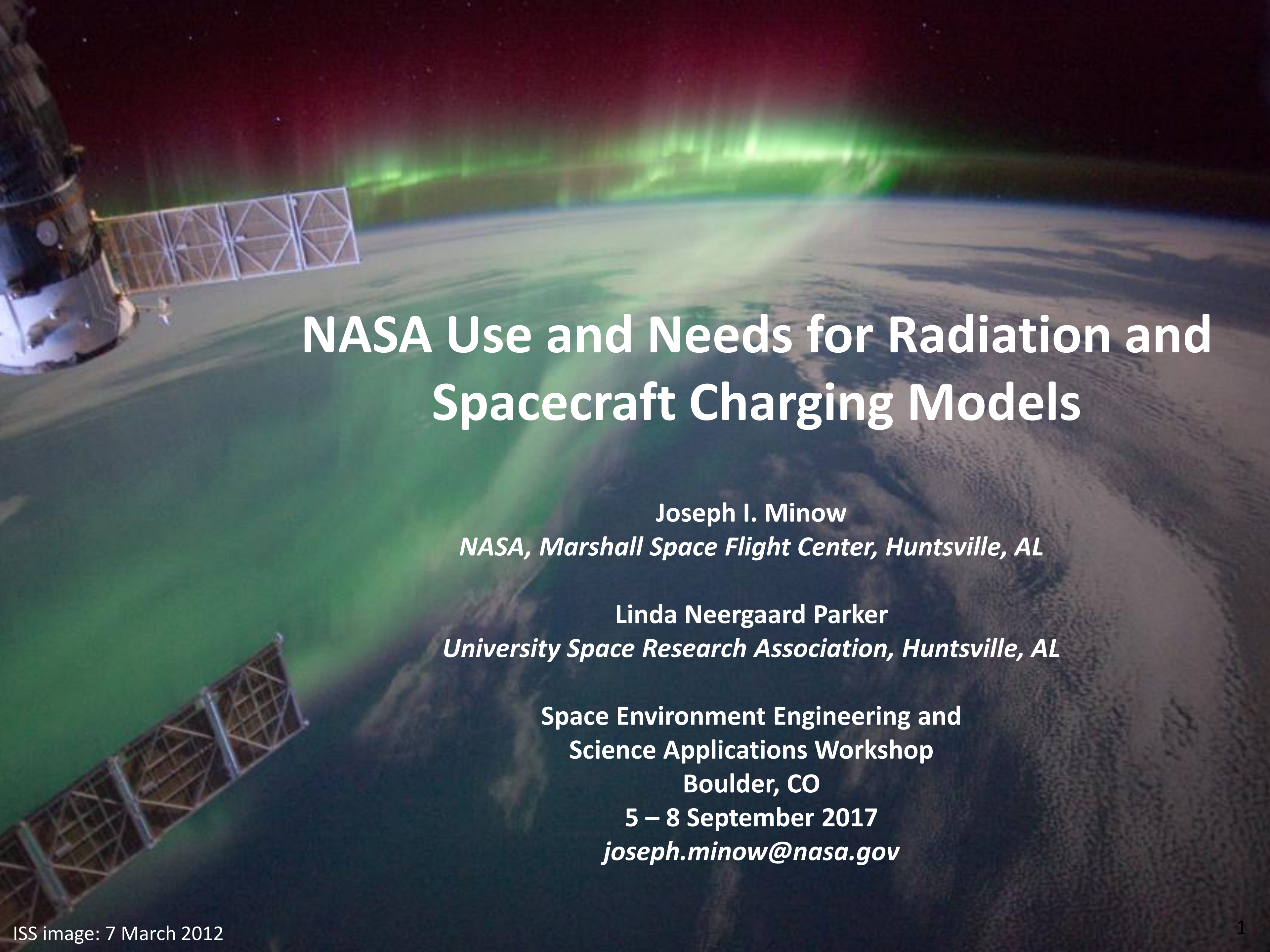

ISS image: 7 March 2012

NASA Use and Needs for Radiation and Spacecraft Charging Models

Joseph I. Minow
NASA, Marshall Space Flight Center, Huntsville, AL

Linda Neergaard Parker
University Space Research Association, Huntsville, AL

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joseph.minow@nasa.gov

NASA Use of Radiation, Charging Models

- NASA utilizes a variety of models to predict space radiation and plasma environments and their effects on space systems

- Models are developed in-house at NASA Centers or obtained from other agencies, private industry, and foreign sources where appropriate

- Environment models are used to
  - Specify the space radiation and space plasma environment for mission design
  - Evaluate on-orbit environments for operations support
  - Best estimate of on-orbit environment for anomaly investigations

- Effects models are used to evaluate the impact of the space radiation and plasma environments on hardware and humans including
  - Total ionizing dose, displacement damage dose, single event effects, sputtering, PVA degradation
  - Surface charging, internal charging, plasma interactions with PVA
  - Biological effects of radiation on crew

Radiation, Plasma Environment, Effects Models

Model	Environment/ Effect	Source	Comments
AE8/AP8	Earth, trapped radiation	NASA GSFC, https://ccmc.gsfc.nasa.gov/pub/modelweb/radiation_belt/radbelt/	NASA standard Earth radiation belt energetic electrons, ions
AE9/AP9/SPM	Earth, trapped radiation, plasma, dose	https://www.vdl.afrl.af.mil/programs/ae9ap9/	New generation Earth radiation belt energetic electrons, ions, plasma
CREME96, CRÈME-MC	GCR, SPE, trapped protons	https://creme.isde.vanderbilt.edu/CREME-MC	Single event effect rate predictions and radiation environments
PROTEST	GCR, trapped protons	NASA JSC (O'Neill/Reddell)	Scale laboratory proton upset rates to on-orbit proton and heavy ion rates
ESP	SPE protons	NASA GSFC (Xapsos), SPENVIS	Statistical solar proton fluence
PSYCHIC	SPE heavy ions	NASA GSFC (Xapsos), SPENVIS	Statistical solar heavy ion fluence
JPL-91	SPE protons	NASA JPL (Feynman), SPENVIS	Solar proton fluence
King 1972	SPE protons	King (1974), SPENVIS	Solar proton fluence, basis for NASA crew dose analysis
CREME96 GCR	GCR protons	Nymmik et al, (1992), CREME96, SPENVIS	Solar max, min GCR
Badhwar-O'Neill	GCR	NASA JSC (O'Neill/Reddell)	Z=1 to 92 from 50 meV/n-20 GeV/n
GIRE	Jovian trapped protons, electrons, heavy ions	NASA JPL (Garrett/Jun)	JPL developed models of the jovian trapped radiation and plasma
SATRAD, UMOD	Saturn, Uranus trapped radiation	NASA JPL (Garrett/Jun)	JPL developed models of outer planet radiation belts

NASA Use of Radiation, Charging Models

Model	Environment/ Effect	Source	Comments
NAIRAS	SPE, GCR	NASA LaRC (Mertens), http://sol.spacenvironment.net/~nairas/	Global, real-time, data-driven predictive system needed to assess biologically harmful radiation exposure levels for aviation
International Reference Ionosphere	Ionosphere Ne, Te, Ni, Ti , ion composition, vertical drift, TEC	https://iri.gsfc.nasa.gov/, https://ccmc.gsfc.nasa.gov/pub/modelweb/ionospheric/iri/	Ionosphere climatology model
Statistical IRI	Ne, Te variability in ionosphere	NASA MSFC (Minow)	Statistical Ne, Te variability about IRI output
IRTAM	Ne, foF2, hmF2	http://giro.uml.edu/IRTAM/	Assimilative ionosphere model
CTIPe	Ne, Ni, Te, Ni and other parameters	https://ccmc.gsfc.nasa.gov/models/ctip.php	Physics-based couple theremosphere-ionosphere-plasmasphere model

NASA Use of Radiation, Charging Models

Model	Environment/ Effect	Source	Comments
FLUKA	Radiation transport, interactions with matter	http://www.fluka.org/fluka.php	Fully integrated particle physics Monte Carlo simulation package.
Geant4	Radiation transport, interactions with matter	http://geant4.cern.ch/	Monte Carlo toolkit for the simulation of the passage of particles through matter
HZETRN	Heavy ion/neutron transport code	NASA LaRC, OLTARIS	A heavy ion/nucleon transport code for space radiations
NUCFRG	Heavy ion transport	NASA LaRC	Heavy ion nuclear fragmentation model
Integrated Tiger Series	Electron/photon transport code	Sandia Nat'l Laboratory, https://rsicc.ornl.gov/rsic.html	Time-independent coupled electron/ photon Monte Carlo transport codes
TRIM/SRIM	Proton, heavy ion transport and radiation interactions	http://www.srim.org/	Collection of software packages for calculating ion transport in matter
MCNP	Radiation transport	Los Alamos Nat'l Laboratory https://mcnp.lanl.gov/	General-purpose Monte Carlo N-Particle code for neutron, photon, electron, or coupled neutron/photon/electron transport
NOVICE	Trapped, GCR, SPE	https://empc.com/	3-D radiation transport and effects
SPACERAD	Multiple radiation environments and effects analysis tool	http://www.spacerad.com/	Ionizing radiation environments and effects
Shieldose	1-D radiation transport	NIST, SPENVIS https://ccmc.gsfc.nasa.gov/pub/modelweb/radiation_belt/shieldose/	Dose as function of depth in Al shielding for electrons, protons

NASA Use of Radiation, Charging Models

Model	Environment/ Effect	Source	Comments
NASCAP-2k	LEO, GEO, auroral, interplanetary surface charging	AFRL, https://see.msfc.nasa.gov/	Standard US surface charging code
EQUIPOT	LEO, GEO, user defined surface charging	SPENVIS	Surface charging of patches
SOLARC	Current collection, structure potential, and material erosion of PVA in plasma environment	SPENVIS	Solar array interaction with plasma environment
NUMIT	1-D Internal charging	NASA JPL (Kim), NASA MSFC (Minow)	Time dependent internal charging code
3D NUMIT	3-D internal charging	NASA JPL (Kim)	Time dependent 3D internal charging code
DICTAT	1-D Internal charging	SPENVIS	Time dependent internal charging code
JWST Deep Charging Tool	1-D internal charging	NASA GSFC (Meloy)	Internal charging analysis tool
Plasma Interaction Model (PIM)	Ionosphere interaction with ISS high voltage solar arrays	NASA JSC (ISS Program)	ISS frame charging model
Interactive Spacecraft Charging Handbook	LEO, GEO surface charging	Leidos (Davis)	Web-based multimedia interactive spacecraft charging handbook with integrated spacecraft charging models
Spacecraft Plasma Interaction System (SPIS)	Spacecraft charging and plasma interactions	http://dev.spis.org/projects/spine/home/spis	Software toolkit for spacecraft-plasma interactions and spacecraft charging modelling
COMSOL	Spacecraft charging	https://www.comsol.com/	Electromagnetic equation solver for charging analysis

NASA Use of Radiation, Charging Models

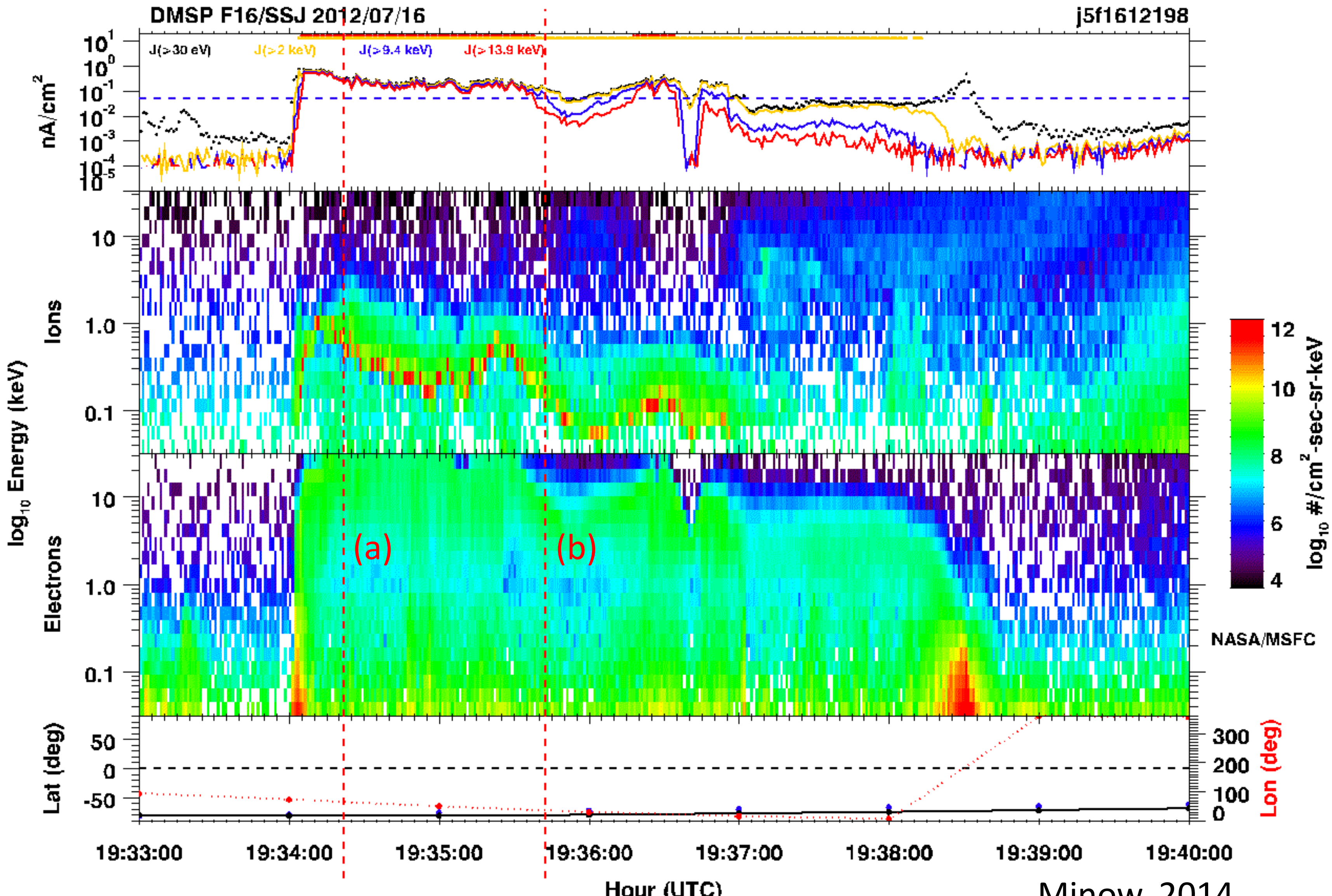
Model	Environment/ Effect	Source	Comments
SPENVIS	Trapped planetary, GCR, SPE	https://www.spenvis.oma.be/	Web interface to space environment and effects models
OLTARIS	Radiation transport, GCR, SPE, lunar albedo	https://oltaris.larc.nasa.gov/	On-line implementation of HZETRN
Community Coordinated Modeling Center	Multiple high fidelity space environment science models	https://ccmc.gsfc.nasa.gov/index.php	Multi-agency partnership to enable, support and perform the research and development for next-generation space science and space weather models
Integrated Space Weather Analysis System	Multiple data sources and environment models	https://ccmc.gsfc.nasa.gov/iswa/	Flexible, turn-key, Web-based dissemination system for NASA-relevant space weather information
Environments Workbench	Multiple LEO environments and effects	Leidos (Davis)	Desktop, integrated analysis tool for the study of a spacecraft interactions with its environment.
AF-GEOSpace	Multiple LEO environments and effects	AFRL (Hilmer)	Air Force space environment toolset

NASA Needs

- NASA users are always interested in improvements in existing codes and access to new models for both environments and effects

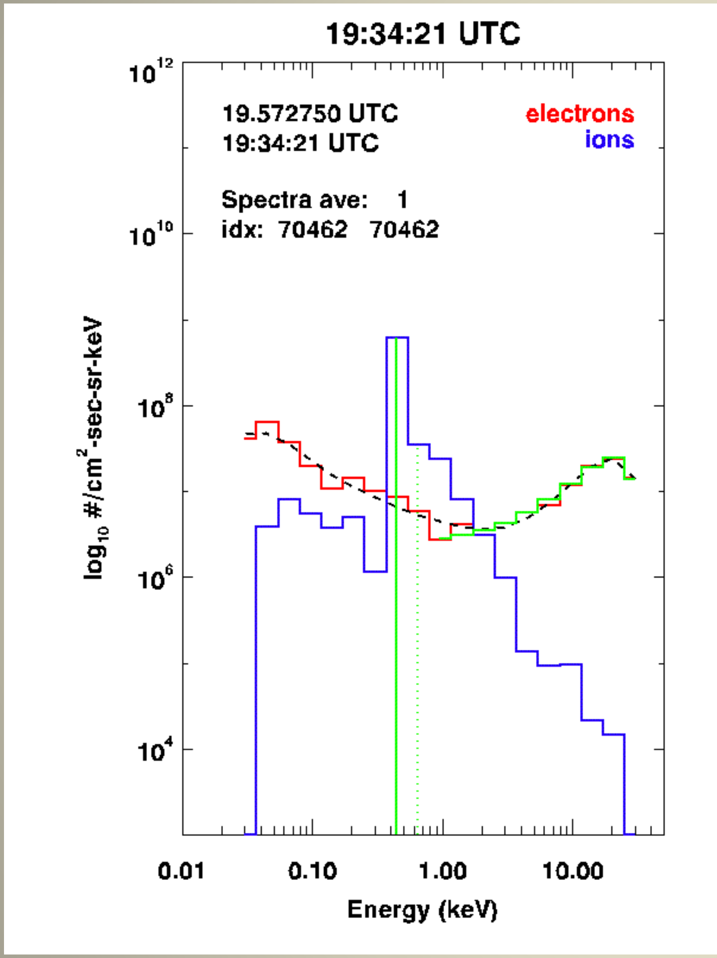
- Areas where users have mentioned particular needs in recent years:
  - **Solar cycle variation in AE9/AP9 output**
  - Pitch angle information in AE9/AP9?
  - Statistical SPE flux or fluence models for periods less than a year
  - Statistical GCR models for design (for range of z, E, and LET)
  - Quantitative tools for predicting SPE time-dependent spectra following flare and/or CME on sun
  - Tools for predicting SPE ion flux increase and maximum flux following onset (particularly useful for space weather constraints for launch, satellite operations)
  - Access to GAIM or other assimilative ionosphere models generating both Ne and Te
  - **Models that generate environments in format used in effects codes (e.g., Nascap)**
  - **Statistical information on extreme auroral, GEO charging environments**

Auroral Charging

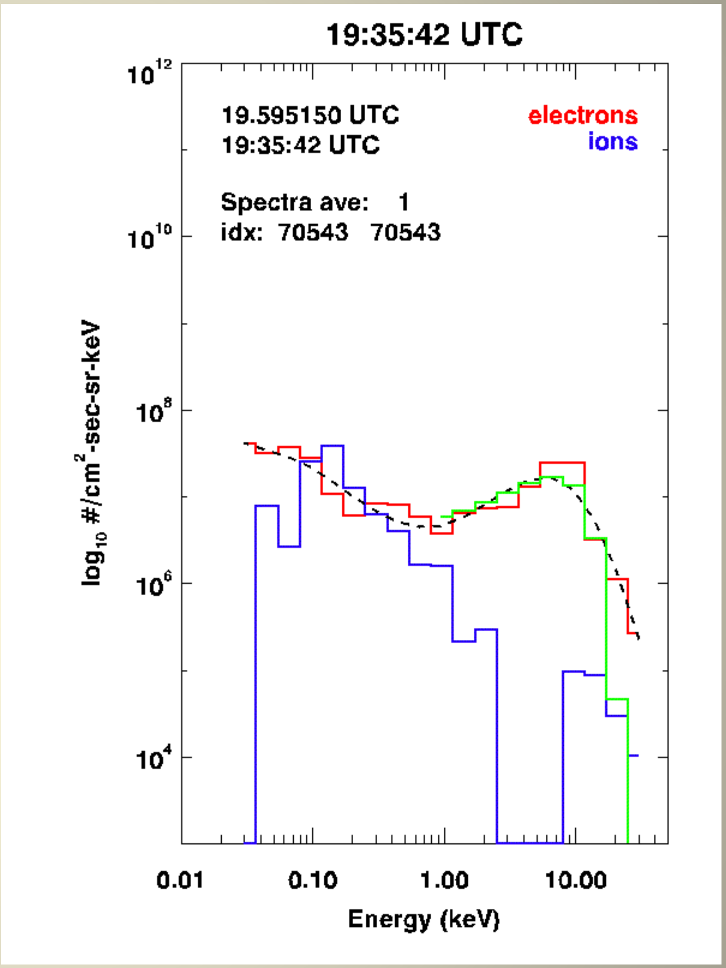


Minow, 2014

Individual Spectra



(a)



(b)

Minow, 2014

Fontheim Distribution

Ambient background

n=1.0e10 1/m3

Te=0.2 eV

Maxwellian

Jmax = 4.0e-6 A/m²

Te = 3.0e3 eV

Gaussian (beam)

Jgau =0.9e-4 A/m²

Egau = 10.0e3 eV beam energy

dgau = 4.0e3 eV beam width

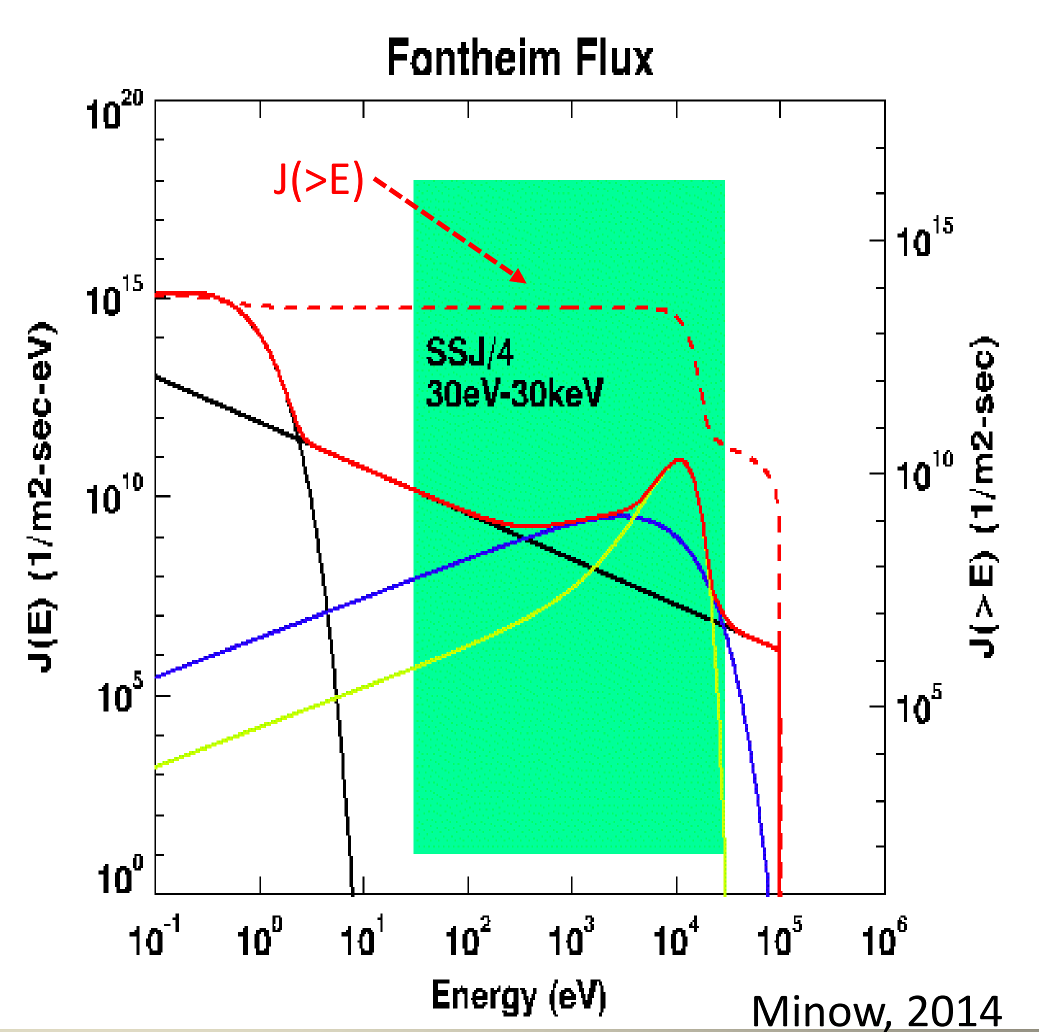
Power Law

Jpwr = 3.0e-7 A/m²

alpha = 1.15 exponent

E1=50.0 eV, first energy

E2=1.0e5 eV, second energy



Minow, 2014

$$\mathrm{Flux}(E)=\sqrt{\frac{e}{2\pi\theta m_e}}\frac{E}{\theta}n\exp\left(-\frac{E}{\theta}\right)+\pi\zeta_{max}E\exp\left(-\frac{E}{\theta_{max}}\right)+\pi\zeta_{gauss}E\exp\left(-\left(\frac{E_{gauss}-E}{\Delta}\right)^2\right)+\pi\zeta_{power}E^{-\alpha}$$

[Davis et al., 2011]

Nascap-2k Auroral Environment

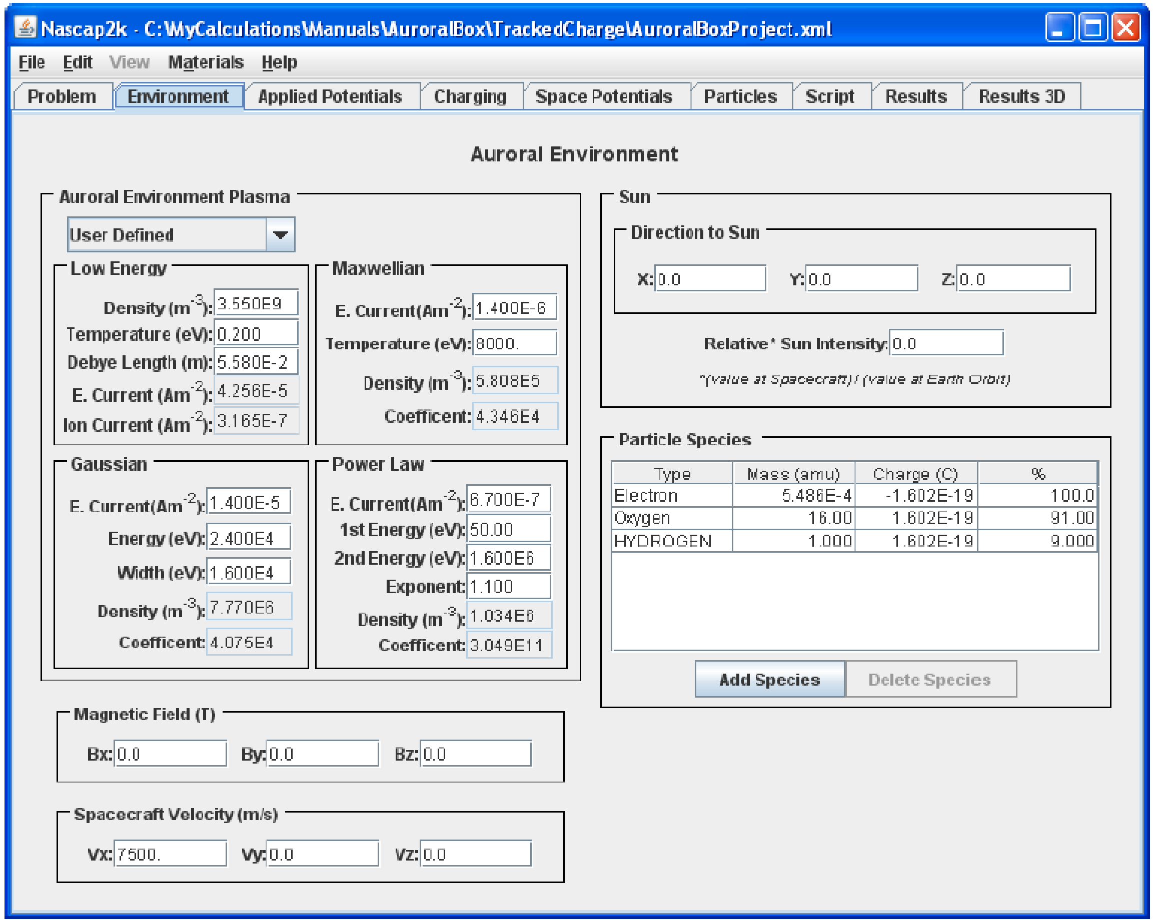


Figure 14. The Environment Tab for Studies in an Auroral Environment

Davis et al., NASCAP-2K Version 4.2 User's Manual AFRL-RV-PS-TR-2015-0107, 2014.

$$\mathrm{Flux}(E) = \sqrt{\frac{e}{2\pi\theta m_e}}\frac{E}{\theta} n \exp\left(-\frac{E}{\theta}\right) + \pi\zeta_{max} E \exp\left(-\frac{E}{\theta_{max}}\right) + \pi\zeta_{gauss} E \exp\left(-\left(\frac{E_{gauss}-E}{\Delta}\right)^2\right) + \pi\zeta_{power} E^{-\alpha}$$

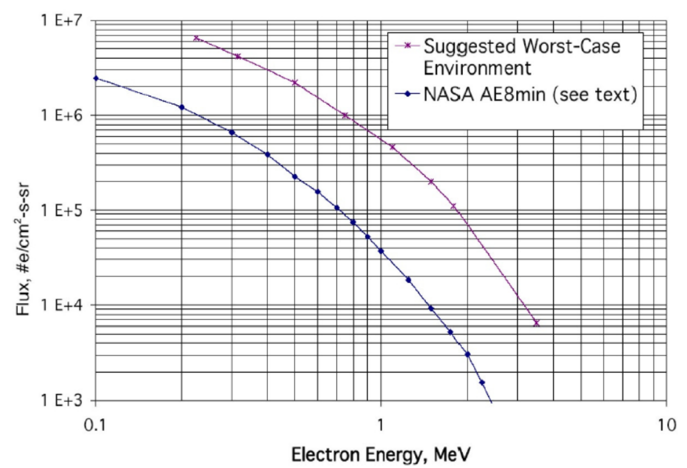
GEO Charging Environments

- NASA guidelines for worst case charging in GEO are based on
  - Surface charging: moments for extreme plasma environment
  - Internal charging: spectrum for extreme electron environment

- NASA would benefit from access to statistical information on occurrence rates of these environments, percentile environments, and durations

Table 1—Worst-Case Geosynchronous Plasma Environment

ITEM	UNITS	VALUE	DESCRIPTION
N_E	cm^{-3}	1.12	electron number density
T_E	eV	$1.2x10^4$	electron temperature
N_I	cm^{-3}	0.236	ion number density
T_I	eV	$2.95x10^4$	ion temperature



Upper: Worst-case short-term GEO environment (May 11, 1992, 197 deg East longitude peak daily environment over several hour period, with no added margin).

Lower: NASA AE8min long-term average environment (200 deg East longitude).

[NASA-HDBK-4002A, Mitigating In-Space Charging Effects – A Guideline, 2011]

Average GEO Charging Environments

Table 9—Average Parameters from Referenced Spacecraft

ELECTRON PARAMETERS			
PARAMETER	**ATS-5**	**ATS-6**	**SCATHA**
Number density (cm^{-3})	0.80	1.06	1.09
Current density ($nA\text{-}cm^{-2}$)	0.068	0.096	0.115
Energy density ($eV\ cm^{-3}$)	1970	3590	3710
Energy flux ($eV\ cm^{-2}s^{-1}sr^{-1}$)	0.98×10^{12}	2.17×10^{12}	1.99×10^{12}
Number density for population 1 (cm^{-3})	0.578	0.751	0.780
Temperature for population 1 (keV)	0.277	0.460	0.550
Number density for population 2 (cm^{-3})	0.215	0.273	0.310
Temperature for population 2 (keV)	7.04	9.67	8.68
Average temperature (keV)	1.85	2.55	2.49
Root-mean-square temperature (keV)	3.85	6.25	4.83
ION PARAMETERS (ASSUMED TO BE PRIMARILY H^+)			
PARAMETER	**ATS-5**	**ATS-6**	**SCATHA**
Number density (cm^{-3})	1.36	1.26	0.58
Current density ($pA\ cm^{-2}$)	5.1	3.4	3.3
Energy density ($eV\ cm^{-3}$)	13,000	12,000	9,440
Energy flux ($eV\ cm^{-2}s^{-1}sr^{-1}$)	2.6×10^{11}	3.4×10^{11}	2.0×10^{11}
Number density for population 1 (cm^{-3})	0.75	0.93	0.19
Temperature for population 1 (keV)	0.30	0.27	0.80
Number density for population 2 (cm^{-3})	0.61	0.33	0.39
Temperature for population 2 (keV)	14.0	25.0	15.8
Average temperature (keV)	6.8	6.3	11.2
Root-mean-square temperature (keV)	12.0	23.0	14.5

[NASA-HDBK-4002A, Mitigating In-Space Charging Effects – A Guideline, 2011]

GEO Standard Deviations

Table 10—Standard Deviations

ELECTRON STANDARD DEVIATIONS			
PARAMETER STANDARD DEVIATION (±)	**ATS-5**	**ATS-6**	**SCATHA**
Number density (cm^{-3})	0.79	1.1	0.89
Current density (nA cm^{-2})	0.088	0.09	0.10
Energy density (eV cm^{-3})	3,100	3,700	3,400
Energy flux (eV $cm^{-2}s^{-1}sr^{-1}$)	$1.7x10^{12}$	$2.6x10^{12}$	$2.0x10^{12}$
Number density for population 1 (cm^{-3})	0.55	0.82	0.70
Temperature for population 1 (keV)	0.17	0.85	0.32
Number density for population 2 (cm^{-3})	0.38	0.34	0.37
Temperature for population 2 (keV)	2.1	3.6	4.0
Average temperature (keV)	2.0	2.0	1.5
Root-mean-square temperature (keV)	3.3	3.5	2.9
ION STANDARD DEVIATIONS (ASSUMED TO BE PRIMARILY H^+)			
PARAMETER STANDARD DEVIATION (±)	**ATS-5**	**ATS-6**	**SCATHA**
Number density (cm^{-3})	0.69	1.7	0.35
Current density (pA cm^{-2})	2.7	1.8	2.1
Energy density (eV cm^{-3})	9,700	9,100	6,820
Energy flux (eV $cm^{-2}s^{-1}sr^{-1}$)	$3.5x10^{11}$	$3.6x10^{11}$	$1.7x10^{11}$
Number density for population 1 (cm^{-3})	0.54	1.78	0.16
Temperature for population 1 (keV)	0.30	0.88	1.0
Number density for population 2 (cm^{-3})	0.33	0.16	0.26
Temperature for population 2 (keV)	5.0	8.5	5.0
Average temperature (keV)	3.6	8.4	4.6
Root-mean-square temperature (keV)	4.8	8.9	5.3

[NASA-HDBK-4002A, Mitigating In-Space Charging Effects – A Guideline, 2011]

GEO Worst Case Charging Environments

- Worst case GEO charging environments that are typically used for design are based on ATS-6 and SCATHA case studies
- New studies using data from LANL satellites are available and should be considered for updating the extreme design environments

Table 16—Worst-Case Geosynchronous Environments

ELECTRONS	Deutsch* ATS-6	Mullen** SCATHA	Mullen*** SCATHA
Number density (ND) (cm^{-3})	1.22	0.9	3
Current density (J) (nA cm^{-2})	0.41	0.187	0.501
Energy density (ED) (eV cm^{-3})	2.93E+04	9.60E+03	2.40E+04
Energy flux (EF) (eV cm^{-2} s^{-1} sr^{-1})	2.64E+13	6.68E+12	1.51E+13
Number density for population 1, N1, cm-3	0	--	--
Parallel	–	0.2	1.0
Perpendicular	–	0.2	0.8
Temperature for population 1(T1) (keV)	0	--	--
Parallel	–	0.4	0.6
Perpendicular	–	0.4	0.6
Number density for population 2 (N2) (cm^{-3})	1.22	--	--
Parallel	–	0.6	1.4
Perpendicular	–	2.3	1.9
Temperature for population 2 (T2) (keV)	16.0	--	--
Parallel	–	24.0	25.1
Perpendicular	–	24.8	26.1
Electron average temperature (Tav) (keV)	16	7.7	5.33
Electron root-mean-square temperature (Trms) (keV)	16.1	9	7.33
IONS (PROTONS)	**Deutsch* ATS-6**	**Mullen** SCATHA**	**Mullen*** SCATHA**
Number density (ND) (cm^{-3})	0.245	2.3	3
Current density (J) (nA cm^{-2})	0.00252	0.00795	0.0159
Energy density (ED) (eV cm^{-3})	1.04E+04	1.90E+04	3.70E+04
Energy flux (EF) (eV cm^{-2} s^{-1} sr^{-1})	2.98E+11	3.42E+11	7.48E+11
Number density for population 1, N1, cm-3	0.00882	--	--
Parallel	–	1.6	1.1
Perpendicular	–	1.1	0.9
Temperature for population 1, T1, keV	0.111	--	--
Parallel	–	0.3	0.4
Perpendicular	–	0.3	0.3
Number density for population 2, N2, cm-3	0.236	--	--
Parallel	–	0.6	1.7
Perpendicular	–	1.3	1.6
Temperature for population 2, T2, keV	29.5	--	--
Parallel	–	26	24.7
Perpendicular	–	28.2	25.6
Ion average temperature (Tav) (keV)	28.4	5.5	8.22
Ion root-mean-square temperature (Trms) (keV)	29.5	12	11.8

Note: Tav, Trms, and the ATS-6 two-Maxwellian parameters are averaged over all angles. The SCATHA two-Maxwellian parameters are for fluxes parallel and perpendicular to the magnetic field.
*Deutsch, 1982 ** Mullen and others (1981) *** Mullen, Gussenhoven, and Garrett, 1981

[NASA-HDBK-4002A, Mitigating In-Space Charging Effects – A Guideline, 2011]

Nascap-2k GEO

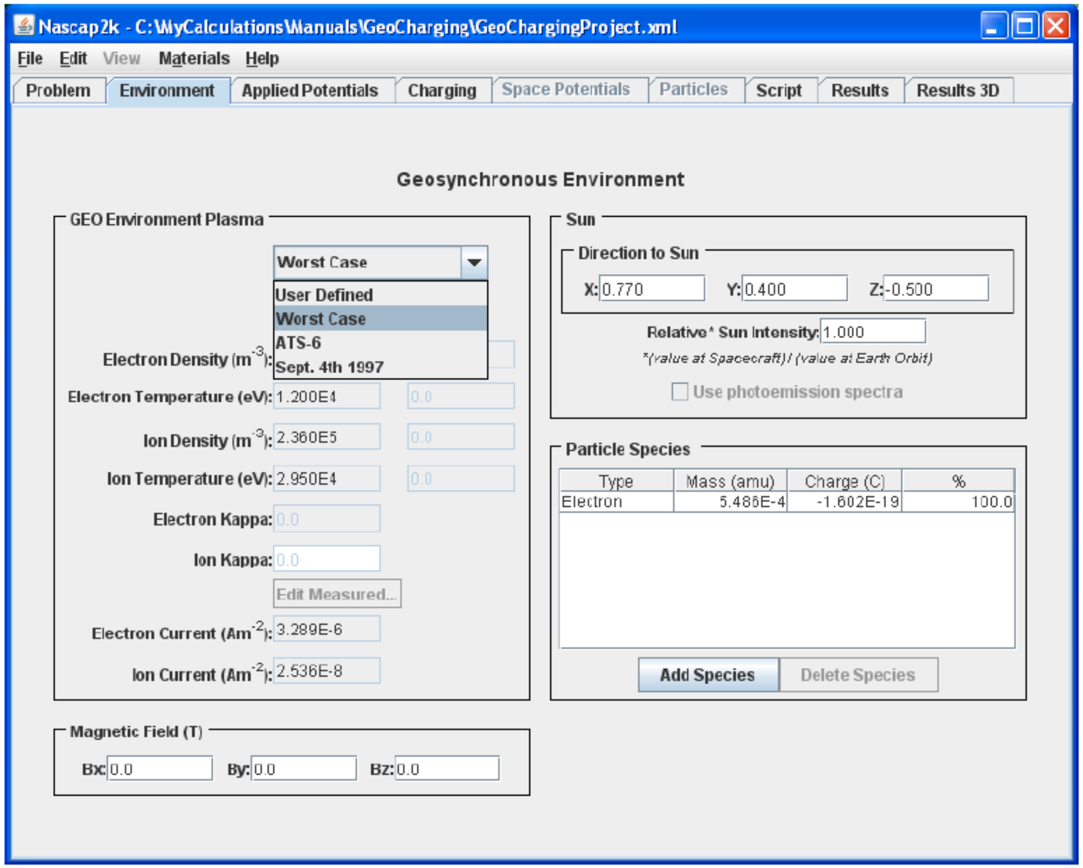


Figure 11. The Environment Tab for Studies in a Geosynchronous Plasma

Solar Cycle Variation in Trapped Radiation Models

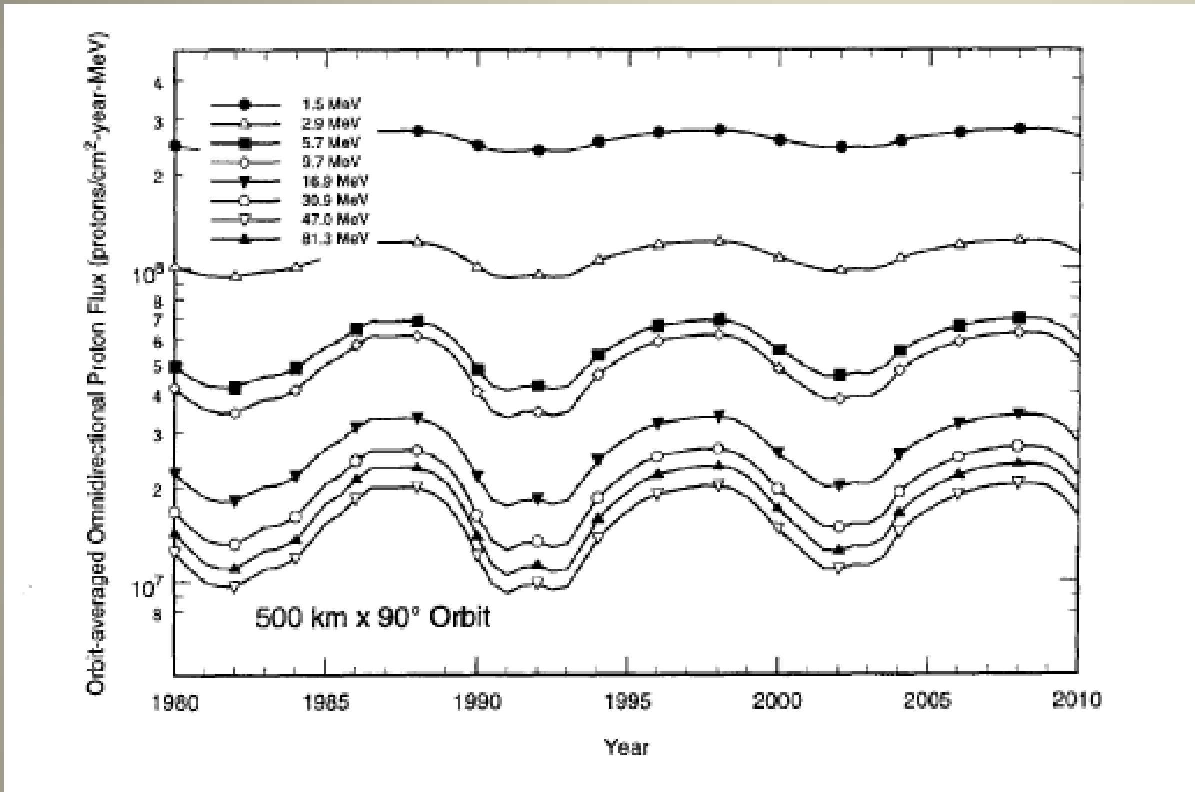
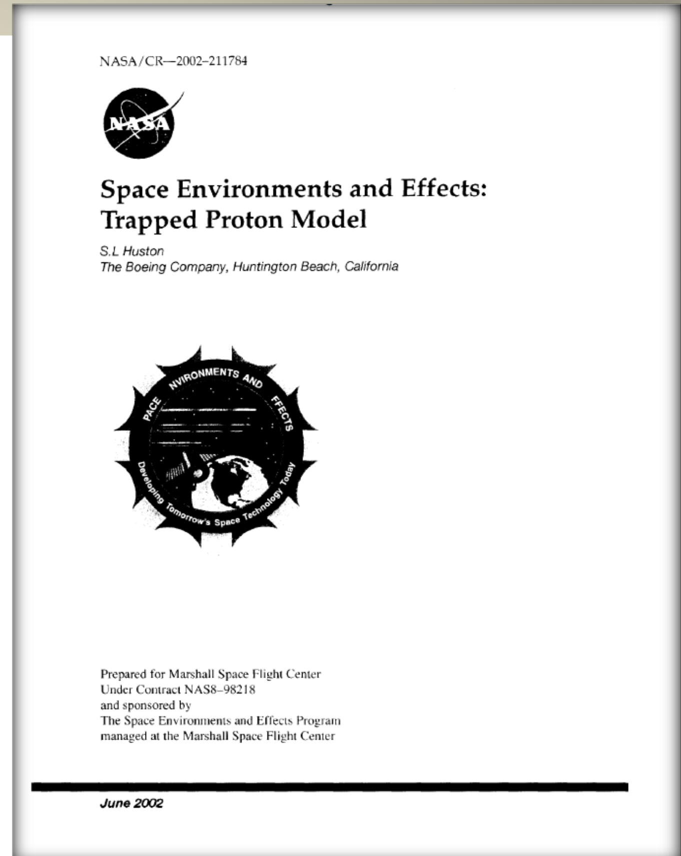


Figure 17. Solar cycle variation of trapped proton flux at several energies.



NASA/CR—2002-211784

Space Environments and Effects: Trapped Proton Model

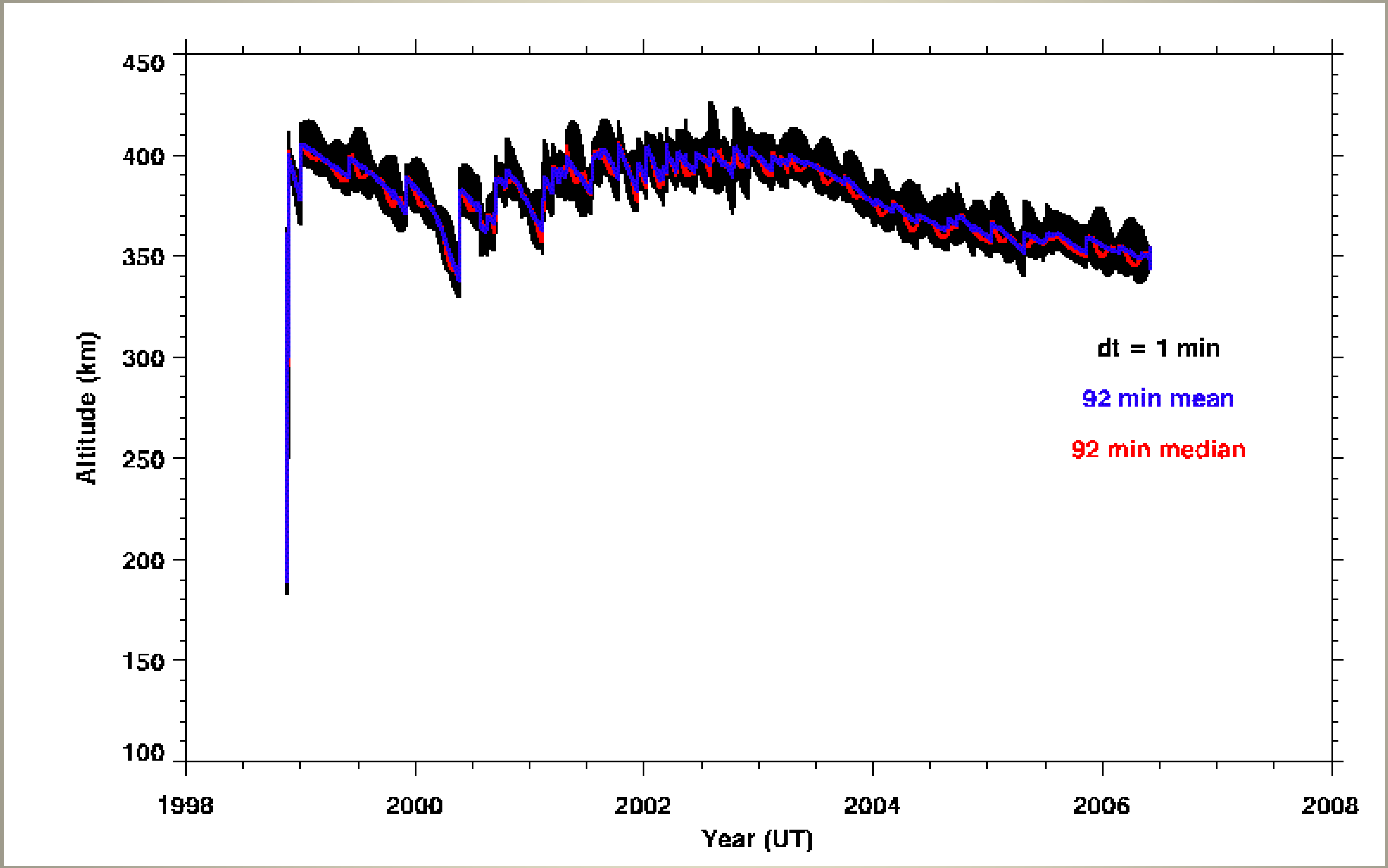
S.L Huston
The Boeing Company, Huntington Beach, California

Prepared for Marshall Space Flight Center
Under Contract NAS8–98218
and sponsored by
The Space Environments and Effects Program
managed at the Marshall Space Flight Center

June 2002

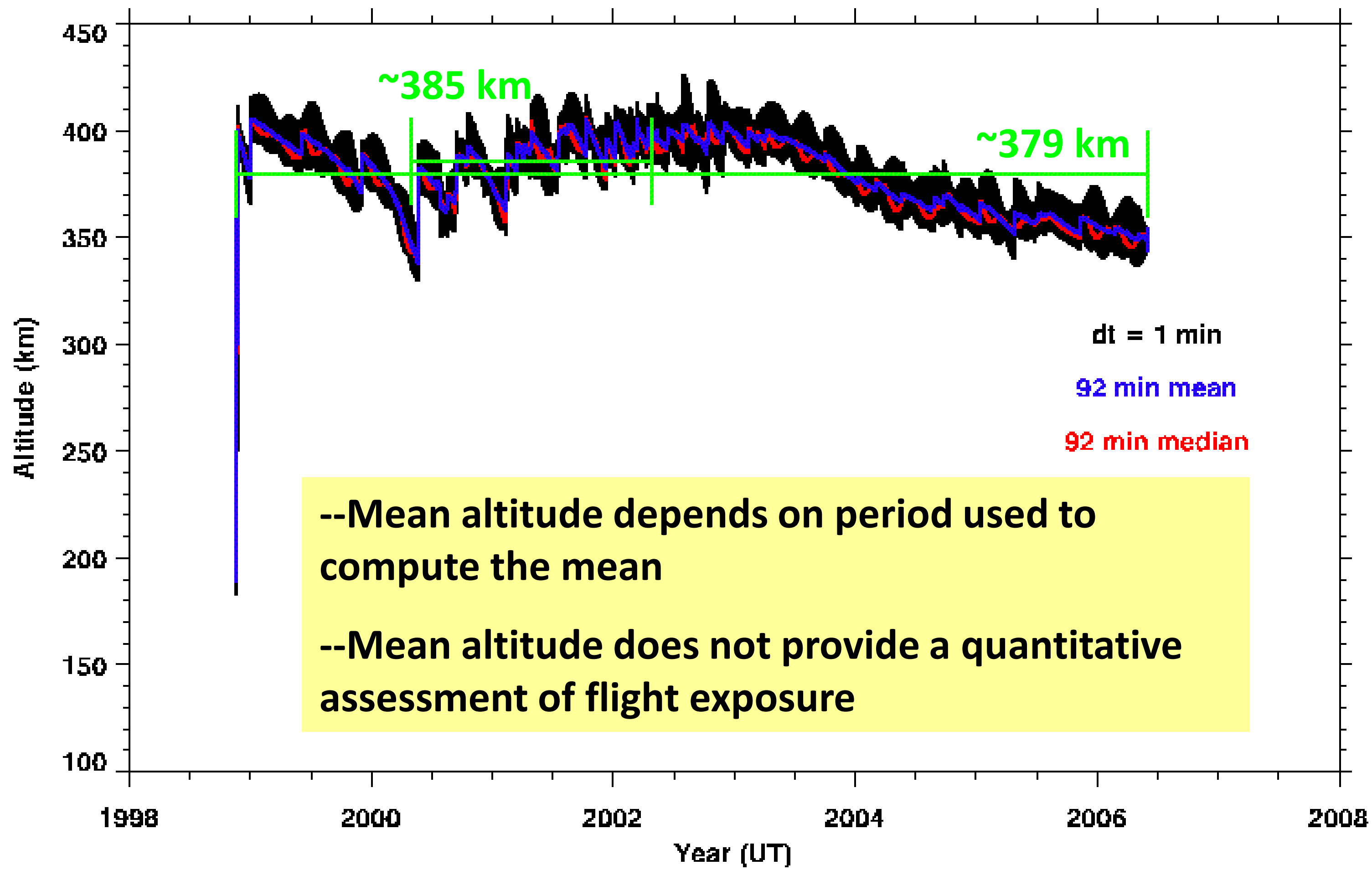
- Trapped Proton Model was an early attempt to include solar cycle variations in trapped radiation belt models
- Including this physics in AE9/AP9 would be useful for design, operations, and anomaly assessments.

ISS Altitude



Minow et al., 2006

ISS Altitude



--Mean altitude depends on period used to compute the mean

--Mean altitude does not provide a quantitative assessment of flight exposure

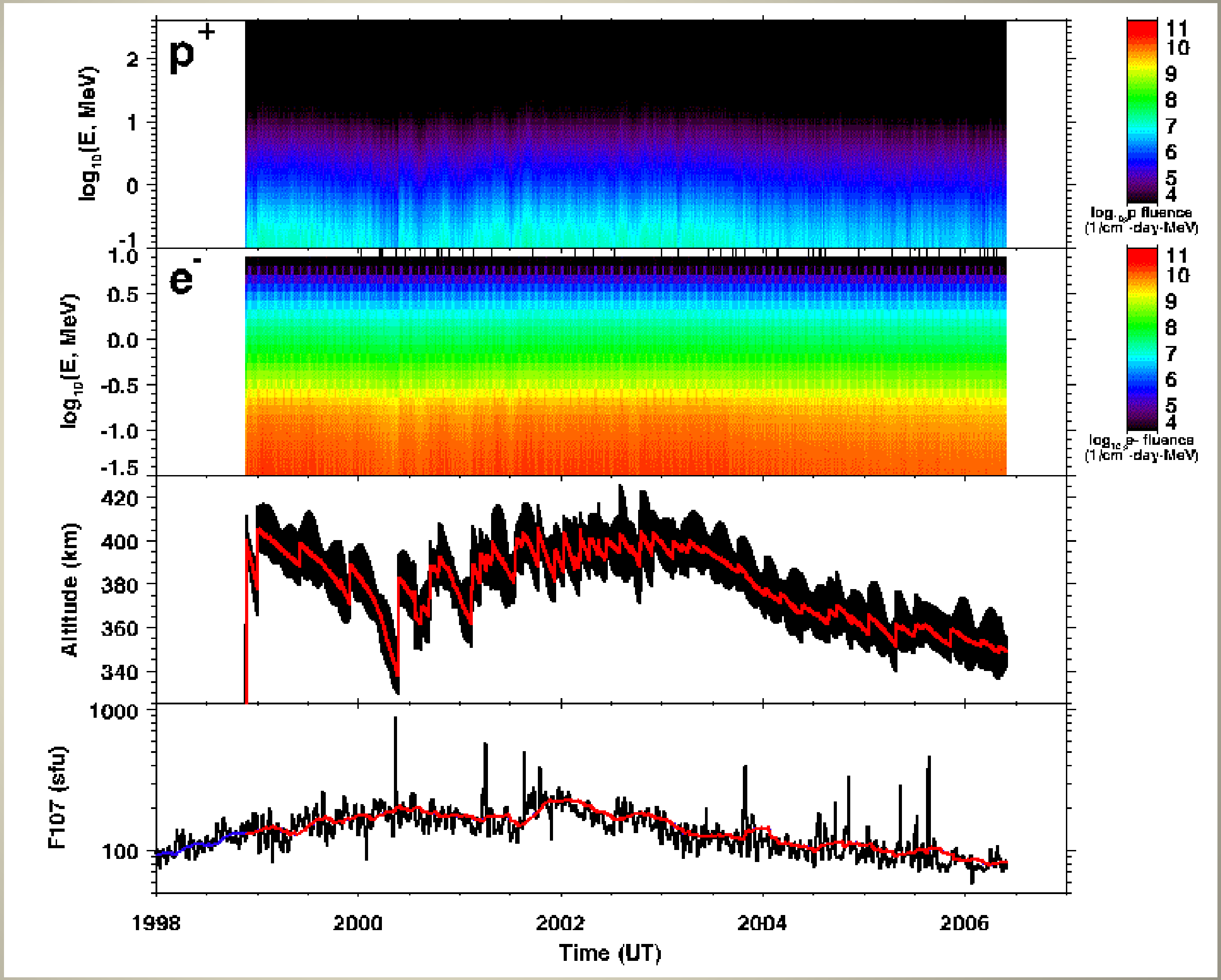
Minow et al., 2006

Reconstructed ISS "As flown" Environment

AE-8 min

AP-8 min

No SPE



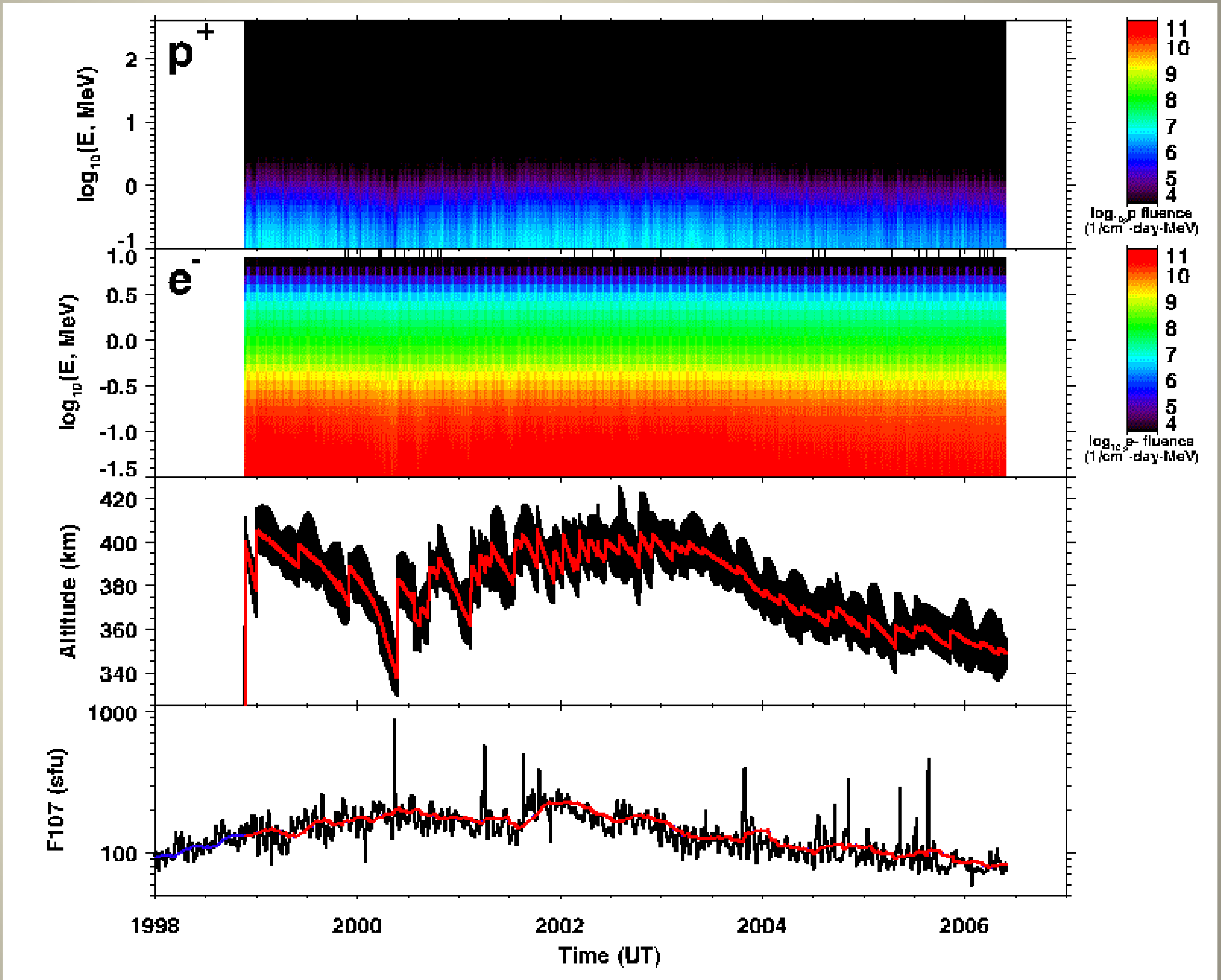
Minow et al., 2006

Reconstructed ISS "As flown" Environment

AE-8 max

AP-8 max

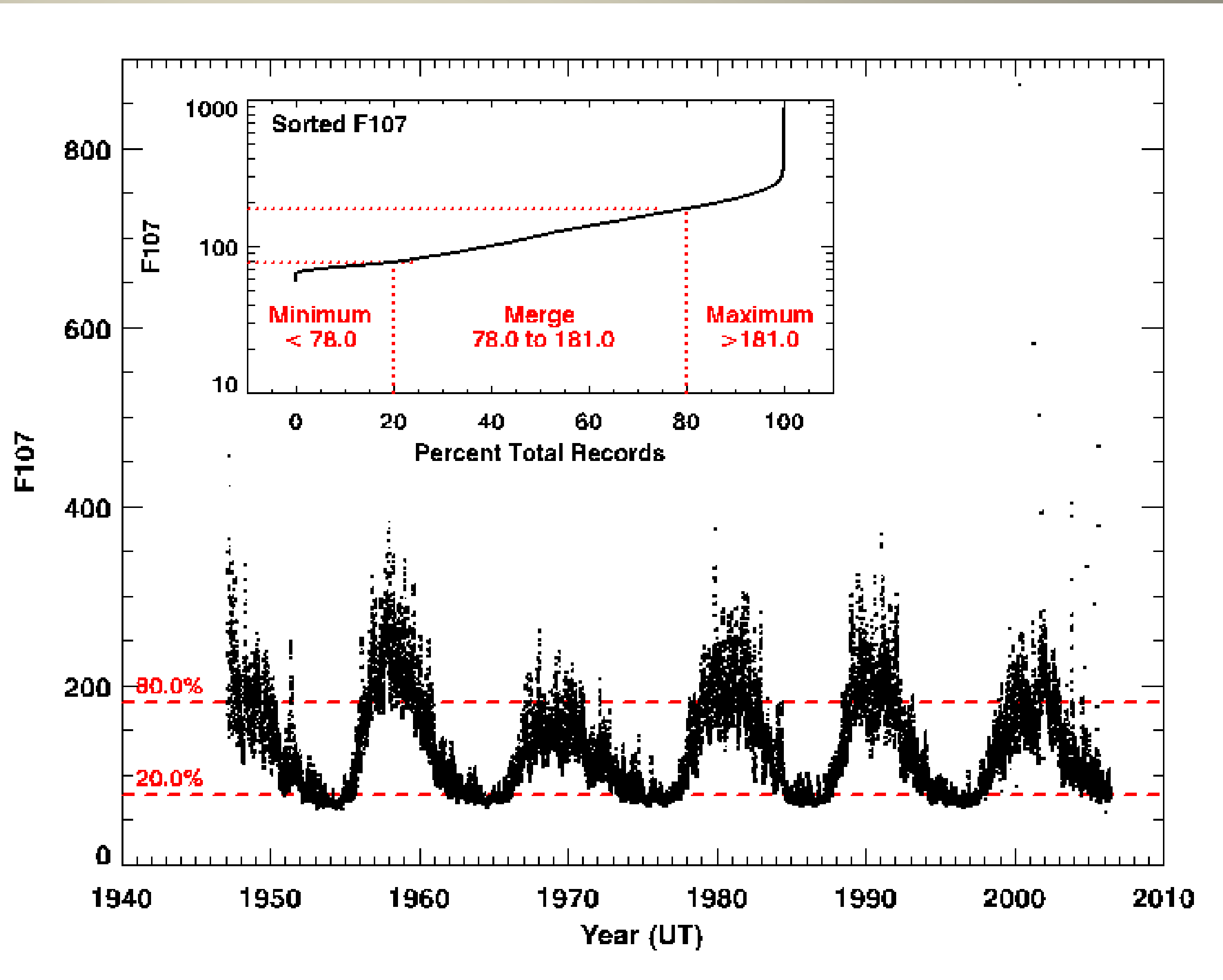
No SPE



Minow et al., 2006

Objective Assignment of Solar Min or Max Models

- **AE/AP models apply to solar max, min conditions only**
- **Strategies typically adopted for use include:**
  - **Most severe model for conservative design applications**
  - **7 yrs max, 5 yrs min for 11 year solar cycle**



Minow et al., 2006

Solar Min/Max Weighting

- **Watts et al. [1996] technique used to objectively determine when to use solar minimum or solar maximum version of the AE-8, AP-8 models**

- $\Phi = \alpha\Phi_{max} + (1-\alpha)\Phi_{min}$

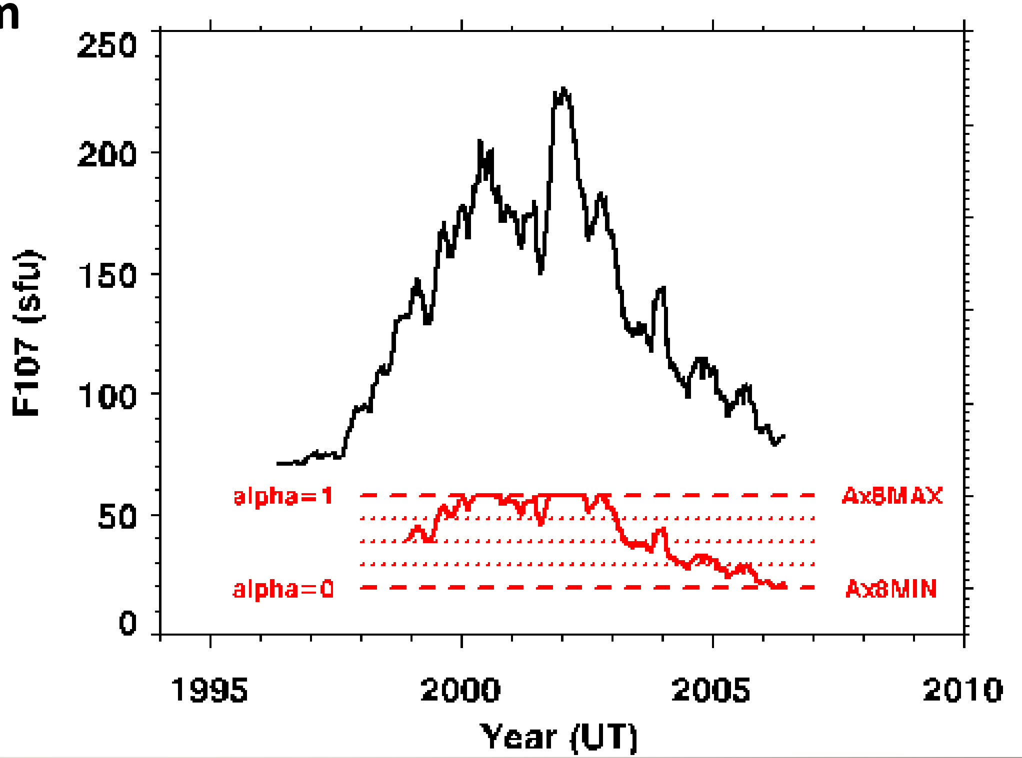
Φ_{max} = AE-8, AP-8 max flux

Φ_{min} = AE-8, AP-8 min flux

α = F107 weighting factor

= 0 for solar min

= 1 for solar max



Minow et al., 2006

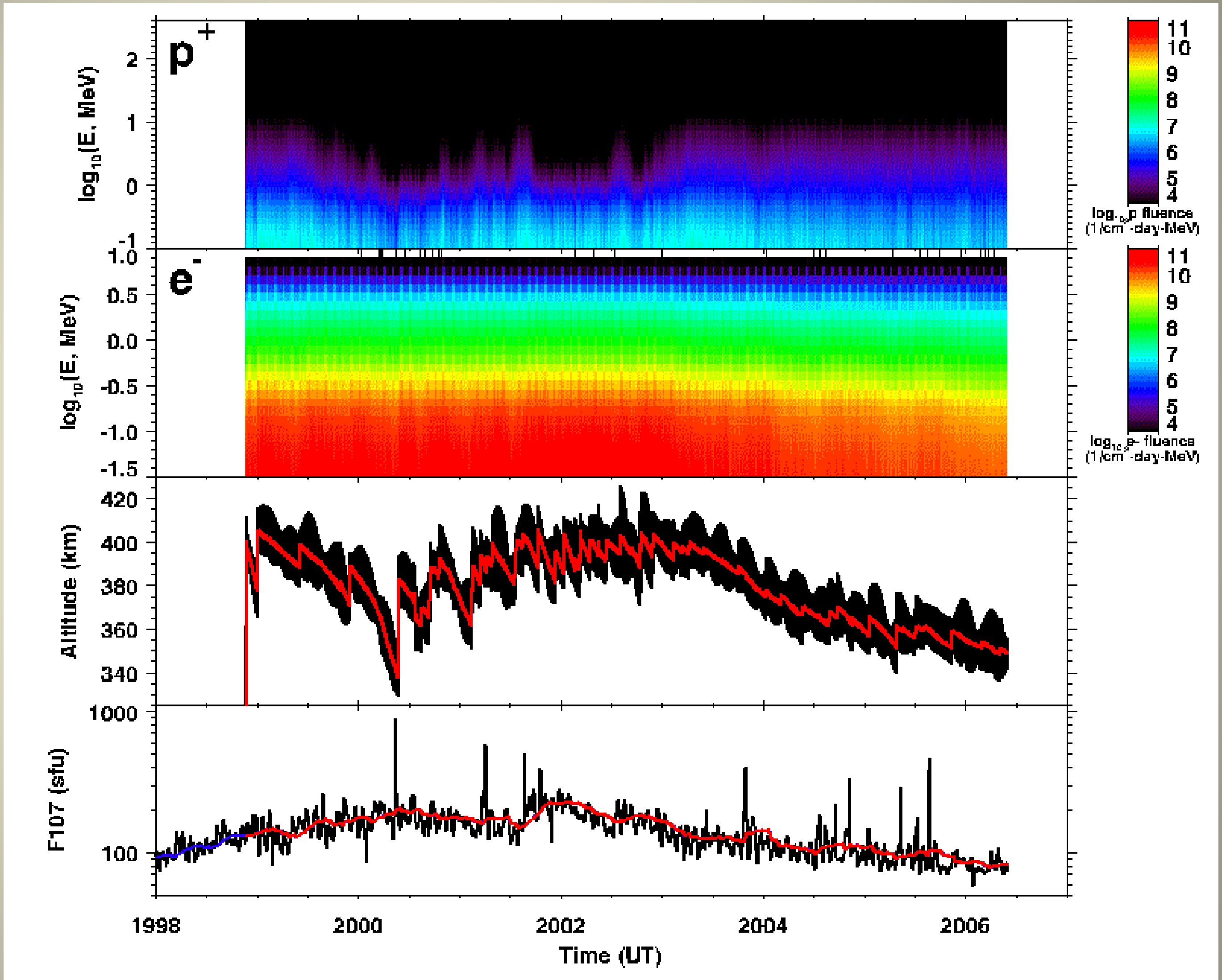
Reconstructed ISS "As flown" Environment

AE-8

AP-8

Merged max/min

No SPE



Minow et al., 2006

Reconstructed ISS "As flown" Environment

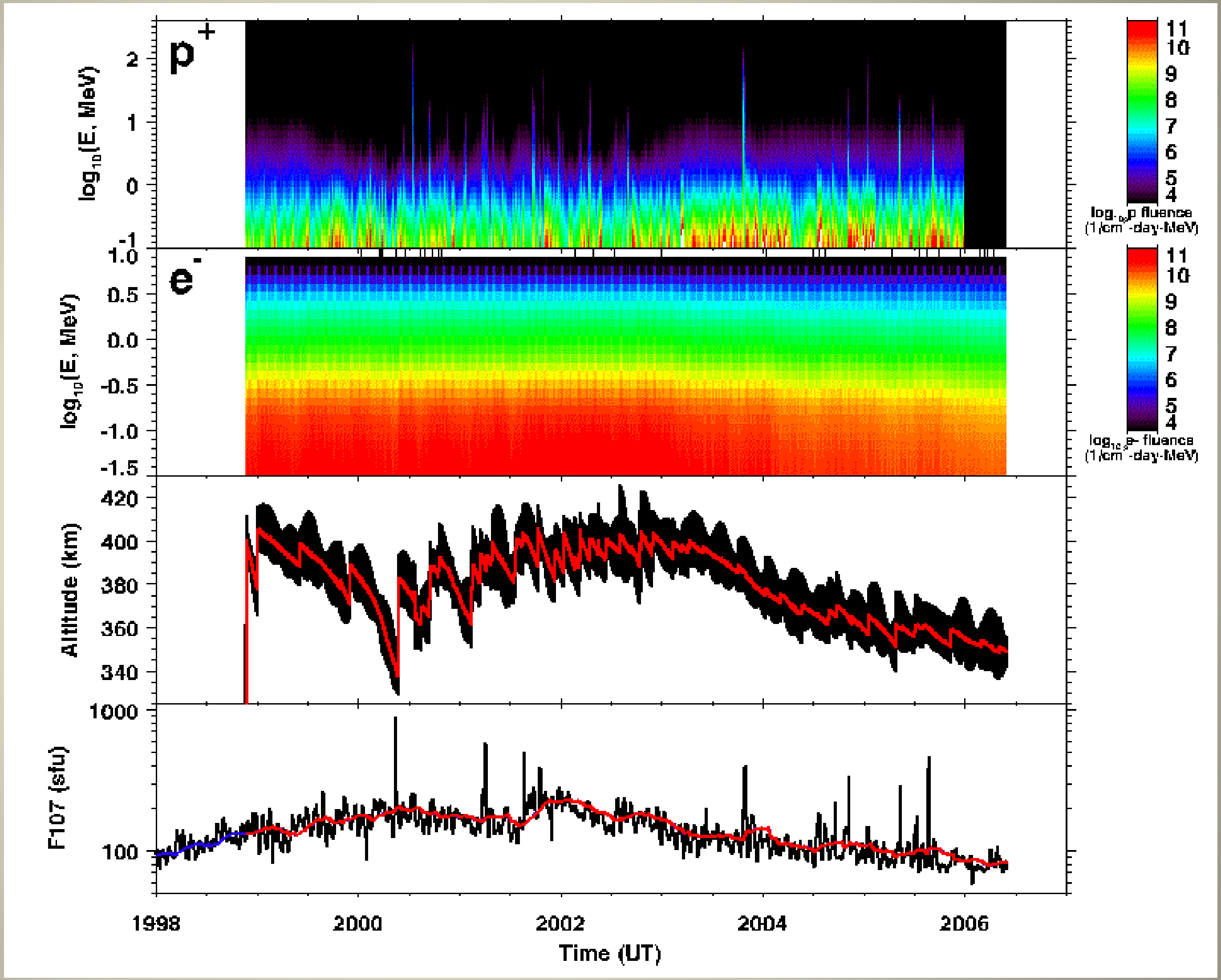
AE-8

AP-8

Merged max/min

+ GOES protons

CREME96 geomagnetic cutoff model used to estimate solar proton fluence at ISS orbit



Minow et al., 2006

ISS image: 7 March 2012