Air Force Research Laboratory

The AE9/AP9 Next Generation Radiation Specification Models – Challenges

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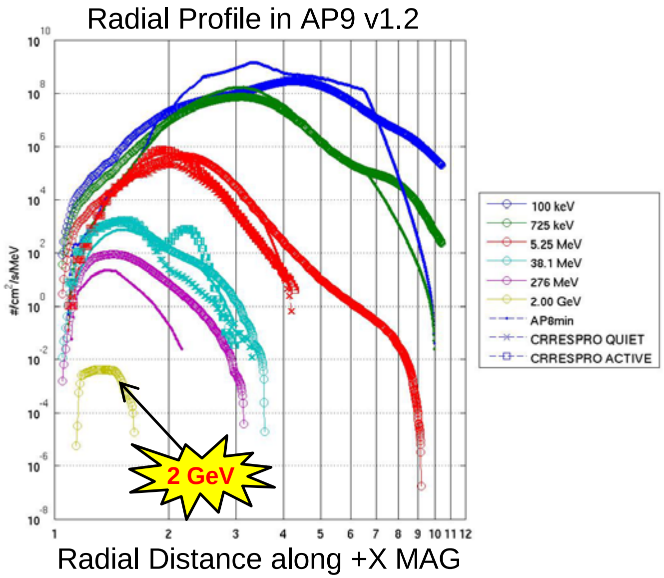
Outline

- Current Status: V1.2
  - Changes from V1.0
  - Validation results
- Future versions: V1.5 and V2.0
- Challenges
- Summary

Version 1.2 (I)

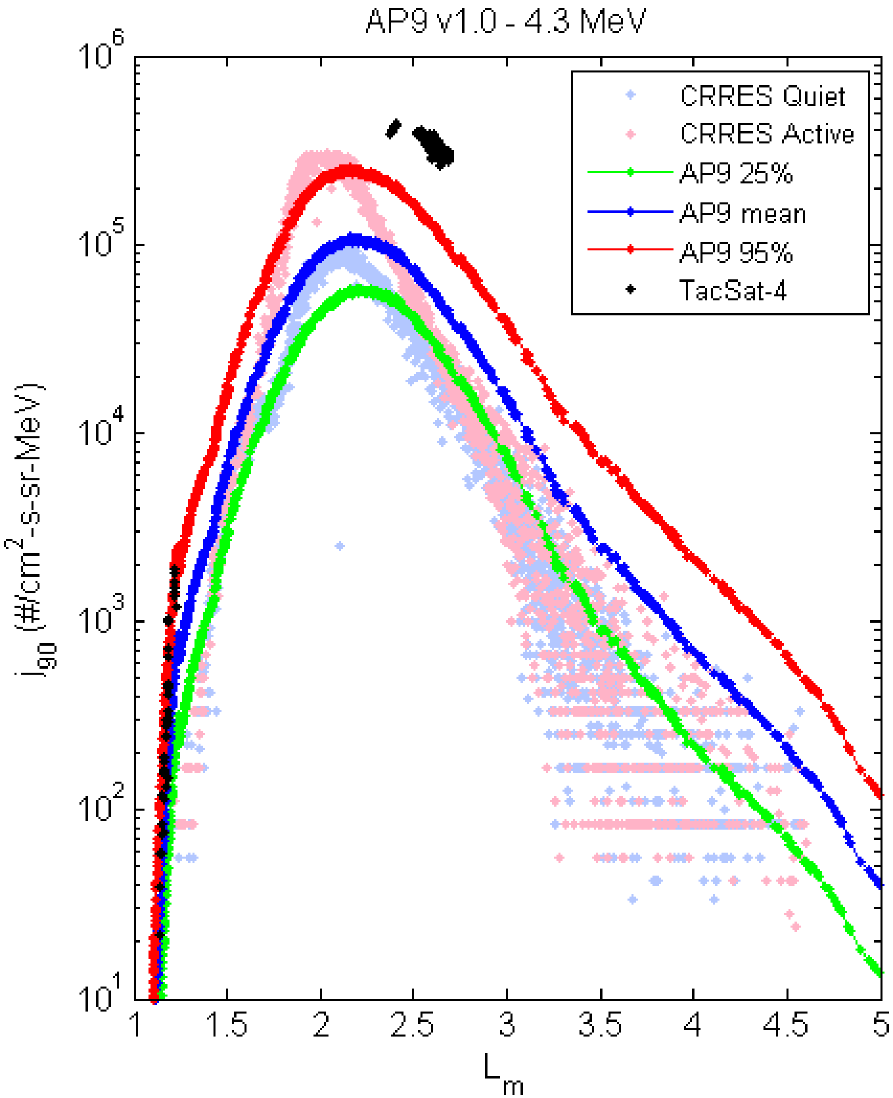
- New data sets (first new data to be added):
  - TacSat-4/CEASE proton data—captures new observations of elevated 1-10 MeV protons
  - Additional plasma data: THEMIS/ESA
- New electron templates
  - Improvements for inner zone electrons and for >3 MeV spectra
- New proton templates
  - Incorporate E/K/Φ and E/K/h_{min} profiles observed by RBSP/Relativistic Proton Spectrometer
  - Extend proton energies to 2 GeV
- Low altitude taper
  - Force fast fall-off of flux for h_{min} < 100 km.
  - Cleans up radial scalloping at altitudes below ~1000 km

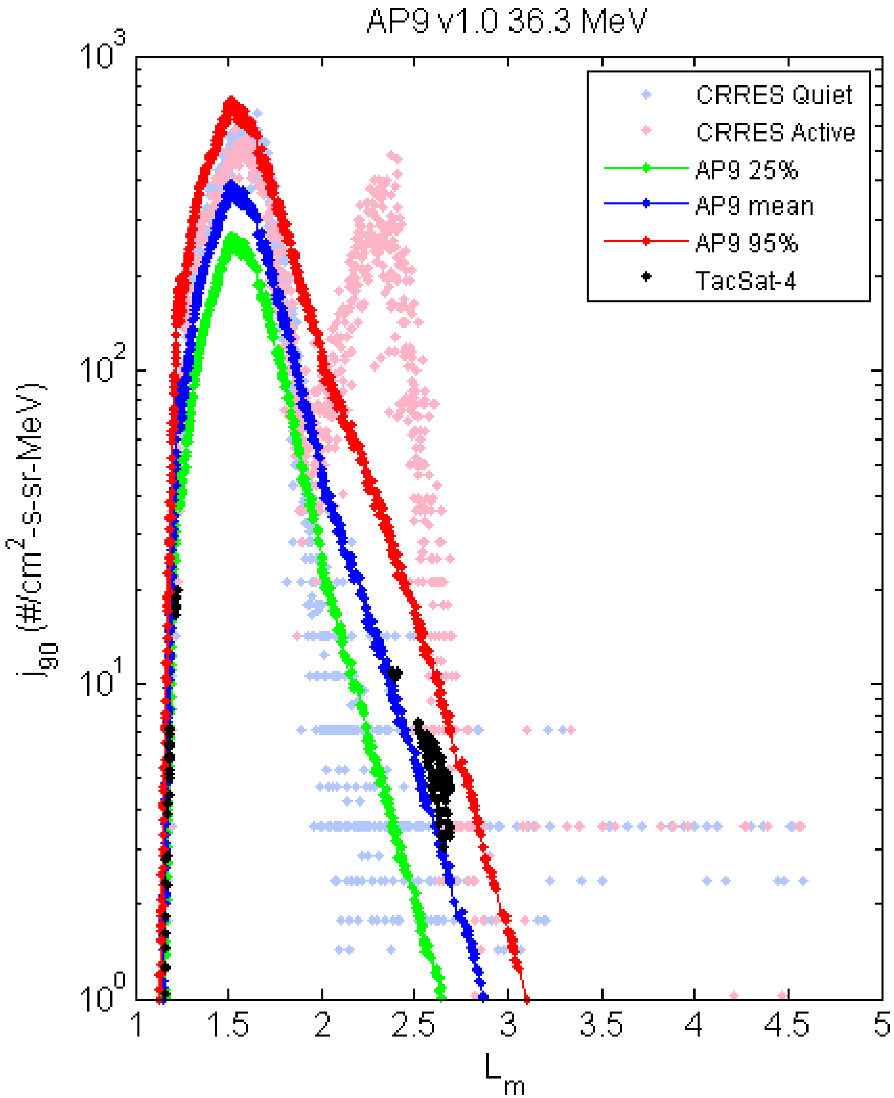


Version 1.2 (II)

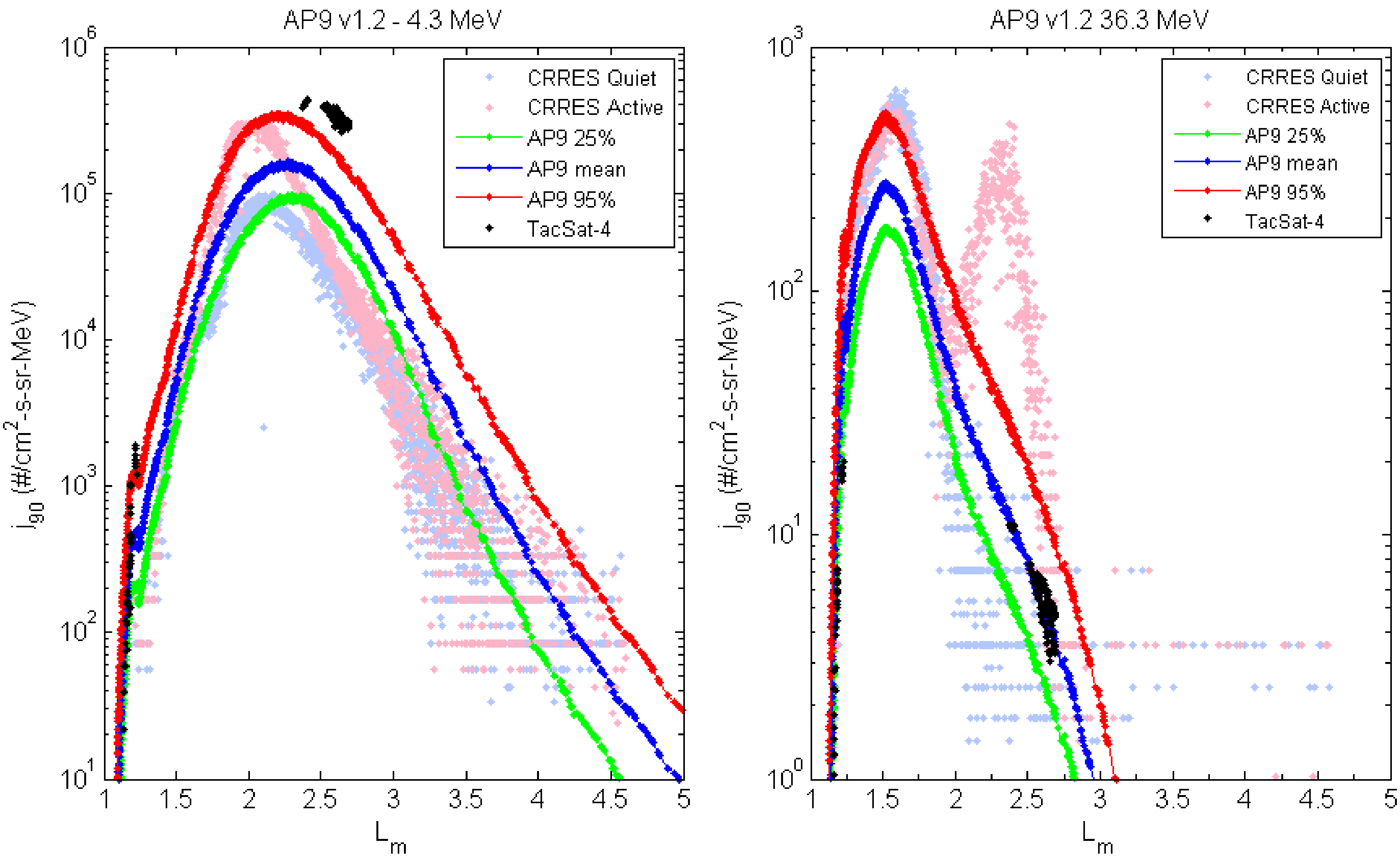
- Feature improvements
  - More options for orbit element input and coordinates
  - Third party developers guide (available now)
  - Pitch angle tool—users can query directional fluxes by pitch angle
  - Option to access/output internal magnetic field quantities and adiabatic invariants
- Public release in fall 2014

L-Profiles AP9 v1.0

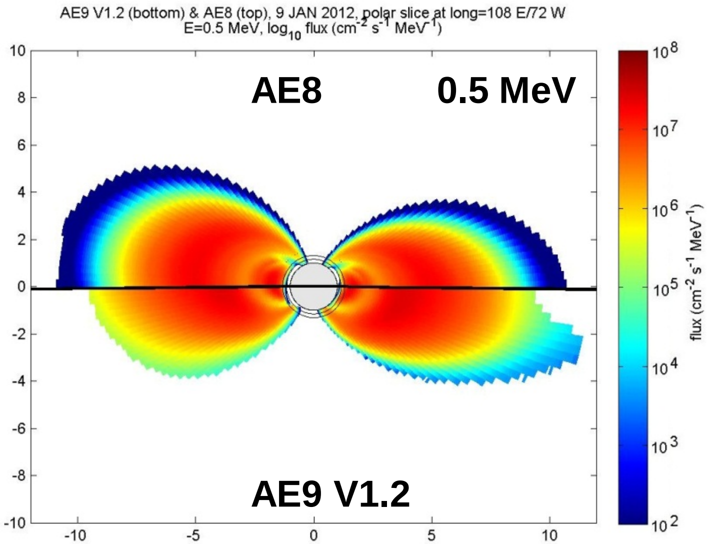


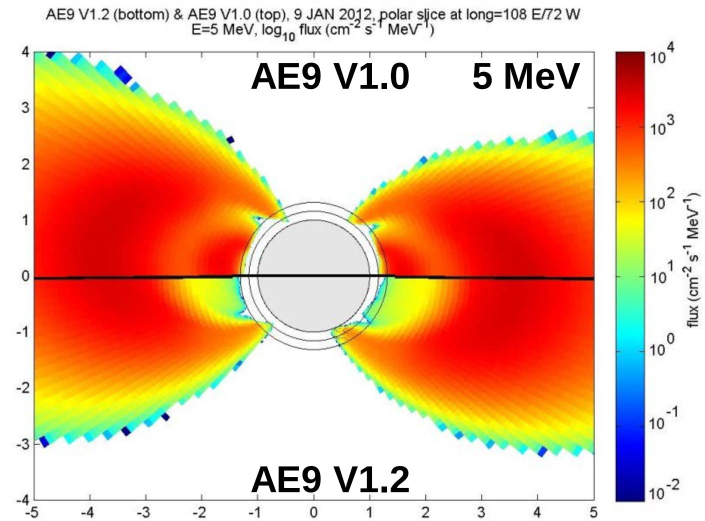


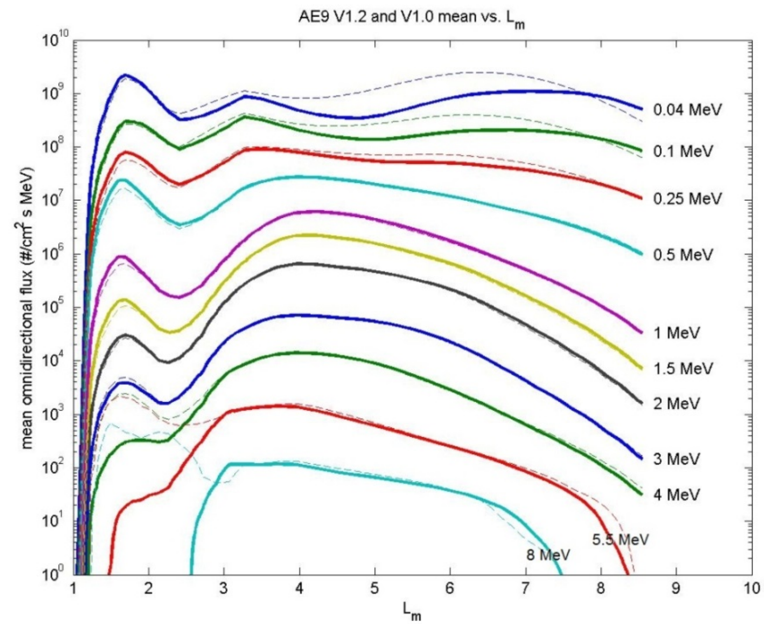
L-Profiles AP9 v1.2



AE9 V1.2 Model Comparison





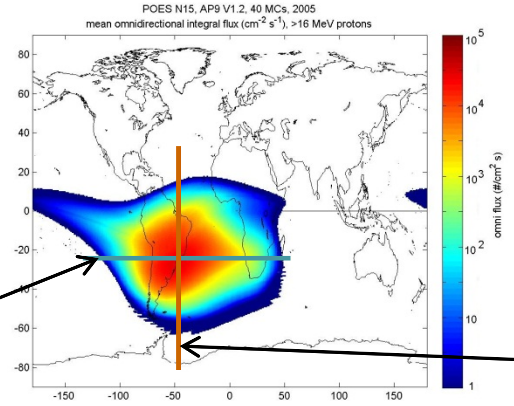


- Inner zone electrons at E>3 MeV are lower in V1.2 than V1.0
  - Result is more consistent with Van Allen Probe results

AP9 V1.2 Validation (I)

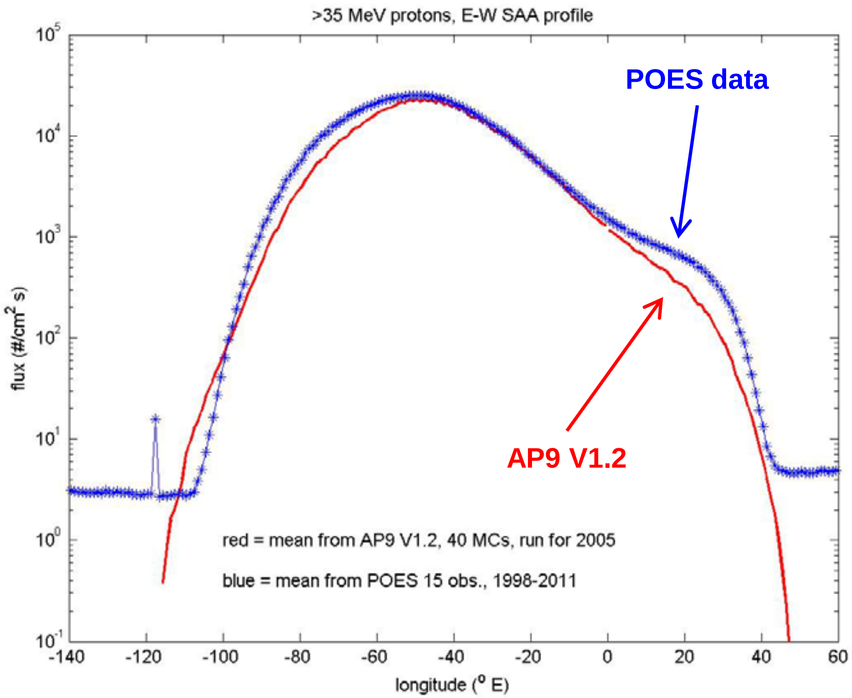
>35 MeV protons

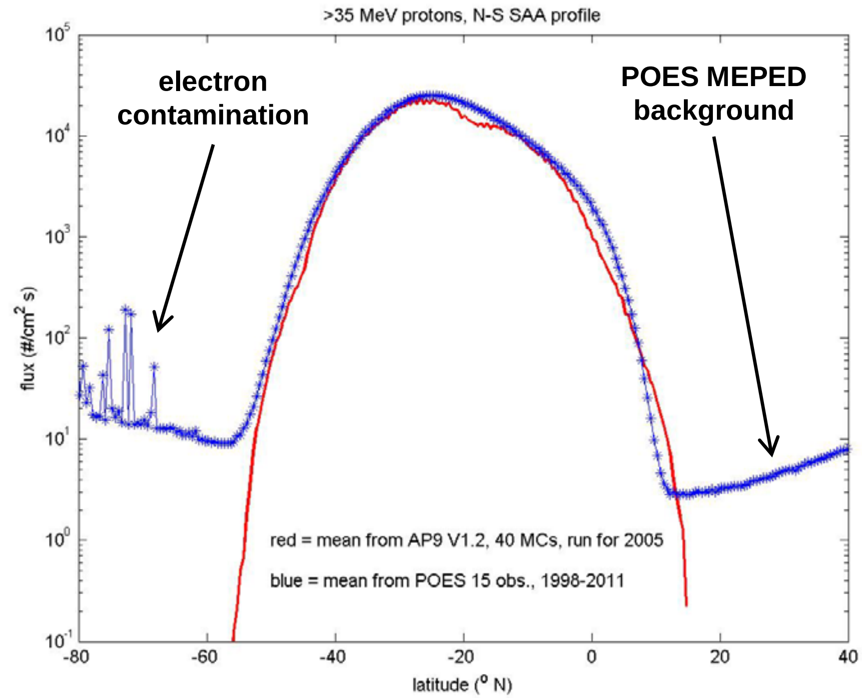
- SAA flux profiles are improved in V1.2 as compared to POES observations



East-west profile

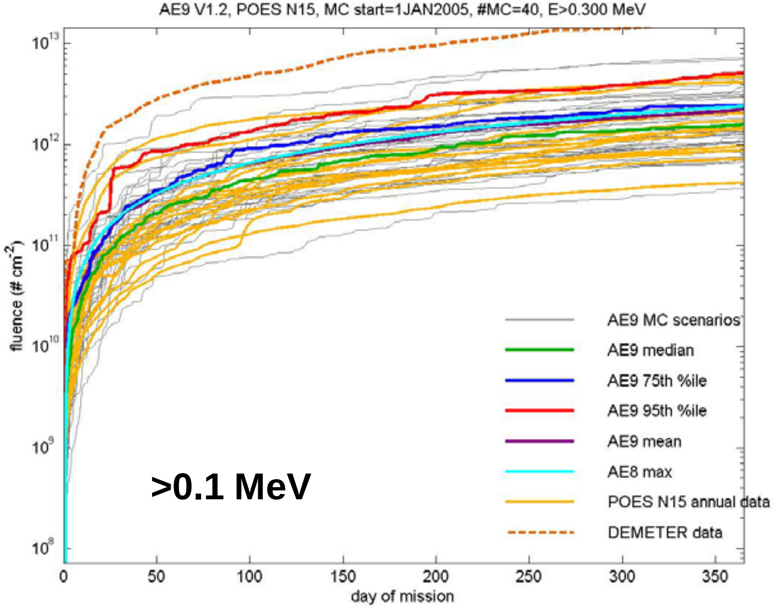
North-south profile

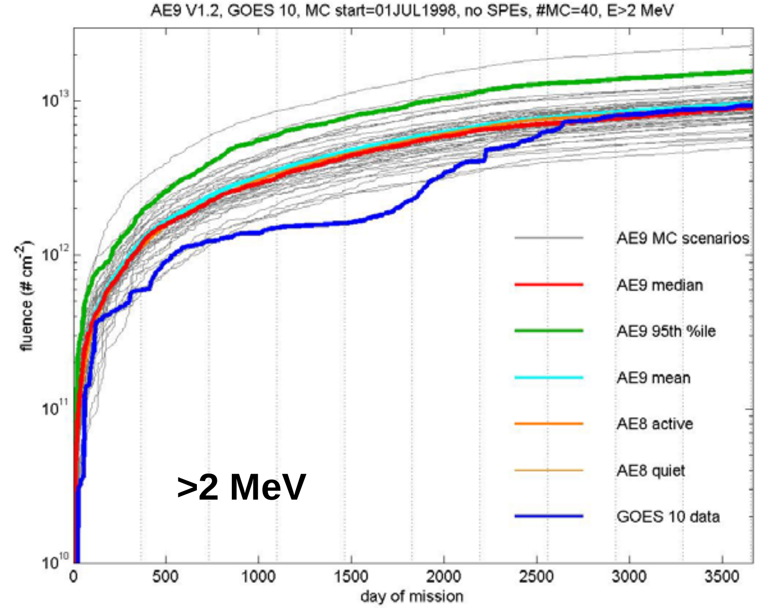




AE9 V1.2 Validation

- LEO: Fluence vs. time from AE9 V1.2 MCs, POES data (multiple years), and DEMETER
  - Range of AE9 MC results is comparable to range of annual POES data
- GEO: Fluence vs. time from AE9 V1.2 MCs and GOES data for full solar cycle
  - GOES data compares well to AE9 median when a full solar cycle is represented





Version 1.5

- Expected public release in late 2015
- New data:
  - Protons: **Azur**, Van Allen/MagEIS & REPT
  - Electrons: **DEMETER/IDP**, Van Allen/MagEIS & REPT
  - Plasma: SCATHA/SC8, AMPTE/CCE & CHEM
- New features
  - Introduce kernel-based methods for fast dose/effects calculations
  - Fix flux-to-fluence calculations to cover variable time steps—supports optimizing time steps for shorter run times
  - Capability for parallelization across scenarios—improves run times
  - IGRF update (if new coefficients are available in time)
  - Allow selection of time period for calculation of fluence—supports different time periods for different effects
- **International collaborators on board—with new model name: IRENE**
  - **International Radiation Environment Near Earth**

Version 2.0

- Major feature changes:
  - Sample 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
  - Incorporate untrapped solar protons with statistics
  - Parallelization capability for runs on clusters—needed to speed up long runs
  - Mac OSX build?
- 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
- Subsequent releases will include new data
  - DSX/SWx, ERG

Challenges

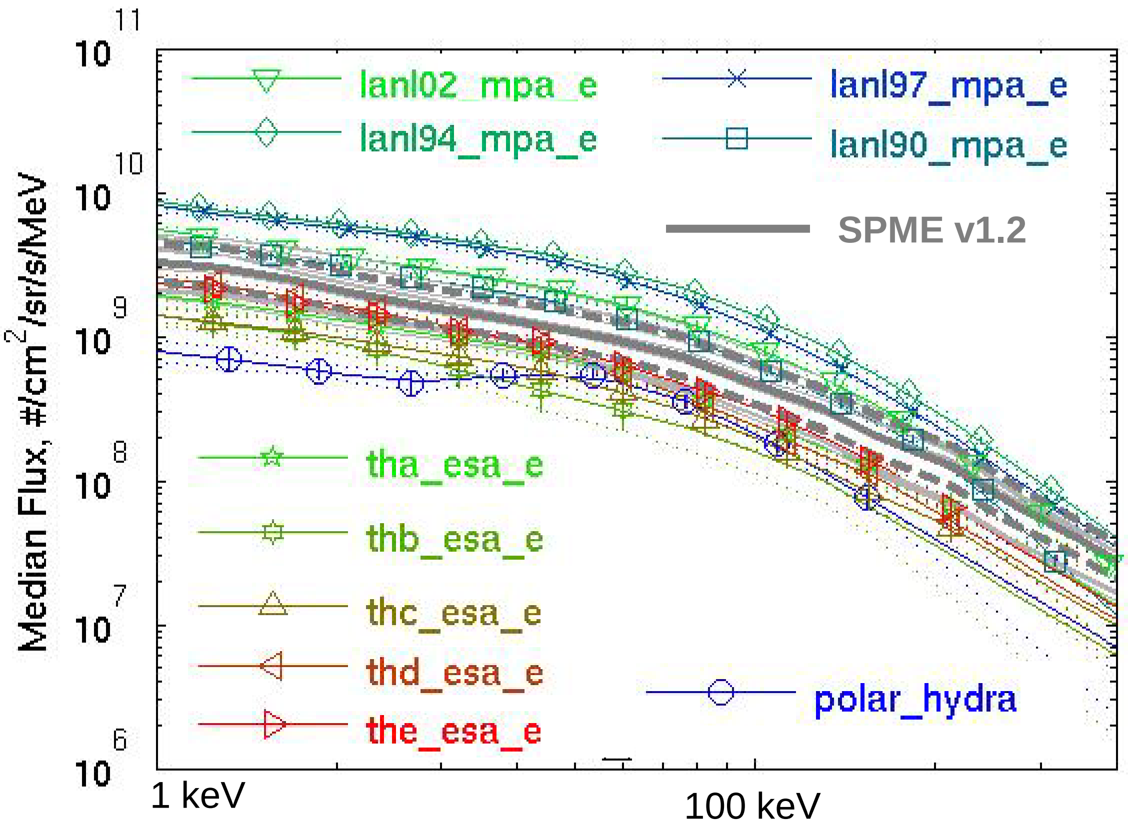
- Data inadequacies
- Data – Model Comparisons
- IGRF extrapolation
- Low Altitude Behavior
- Integrating Solar Protons
- Sample Solar Cycle
- Arbitrary Radiation Effects
- Stitching Domains
- Plasma Coordinate Systems
- Shabansky Orbits
- Speed / Parallelization

Data Inadequacies

- Plasma composition
  - Helium, Oxygen only from Polar CAMMICE/MICS
  - Looking at AMPTE, CRRES, Van Allen Probes
- Inner zone electrons
  - Van Allen Probes see no electrons above ~700 keV
  - Past measurements are not clear on this
  - Is this a temporary state, or is this typical?
- Low altitude gradients are difficult to measure
  - Small differences in local pitch angle at high altitude lead to large differences in flux at low altitude
  - Low altitude flux is often confined to very near 90° pitch angle
- Data does not cover everywhere
  - Physics-based and assimilative models can teach us how to extrapolate
- Data cannot provide adequate correlation in space and time
  - Physics-based and assimilative models can provide correlations

Single-Data-Set vs. Model

Median and 1-σ for each data set and the model



Electron Plasma Model (SPME), v1.2

L_m=7, α=35

- It is common to compare a single data set to AE9/AP9 and draw some kind of conclusion, e.g., “AP9 is too high”
- This is typically incorrect
- In the example at left from SPME:
  - The data sets spread over about a factor of 10
  - The model error is about a factor of 3
  - The model error is *small* because there are many data sets
- If the model error covered the spread of the data *it would never shrink no matter how many data sets we added*
- The model error bars are designed so that a model update with a new data set will still fall within the error bars of the prior model release

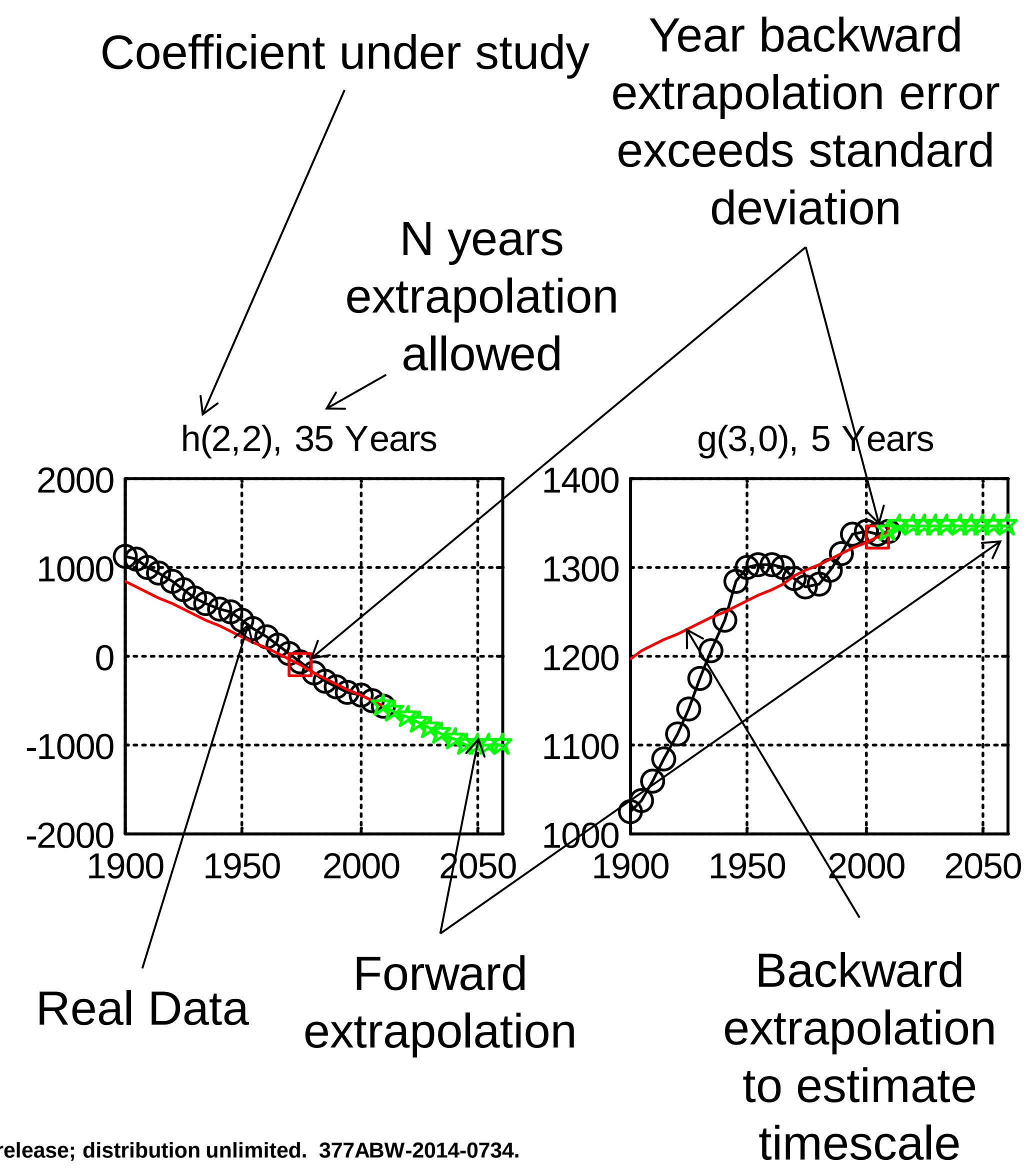
<u>We do not expect any individual data set to fall within the model error bars</u>

IGRF Extrapolation

- IGRF only extrapolates 5 years
- Mission planners plan up to 25 years ahead
- We need a way to extrapolate IGRF many years into the future

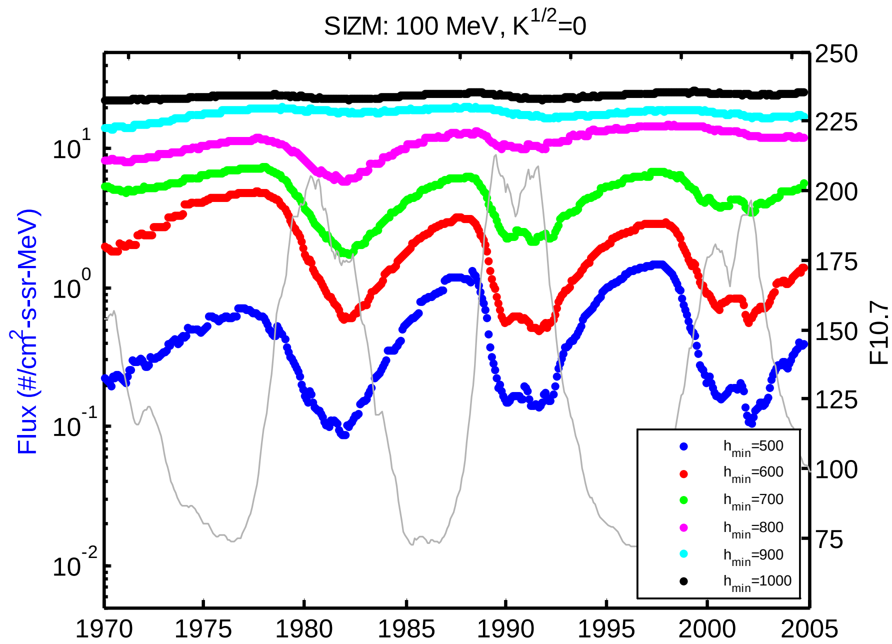
- Physics-based prediction is very complicated because the Earth's Dynamo is chaotic

- One Empirical Approach
  - Extrapolate each coefficient N years into the future
  - N is unique for each coefficient
  - N depends on how well a backward linear projection matches historical data



Low Altitude Behavior

- LEO Protons vary systematically with the solar cycle
  - No comprehensive, quantitative empirical model of this variation exists
  - We plan to use SIZM + POES
  - Allow model statistical parameters to vary with F10.7
  - Generate Monte Carlo scenarios of F10.7
- LEO Electrons vary with longitude
  - Depends on level of magnetic activity filling the drift loss cone
  - Will require addition of 4th dimension (dipole longitude) to E/K/h_{min} coordinate system



Summary

- AE9/AP9 exhibits a number of difficult challenges
- We are working on some, and have ideas for how to address others
- We cannot do it all: funds, manpower, expertise

- Collaborate with us, please!

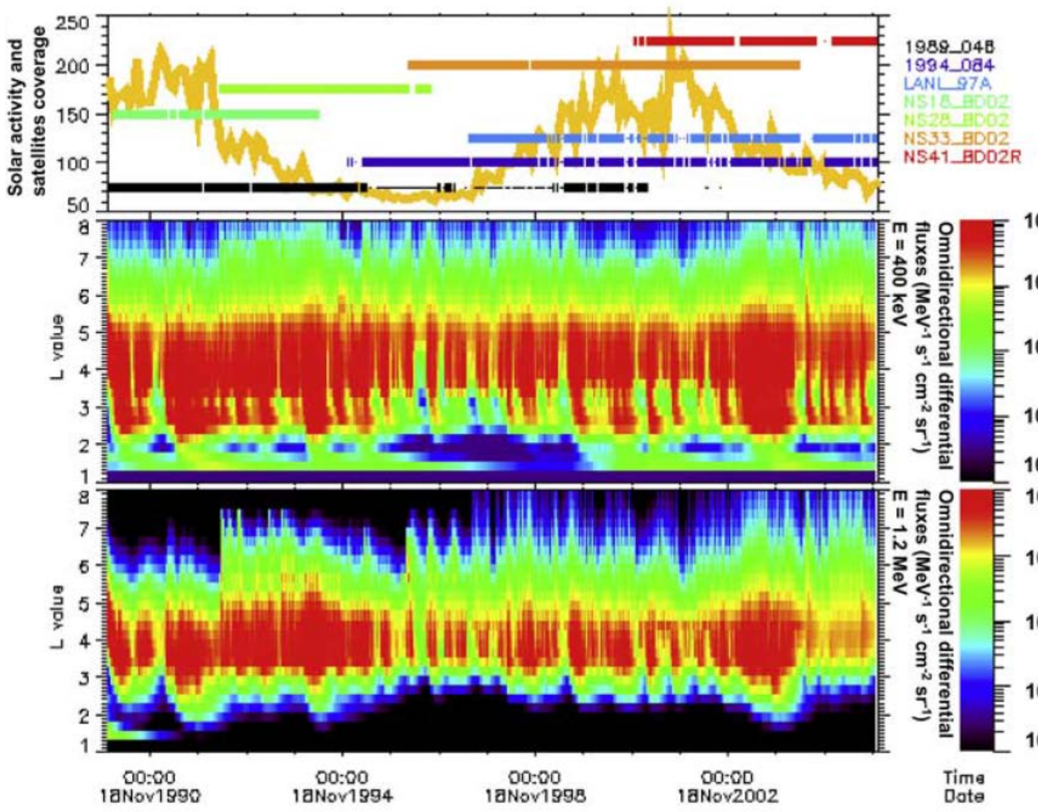
BACKUP MATERIAL

Integrating Solar Protons

- Solar protons contribute to proton effects addressed by AP9:
  - Total Ionizing Dose
  - Displacement Damage
  - Single Event Effects
- Statistical laws disallow adding 95th percentiles from AP9 and a solar model to obtain a combined 95th percentile
  - The statistical distributions must be combined before computing percentiles
  - Combination must include dynamics for Single Event Effects
- We are working with ESA to resolve this problem
  - Developing a Monte-Carlo method for solar protons
  - We will combine that with a geomagnetic cutoff model to limit solar proton access
  - This will enhance mean, perturbed mean, and Monte Carlo runs of AP9

Sample Solar Cycle

- Capture dynamics of realistic 11+ year solar cycle via data assimilative reanalysis
- "Fly through" this simulated dynamic environment as a check on Monte Carlo results
- Use the sample solar cycle to improve correlation matrices that drive Monte Carlo dynamics
- Use the sample solar cycle to help "fill in" flux maps where observations are missing



From Maget et al., Space Weather, 2007

Arbitrary Radiation Effects

- AE9/AP9 currently only provides Total Dose via ShielDose2 for idealized shielding
- Users need to consider other effects:
  - Specific shielding geometry or material
  - Displacement Damage
  - Single Event Effects
  - Internal charging
- Some of these phenomena can be reduced to linear transfer functions (Greens functions)
  - We are developing a generic “Kernel” capability to allow a user-supplied effect via the Greens function
  - Applies only to linear effects
  - First kernel: displacement damage in Si behind spherical Al shields
  - Second kernel: Proton SEE via Weibull response + Al Shielding

Stitching Domains

- AE9/AP9 has 3 distinct domains:
  - High altitude energetic particles: E/K/Φ grid, E > ~40 keV
  - Low altitude energetic particles: E/K/h_{min} grid, E > ~40 keV
  - Single plasma grid: E/α_{eq}/L_m grid, E < ~40 keV
- The high-low altitude stitching is done when the model data tables are computed before runtime
- The plasma – energetic particle stitching is done in post-processing after runtime:
  - Potentially invalid statistics!
  - Mismatch for perturbed means
- We need to switch to a stitching approach that applies at run time
- This will require extending Monte Carlo capabilities to plasma energies (currently only available for energetic particles)
- This is a significant architecture change

Plasma Coordinate Systems

- All plasma are currently modeled in a $E/\alpha/L_m$ system with no MLT dependence
- We will add a 4^{th} dimension for MLT (e.g., to address Sun-synchronous orbits)
- We also will eventually need auroral and plasma sheet coordinate systems and potentially a magnetosheath system

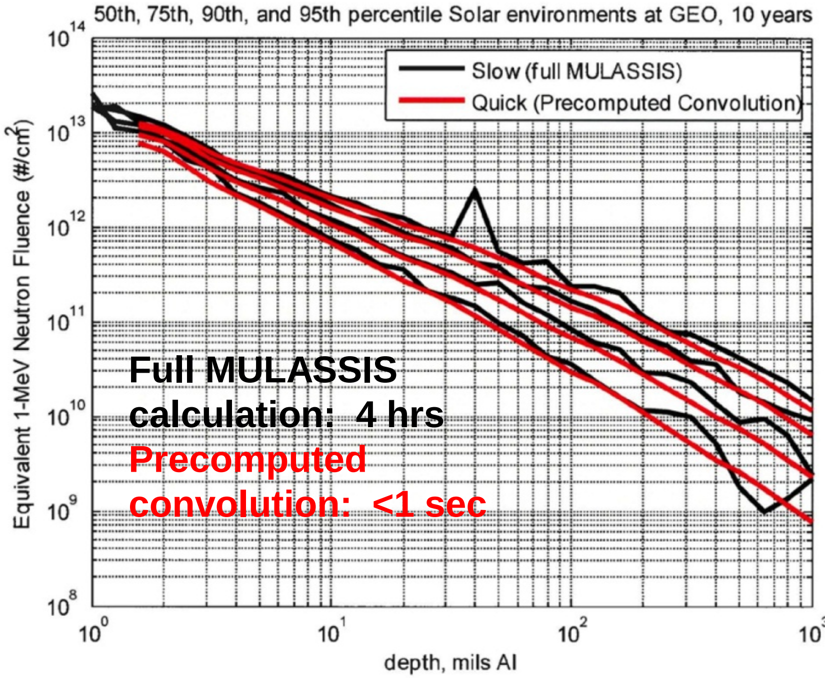
Miscellaneous

- AE9/AP9 has an ad-hoc outer limit defined by Shabansky orbits in Olson-Pfitzer Quiet
  - The flux there is not zero, but how do we represent it?
  - How should we define the Shabansky limit? It depends on K and Φ
- The AE9/AP9 software can be very slow
  - Speed up via parallelization
  - Speed up via optimization (faster sparse matrices?)

Kernel-Based Effects Calculation (V1.5)

- V1.5 will include AE9/AP9 capability to use independently-calculated radiation effects for faster effects results in the AE9/AP9 environment:
  - User precomputes desired effect vs. depth/particle/energy for a particular material/geometry/component, using independent particle simulation code
  - Results are formatted as a “kernel” for import into AE9/AP9/SPM
  - AE9/AP9/SPM environment plus effects kernel yields rapid calculations of specific effects

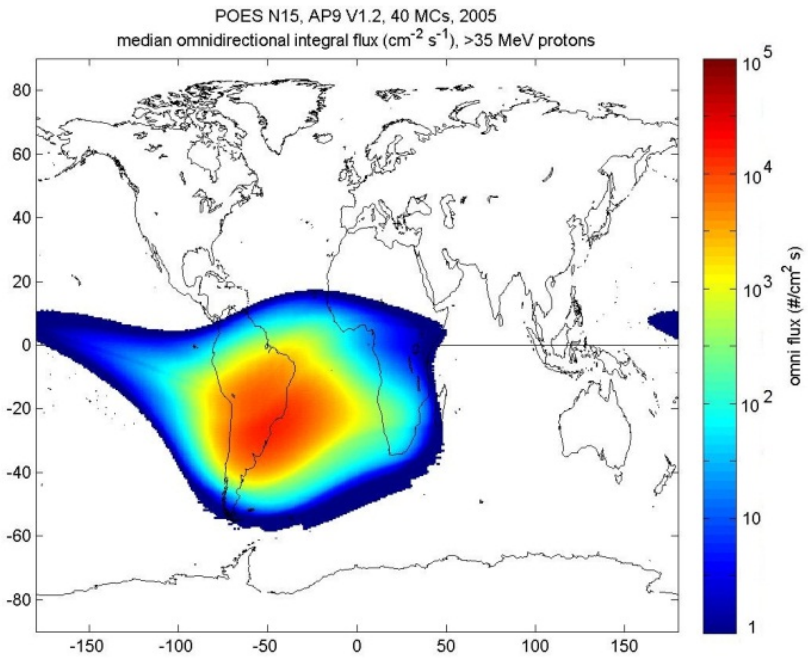
- Sample kernel for single event effects is in development
- Provides ability to rapidly obtain AE9/AP9 environment effects for specific components



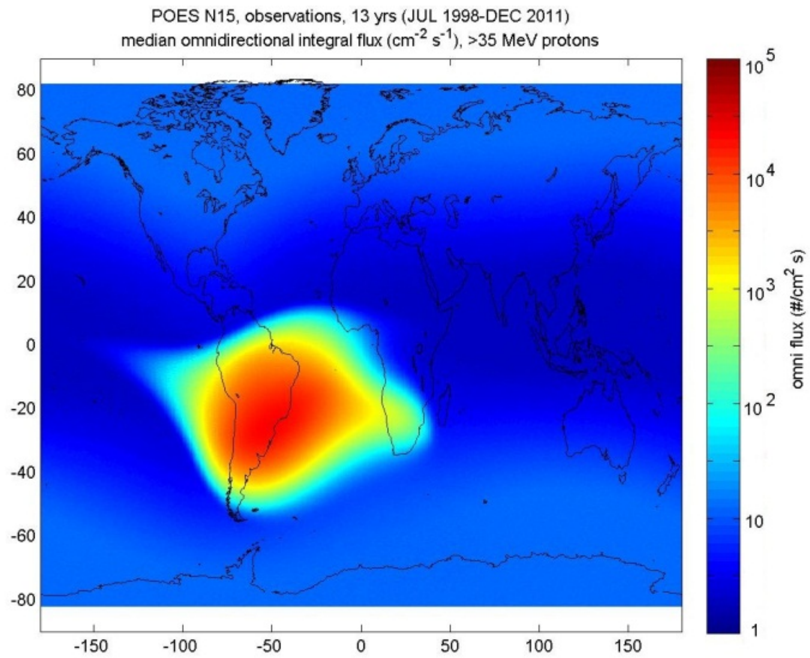
AP9 V1.2 Validation (II)

>35 MeV protons

AP9 V1.2 Monte Carlo median



POES NOAA-15 data, 1998-2011 median



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