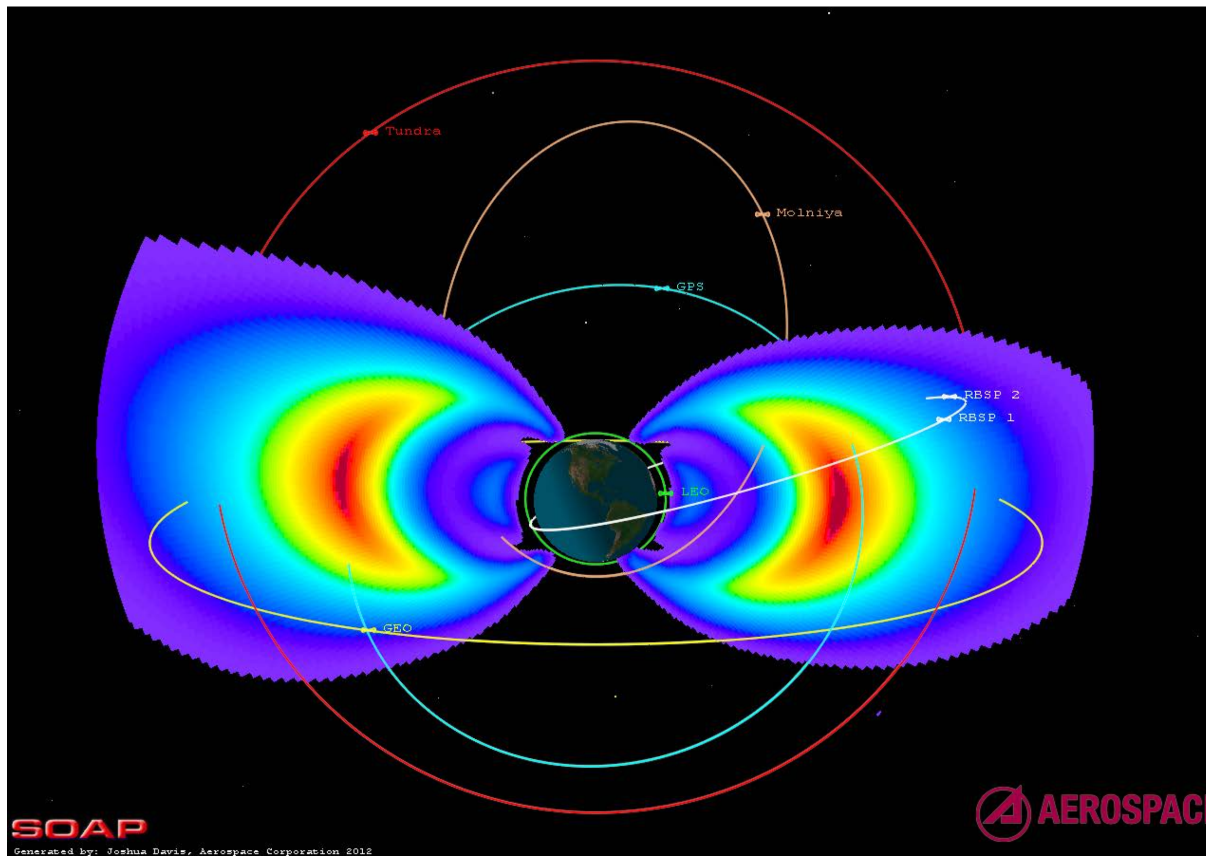
The AE9/AP9 Next Generation Radiation Specification Models

14 June 2012



Outline

- Model overview
- How to use the model
- Bug status

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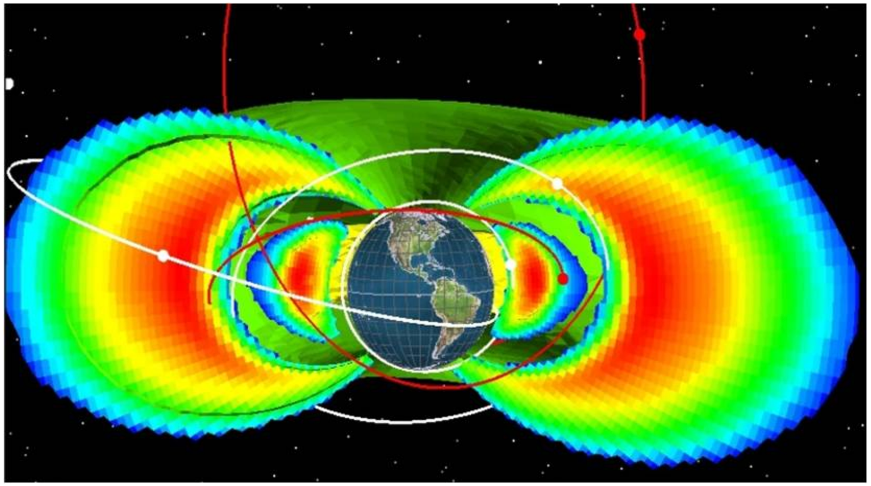
Hope to add more…

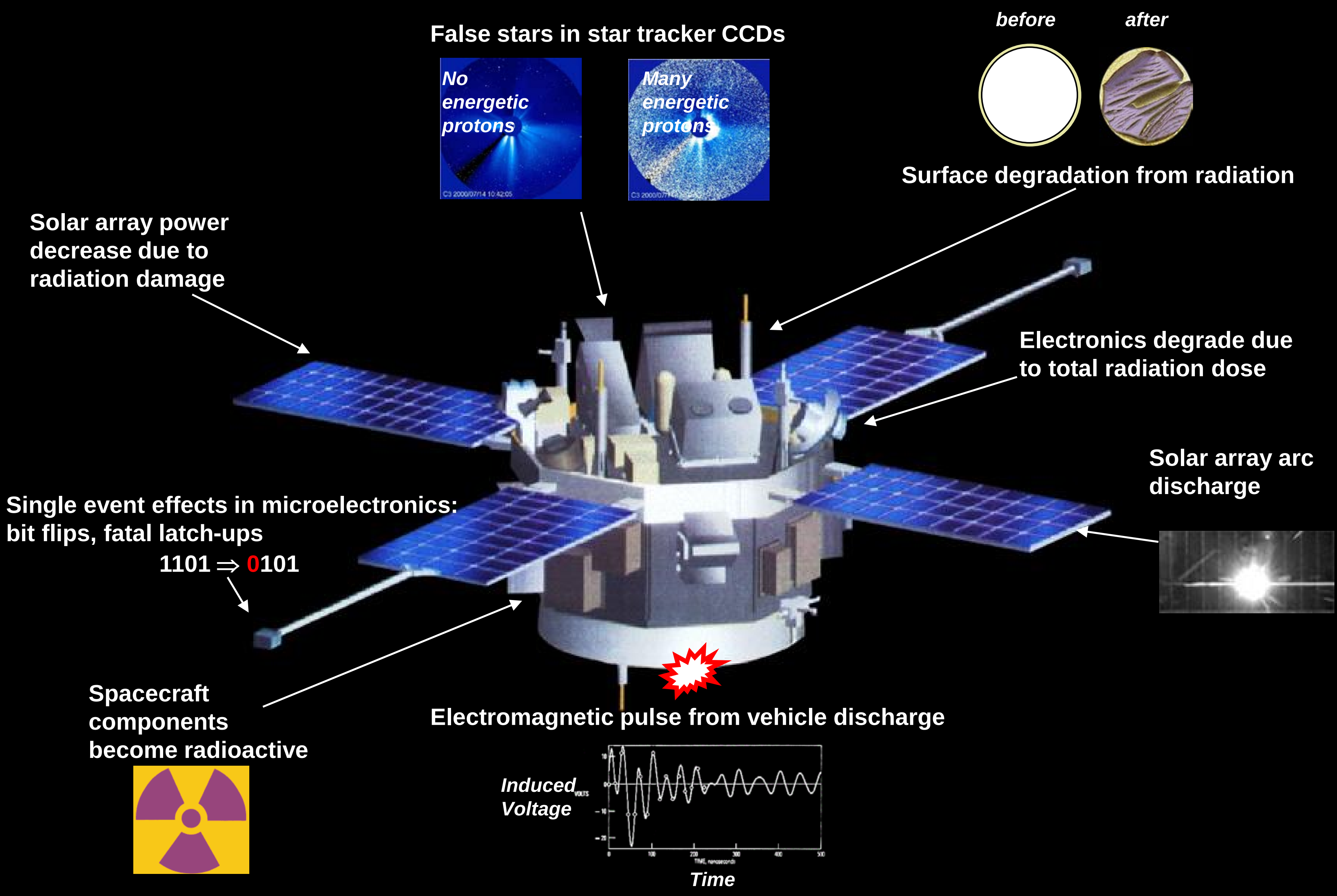
20 Jan 2012: The First Release of AE9/AP9

- AE9/AP9 is the next generation specification of the natural trapped radiation environment near Earth
- The government developed this new tool with industry, FFRDC, and national laboratory partners to improve space system acquisition and survivability
- This briefing introduces AE9/AP9 V1.0 and addresses the way forward for V2.0



The decades-long wait for a new and improved space radiation specification is now over.

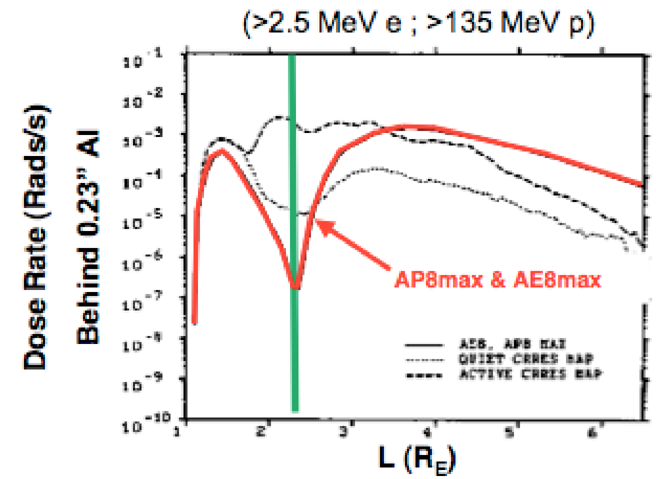
Energetic Particle & Plasma Hazards



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.

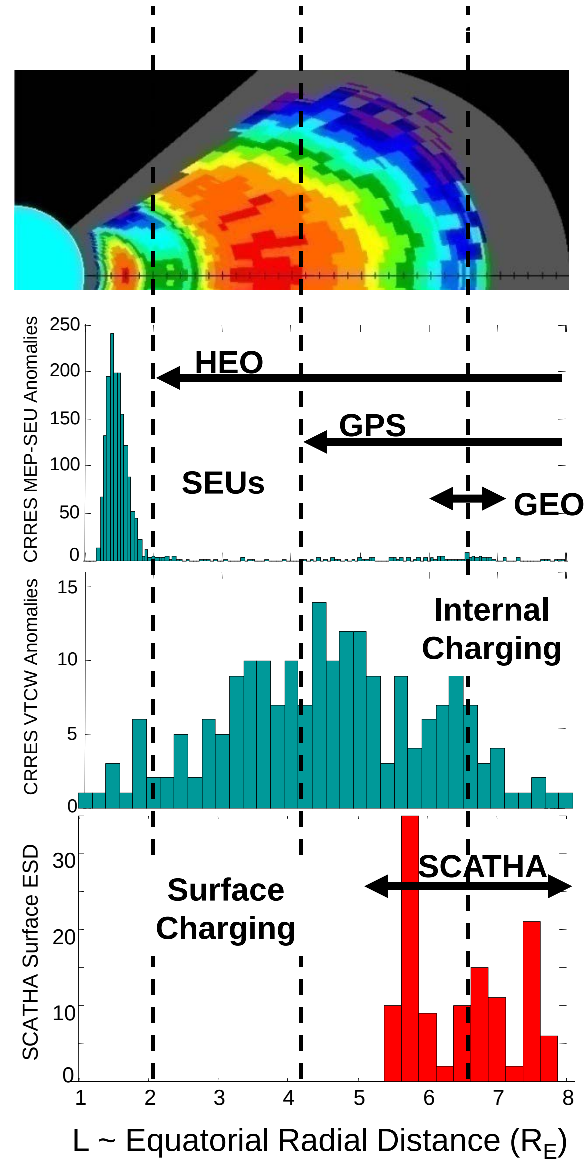
AP9/AE9 Program Objective

Provide satellite designers with a definitive model of the trapped energetic particle & plasma environment

- Probability of occurrence (percentile levels) for flux and fluence averaged over different exposure periods
- Broad energy ranges from keV plasma to GeV protons
- Complete spatial coverage with sufficient resolution
- Indications of uncertainty

Satellite Hazard	Particle Population	Natural Variation
Surface Charging	0.01 - 100 keV e^-	Minutes
Surface Dose	0.5 - 100 keV e^-, H^+, O^+	Minutes
Internal Charging	100 keV - 10 MeV e^-	Hours
Total Ionizing Dose	>100 keV H^+, e^-	Hours
Single Event Effects	>10 MeV/amu H^+, Heavy ions	Days
Displacement Damage	>10 MeV H^+, Secondary neutrons	Days
Nuclear Activation	>50 MeV H^+, Secondary neutrons	Weeks

Space particle populations and hazards



Requirements

Summary of SEEWG, NASA workshop and AE9/AP9 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:

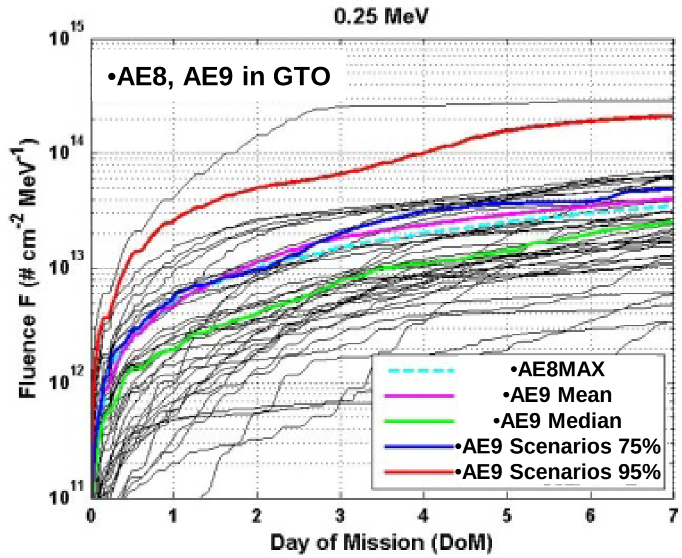
- **Orbital elements, start & end times**
- **Species & energies of concern (optional: incident direction of interest)**

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*



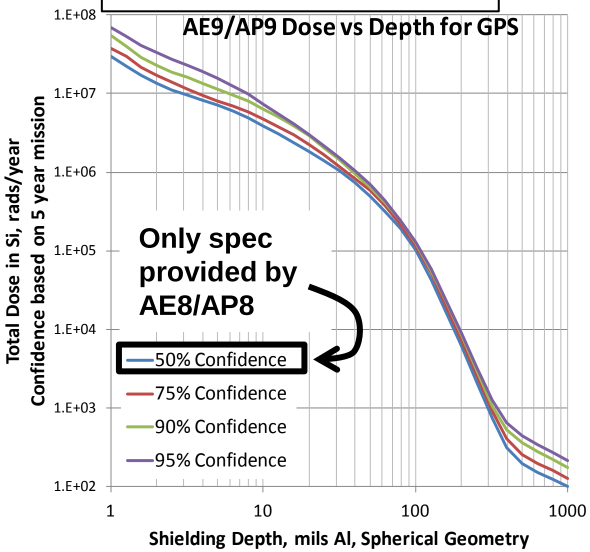
- The model architecture and its datasets are superior to AE8/AP8 in every way
- V1.0 released 20 January 2012 to US Government and Contractors
- Public release, including source code, is imminent

System acquisition now has the first version of the new industry standard environment model.

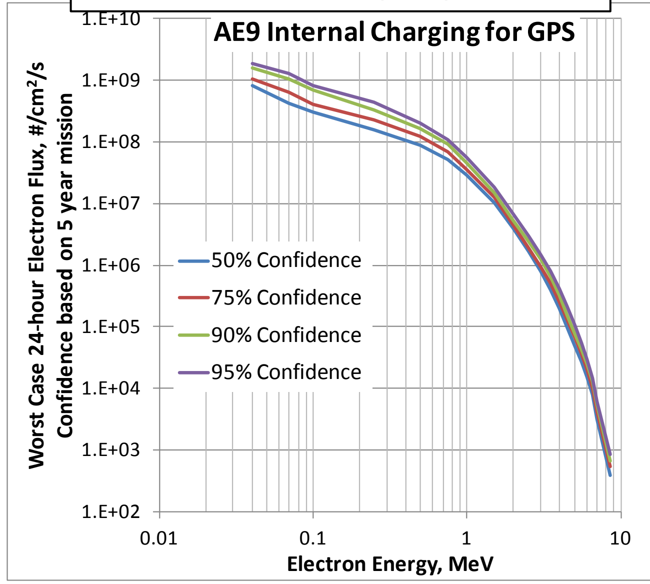
Why your program should use AE9/AP9

- AE9/AP9 includes more and better data than AE8/AP8
- AE9/AP9 addresses more hazards than AE8/AP8
- AE9/AP9 allows you to address risk in terms of confidence rather than arbitrary margin factors

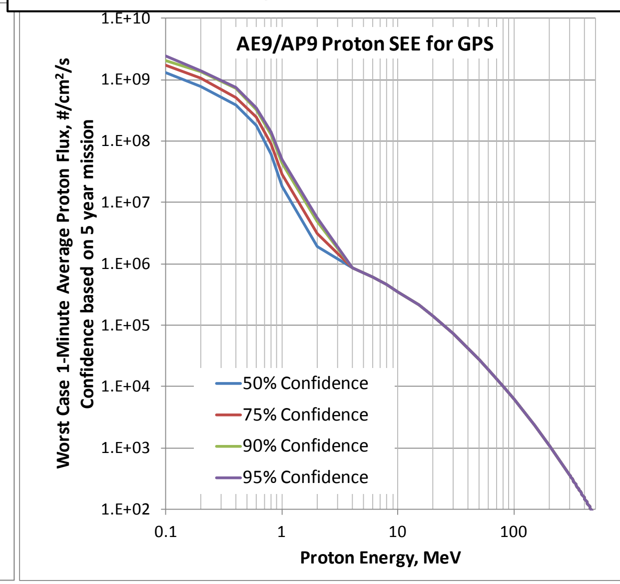
Total Dose, GPS



Internal Charging, GPS



Proton Single Event Effects



Data Sets – Energy Coverage

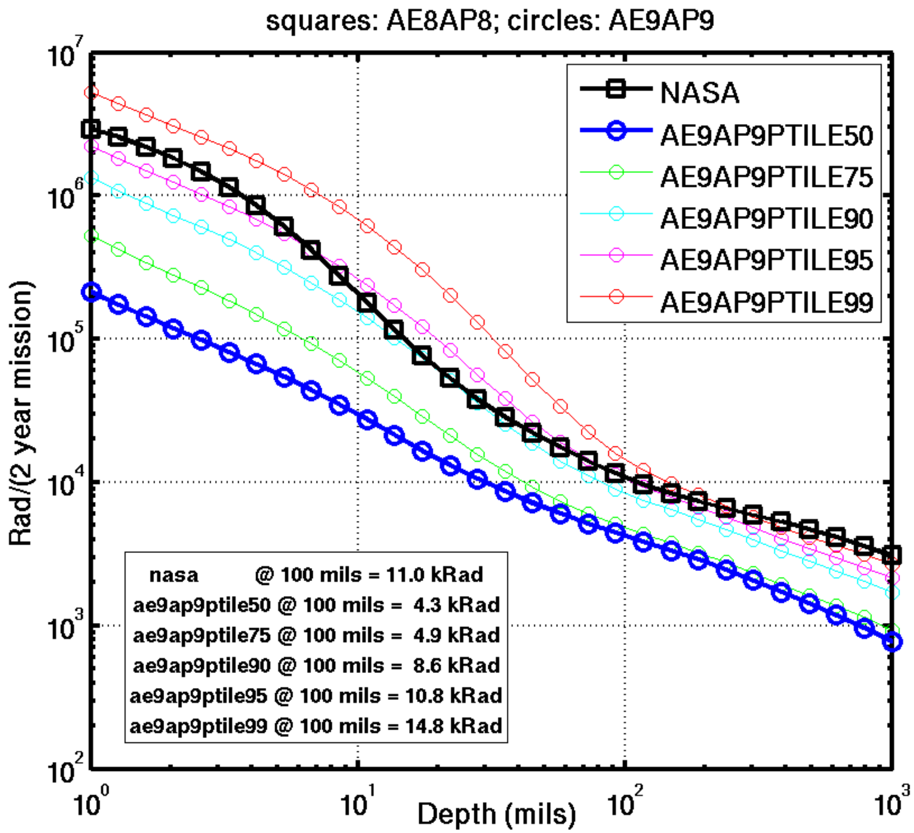
Protons	Orbit				Energy [MeV]																								
	LEO	MEO	HEO	GEO	0.10	0.20	0.40	0.60	0.80	1.00	2.00	4.00	6.00	8.00	10.0	15.0	20.0	30.0	50.0	60.0	80.0	100.0	150.0	200.0	300.0	400.0	700.0	1200.0	2000.0
CRRES/PROTEL	■	■	■	■							■	■	■	■	■	■	■	■	■	■	■								
S3-3/Telescope	■				■	■	■	■	■	■	■																		
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				■		H+,	e-	■	■	■	■	■	■			

AE9/AP9 Use Example: LEO Dipper Concept

- 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

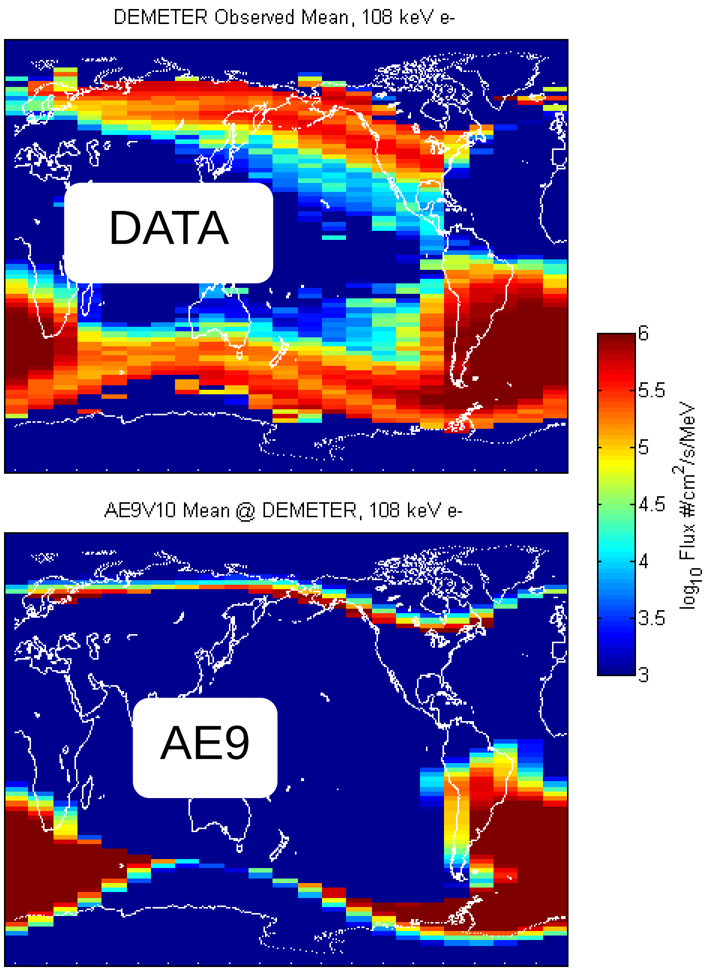


- The AE9/AP9 environment percentiles informed the program of the margin they will have for EEE parts selection

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

AE9/AP9 Limitations

- AE9/AP9 has known issues
  - Protons >100 MeV in the inner zone and South Atlantic Anomaly
  - Electrons < 600 keV in the inner zone and South Atlantic Anomaly
  - Plasma oxygen and electrons have small errors which do not adequately reflect the uncertainty in the measurements
- The model error bars in some places are factors of 10 to 100
- New data sets will reduce the size of these error bars

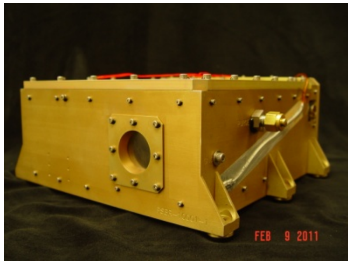


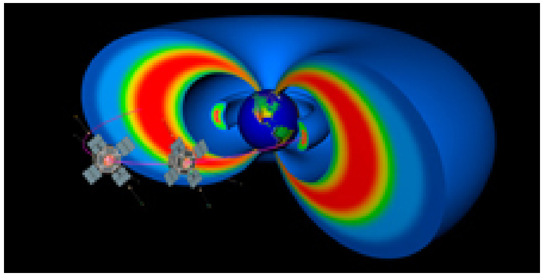
Without further improvements to the model, LEO and MEO systems will continue to be over-designed

The Path to AE9/AP9 V2.0

- 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 2012 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. NASA/RBSP, 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 will host an international collaboration workshop for AE9/AP9 in October 2012

Relativistic Proton Spectrometer





NASA Radiation Belt Storm Probes

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.

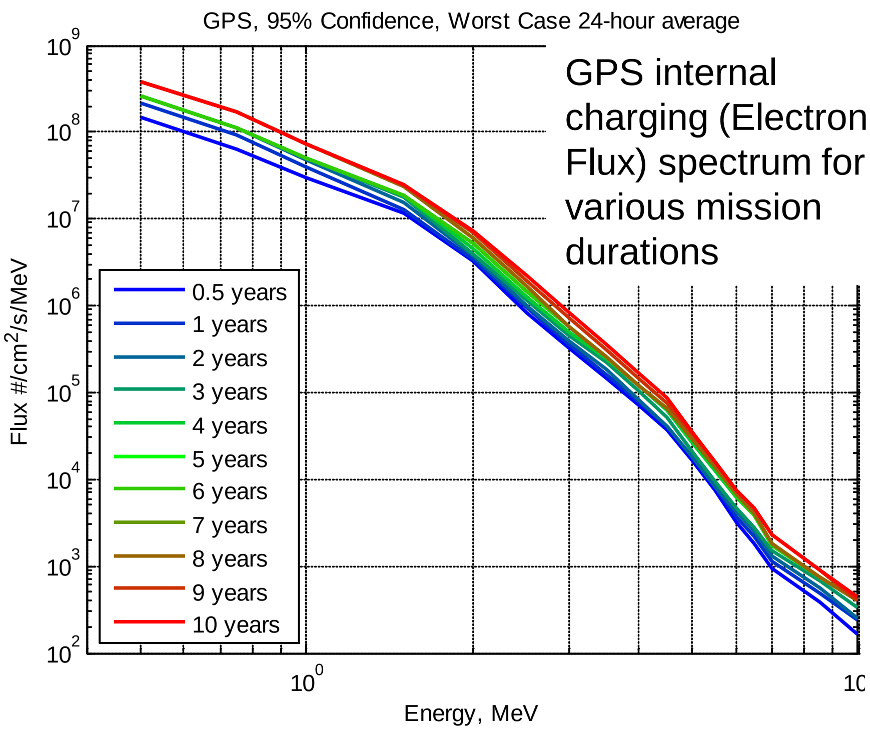
How to Use AE9/AP9

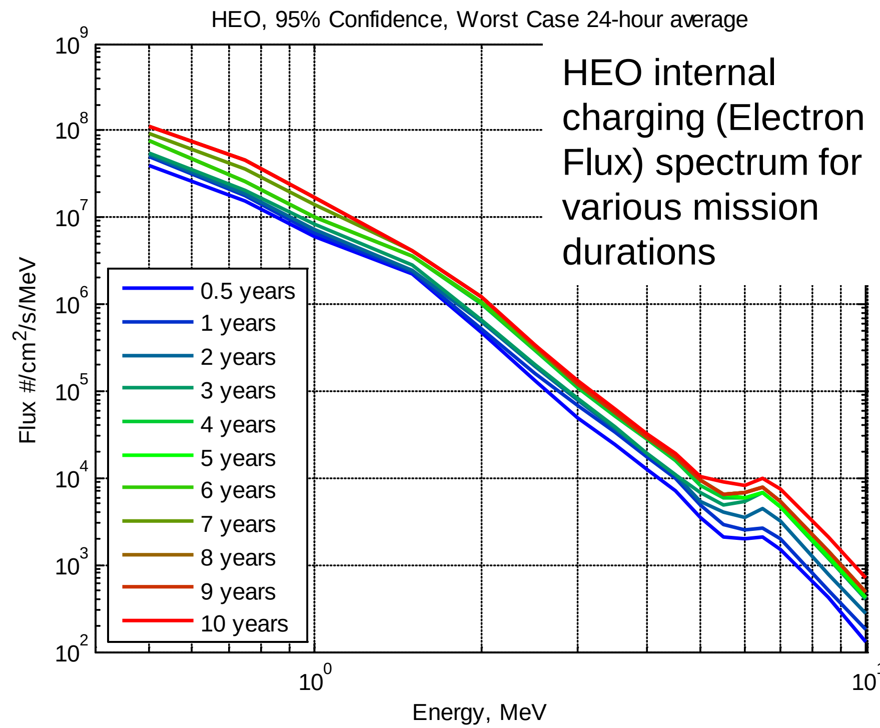
What Type of Run

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 (no SPMH)
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

Do you really need to simulate the whole mission?





- Yes ☹ (Space Weather!)
- Worst case internal charging flux grows by more than a factor of 2 from a 6 month to a 10 year mission
- The effect is orbit dependent and even larger in LEO

Tricks for long runs

- Select appropriate time step
  - Altitude < 2000 km @10 seconds (maybe too fine, don't know yet)
  - Radius < 2 RE @ 1 minute (1 RE ~ 6378 km)
  - Radius < 4.5 RE @ 5 minutes
  - GEO @ 1 hour
  - Elsewhere @ 15 minutes
- Use command line utility
- Do 40 scenarios in parallel
- Break up long Monte Carlo runs in time by repeating first time point in each time chunk
  - E.g., 10 year run, 1/1/2015 to 1/1/2025
  - Break into 10 1-year orbit files
  - In each orbit file prepend time/position for 1/1/2015 00:00:00UT
  - This correctly sets the Monte Carlo epoch to 1/1/2015 00:00:00UT for all time chunks
  - Will later add epoch keyword
  - Cannot do this with built-in aggregators (need new utility)

Caveats

- Orbit propagator – Use Kepler (+J2) for long mission sims
  - Other propagators include orbit physics that is routinely “cancelled out” by maneuvers
  - Using Kepler or Kepler+J2 implicitly accounts for maneuvers
- Plasma-radiation model stitching for integral channels
  - For integral energy channels that cross the plasma-radiation model boundary, the GUI stitches together the models
  - The GUI requests “FluxType=2PtDiff” fluxes from the plasma (SPM*) model
  - The GUI requests “FluxType=Integral” fluxes from the radiation (A*9) model
  - Integral flux (E>X) = [2PtDiff SPM* flux from X to E_0]*[E_0-X] + [Integral A*9 flux >E_0]
  - E_0 is 0.1 MeV for protons, 0.04 MeV for electrons
  - If you run the console application yourself for integral channels from the plasma model, you will have to do this stitching yourself, too
- Warning – window-averaging aggregators have a startup window issue
  - For time points before the first full time window, the average can be artificially elevated due to short (disproportionate) residence time in a high radiation region
  - For example, a GPS orbit that starts in the heart of the outer zone
  - For the first couple hours, the average-so-far will be very intense and will not reflect typical averages on longer timescales
  - <u>These aggregators are only present in the C++ -- They are not accessible from the command line utility or the GUI in the current release</u>
  - In a future release, we will fix the windowing algorithm and provide access via the command line utility

Bug Status

- GUI won't run if SM coordinates are selected for an input ephemeris
  - The GUI creates an input file for the Command Line specifying coordinates as "SM"
  - The Command Line accepts "SSM" not "SM" as a coordinate specification
- GUI/command line may not run >~250 Monte Carlo scenarios in a single run
  - Results from the system's limit on the number of open files
  - You can still break up larger numbers of MC scenarios into multiple runs, then aggregate the results in other software, or change this limit in your system
- GUI sometimes crashes when selecting the plot tab before running a scenario
  - This appears to happen if aborted run files are in the default directory—remove these files

- Report bugs and other issues to: Bob Johnston (afrl.rvborgmailbox@kirtland.af.mil)

Points of Contact

- **Comments, questions, etc. are welcome and encouraged!**
- **Please send feedback to (copy all):**
  - **Gregory Ginet, MIT Lincoln Laboratory, gregory.ginet@ll.mit.edu**
  - **Paul O'Brien, Aerospace Corporation, paul.obrien@aero.org**
  - **Bob Johnston, Air Force Research Laboratory, afrl.rvborgmailbox@kirtland.af.mil**
  - **Dave Byers, National Reconnaissance Office, byersdav@nro.mil**
  - **Michael Starks, Air Force Research Laboratory, afrl.rvborgmailbox@kirtland.af.mil**
- **Information and discussion forum available on NASA SET website:**

  http://lws-set.gsfc.nasa.gov/radiation_model_user_forum.html
- **For access to V1.0 code please contact:**
  - **Gregory Ginet, MIT Lincoln Laboratory, gregory.ginet@ll.mit.edu**

Distribution of V1.0 is currently limited to US Government employees and contractors

- **When cleared for Public Release the code will be made available through the NASA SET website**

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**
- **Version 1.0 is now available to US Government employees and contractors**
  - **Public Release is imminent**
- **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)**

The Government-FFRDC team has committed to the ongoing development of the AE9/AP9 models to ensure the continued viability and improved accuracy through ongoing research and the incorporation of new data sets as part of our mandate to support the National Security Space community