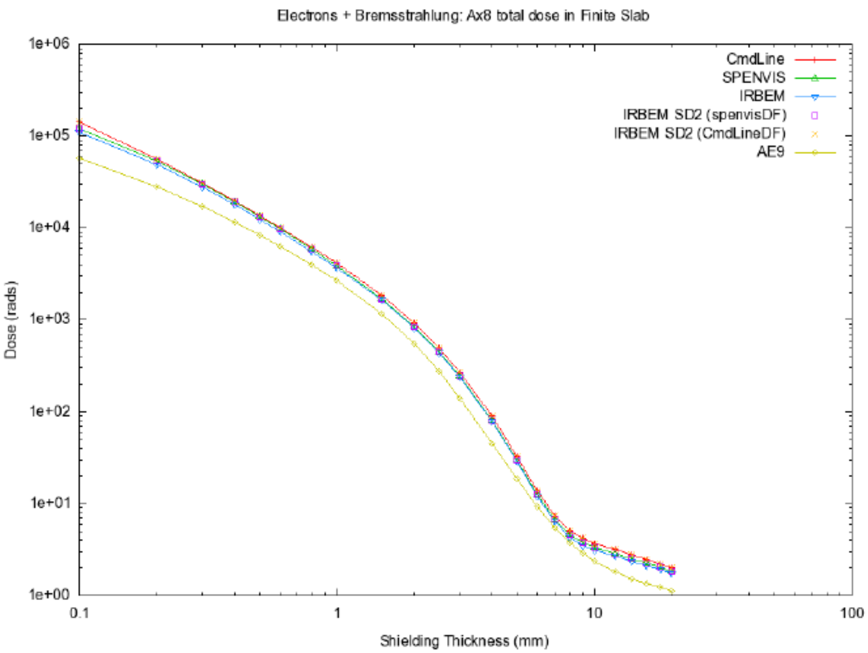
NASA Van Allen Probes (RBSP)

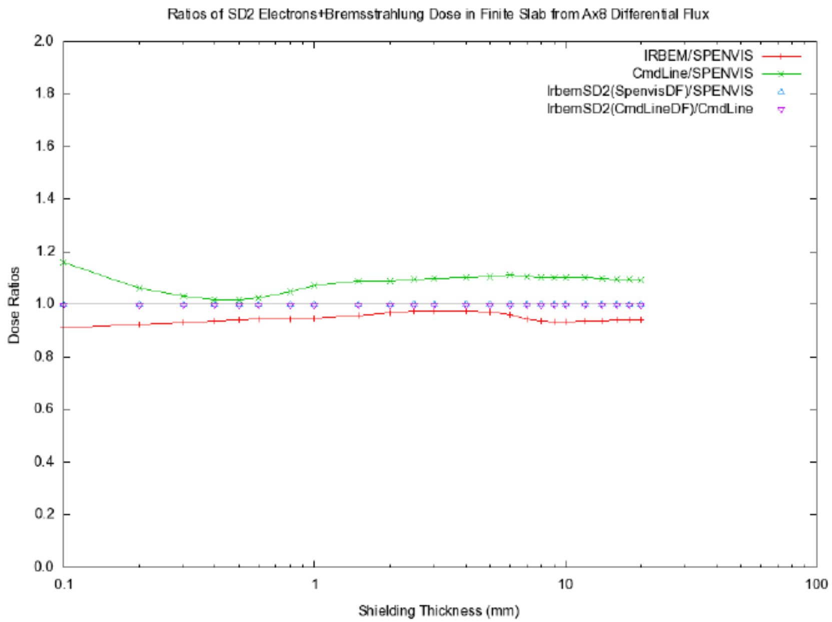
Launch August 2012

Keeping the model alive will insure that it stays in step with concerns in program acquisition and lessons from space system flight experience.

Version 1.05

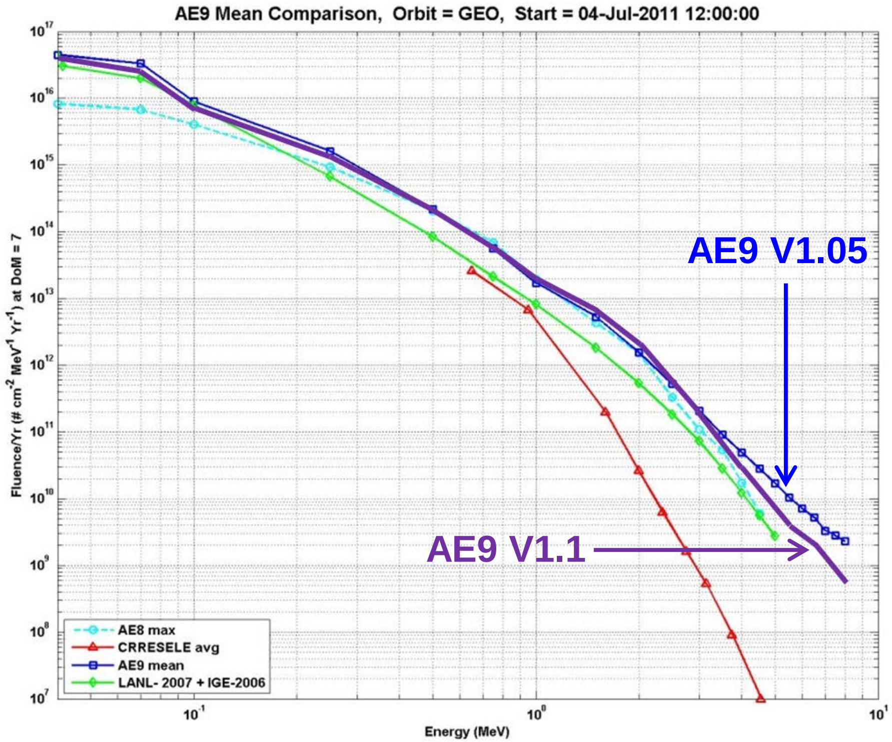
- We recently rediscovered an error in SHIELDOSE2 (NIST version)
  - Swapped data tables for Bremsstrahlung in some geometries
  - SPENVIS and OMERE had the fix already
  - IRBEM-LIB did not (it does now)
  - All implementations now agree to within 20% or better
- Public release in August 2013





Version 1.1

- We recently identified an error affecting some cross calibrations in AE9
  - Incorrect data set version was used in CRRES to LANL-GEO cross calibration
- Result affects relative calibration of LANL-GEO/SOPA datasets, along with error estimates for LANL-GEO/SOPA, CRRES, and POLAR datasets
- Effect is likely small:
  - GEO flux ~20% greater for E>1 MeV
  - GEO flux ~20-50% less for E<0.5 MeV
  - Plot illustrates estimated effect on GEO electron spectra
- Expected public release in Sept.-Oct. 2013



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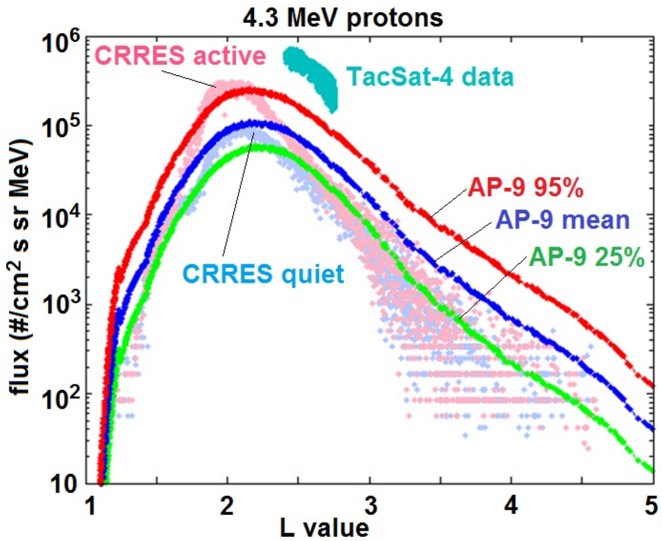
Version 1.2

- New data set (first new data to be added):
  - TacSat-4/CEASE proton data—captures new observations of elevated 1-10 MeV protons
  - Additional plasma data, TBD but likely THEMIS/ESA
- New electron templates
  - Improvements for inner zone electrons and for >3 MeV spectra
- Feature improvements
  - More options for orbit element input and coordinates
  - Fix flux-to-fluence calculations to cover variable time steps—supports optimizing time steps for shorter run times
  - Allow selection of time period for calculation of fluence—supports different time periods for different effects
  - Mac OSX build
- Expected public release in 2014/Q1



Version 1.5

- New data:
  - Protons: Azur, Van Allen/MagEIS & REPT
  - Electrons: DEMETER/IDP, Van Allen/MagEIS & REPT
  - Plasma: SCATHA/SC8, AMPTE/CCE & CHEM
- New features
  - Parallelization capability for runs on clusters—needed to speed up long runs
  - Pitch angle tool—make internal pitch angle calculations accessible to users
- Expected public release in 2014/Q4
- International collaborators on board—with new model name

Version 2.0

- Major feature changes:
  - Standard solar cycle—introduces a full solar cycle reanalysis as a flythrough option
  - New module frameworks for e.g. plasma species correlations, SPM stitching with AE9/AP9, auroral electrons, additional coordinates for MLT variation in SPM
  - AP9 improvements: solar cycle variation in LEO, east-west effect
  - Improved algorithms for faster run times
- New data
  - Van Allen/MagEIS & REPT protons and electrons
  - PAMELA protons—addresses high energy proton spectra
  - Other international data sets: possibilities include Cluster/RAPID-IIMS, ESA SREMs, CORONAS, NINA, Akebono/EXOS-D, SAC-C, Jason2
- Expected public release in 2015/Q4
- Subsequent releases will include new data
  - DSX/SWx, ERG

Summary

- AE9/AP9 improves upon AE8/AP8 to address modern space system design needs
  - More coverage in energy, time & location for trapped energetic particles & plasma
  - Includes estimates of instrument error & space weather statistical fluctuations
  - Designed to be updateable as new data sets become available
- Version 1.04 is now available to the public
- Review paper published in Space Science Reviews: http://link.springer.com/article/10.1007/s11214-013-9964-y
- Updates are in the works
  - Improvements to the user utilities (no change to underlying environments)
  - Improvements to the model environments (new data)
  - Additional capabilities (new features, new models)
- For future versions collaborative development is the goal
  - Being proposed as part of new ISO standard
  - Discussions have begun on collaboration with international partners

Points of Contact

- **Comments, questions, etc. are welcome and encouraged!**
- **Please send feedback to (copy all):**
  - **Bob Johnston, Air Force Research Laboratory, AFRL.RVBXR.AE9.AP9.Org.Mbx@kirtland.af.mil**
  - **Paul O'Brien, Aerospace Corporation, paul.obrien@aero.org**
  - **Gregory Ginet, MIT Lincoln Laboratory, gregory.ginet@ll.mit.edu**
- **Information and discussion forum available on NASA SET website:**

  http://lws-set.gsfc.nasa.gov/radiation_model_user_forum.html
- **V1 code will eventually be available on the NASA SET website**
  - **In the meantime contact Gregory Ginet, MIT Lincoln Laboratory, gregory.ginet@ll.mit.edu**

Thank You

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