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

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ABSTRACT

A new set of models for the flux of particles in the Earth's inner magnetosphere has been developed for use in space system design and other applications requiring a climatological specification. Denoted AE9, AP9, and SPM for energetic electrons, energetic protons and space plasma, respectively, the models are derived from 33 data sets measured by satellite on-board sensors. These data sets have been processed in a manner to create maps of the particle fluxes together with estimates of uncertainties due to both imperfect measurements and space weather variability. Furthermore, the model architecture permits the Monte-Carlo estimation of the time evolution of fluxes and derived quantities, e.g., the median and 95th percentile, along an arbitrary orbit. An overview of the model will be presented, addressing in particular the latest AE9/AP9 version release.

Keywords: radiation belts, AE9/AP9, dose

1. INTRODUCTION

Design for the space environment has made use of a variety of empirical models specifying the near-Earth trapped radiation environment. The most widely used of these models have been the series sponsored by the National Aeronautics and Space Administration (NASA) culminating in AP8 and AE8, describing the proton and electron radiation belts, respectively.[1-3] In the thirty years since their release, the design community has expressed the need for updated and more capable models. To meet these needs, a collaboration led by the Air Force Research Laboratory (AFRL) has developed AE9/AP9/SPM, a suite of models describing the trapped electron, proton, and plasma environments, respectively, in near-Earth space. AE9/AP9/SPM V1.00 was released in 2012, and the current version (V1.05) was released in September 2013.

The AE9/AP9/SPM suite is based on data sets mostly acquired after development of AE8 and AP8 and covers greater spatial and energy ranges than the prior models. Importantly, the new models introduce data-based statistics quantifying uncertainties from both measurement uncertainty and space weather variability. For the AE9 and AP9 models, multiple Monte Carlo (MC) scenarios may be run to provide statistically realistic time histories of particle fluxes over a given mission as well, plus aggregates of scenarios can produce confidence intervals (e.g., 95^{th} percentiles). Thus the new models provide designers with probabilistic risks to permit cost or capability vs. risk tradeoffs. The new architecture is also specifically designed to facilitate updates in both flux maps and features. In 2014 V1.20 will be released incorporating new data for energetic protons and plasma, improvements to electron data, and new features.

This paper will briefly review the new models, providing some focus on how designers can make use of the new capabilities. We will also provide information on pending and planned version updates.

2. OVERVIEW

The AE9/AP9/SPM models have been previously reviewed,[4] and technical documentation of the models will also be released.[5] Here, we provide a summary of the model objectives, architecture, data sets, and validation.

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2.1 Motivating needs

The AE8 and AP8 models represented quite capable descriptions of the radiation belts across the most needed ranges of location and energy. Subsequent satellite observations showed, however, that estimates from these models for various locations/energies were sometimes too low (resulting in risks from underdesign) or too high (resulting in unnecessary costs from overdesign). Further, the lack of explicit statistics for uncertainty or variability could only be addressed by arbitrary design margins added to the model results. Component developers also needed specifications at a wider range of energies than provided by these models. Interim models were subsequently developed, but these suffered drawbacks such as being based on limited data sets or describing a limited range of energy or orbital regimes. The AE9/AP9/SPM project was undertaken to address all these issues: covering the full range of energies and locations described by AE8/AP8, expanded further to meet new needs (e.g., expanded to plasma energies in the Standard Plasma Model or SPM), and incorporating new data sets selected for higher accuracy in regions of concern. In addition, an architecture was developed to provide both data-driven statistics for all results as well as a systematic model production approach that facilitates future updates.

2.2 Architecture

Each of the component models AE9, AP9 and SPM describe fluxes, in particular the median and 95th percentiles, over a spatial and energy grid. These maps are related to arbitrary percentiles via statistical distributions appropriate to each species. The spatial gridding makes use of the magnetic invariants that dictate radiation belt morphology; while such use is invisible to the user (who interrogates the model via orbital elements or ephemerides in standard coordinate systems), this provides a more accurate translation of fluxes over magnetic epochs. For low-Earth orbit (LEO) altitudes, a second grid is used for higher resolution since fluxes there vary significantly with altitude. The models use the International Geomagnetic Reference Field (IGRF) model[6] plus the Olson-Pfitzer Quiet model[7] for the external field. Whereas AE8/AP8 stored omnidirectional fluxes as a function of spatial location, the magnetic invariant spatial grid used in AE9/AP9 effectively stores directional fluxes. These results are still integrated within the model to produce omnidirectional fluxes for common applications, but this approach also provides a more direct ability to provide unidirectional flux estimates as needed. Table 1 summarizes the respective model coverages in energy and spatial location.

Table 1. Species and spatial/energy ranges covered by the AE9/AP9/SPM models.

Model	AE9	AP9	SPM
Species	e^-	H^+	e^-, H^+, He^+, O^+
Energies	40 keV—10 MeV	100 keV—400 MeV (V1.0-V1.05); 100 keV—2 GeV (V1.20)	1—40 keV (e^-); 1.15—164 keV (H^+, He^+, O^+)
Range in L	$0.98 < L^* < 12.4$	$0.98 < L^* < 12.4$	$2 < L_m < 10$

The Monte Carlo capability (limited to AE9 and AP9) uses data-based spatio-temporal covariances and an Nth-order auto-regression to evolve the flux maps for each MC scenario over time in a realistic way. Thus, within a scenario the relation of fluxes at different locations or different times are consistent with the observations used to develop the model. AE9/AP9/SPM does not include solar cycle dependence explicitly, e.g., as with the distinct solar minimum/solar maximum modes of AP8. However, as the data used in the new models span the full range of solar cycle phases, the range of the statistics provided in model output represent the full range of observed variability associated with a solar cycle. Given that most mission design occurs without certainty as what phase of solar cycle the mission will encounter, the model consequently provides statistics representing the potential range of mission conditions.

2.3 Verification and validation

Performance checking of AE9 and AP9 has included both verification against legacy models and validation against independent data sets. Figure 1 shows comparisons of AE8 to AE9 and AP8 to AP9 for meridional cuts through the structure of the radiation belts (this structure is roughly symmetric about the magnetic dipole axis which runs near the x=0 axis in these plots). Morphological differences at high altitudes for the electron models result from AE9's inclusion of an external magnetic field model.

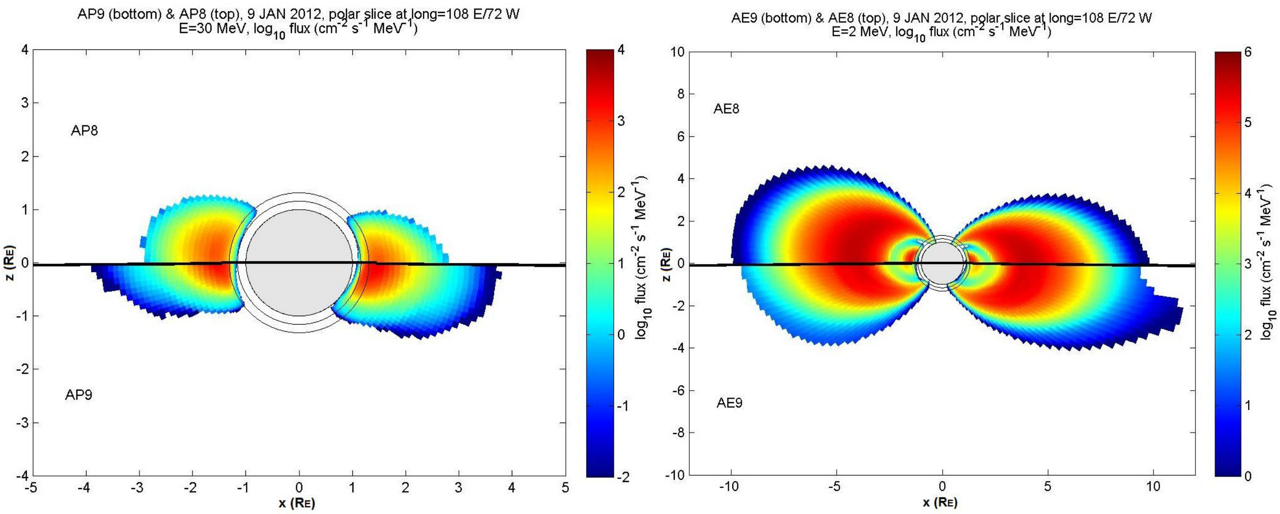

Figure 1. (a) Comparison of AP8 (top) and AP9 V1.05 median (bottom) on a meridional cut through the radiation belts, 30 MeV proton fluxes. (b) Same format, but for AE8 (top) and AE9 V1.05 median (bottom), 2 MeV electron fluxes. Axis labels are in units of Earth radii.

AE9/AP9 has been validated against several independent data sets representing LEO, MEO, and GEO regimes. Figure 2 shows validation of AP9 for LEO orbit for median >36 MeV proton fluxes, with observations from Polar Operational Environmental Satellite (POES) N15 on the left and AE9 results on the right. Figure 3 shows >36 MeV proton flux vs. time over ~5 orbits for POES N15, with AP9 mean predictions (red) reproducing the POES observations (blue) of the South Atlantic Anomaly. Figure 4 shows cumulative mission fluence vs. time for >2 MeV electrons in GEO, with results for 40 AE9 MC runs (grey), AE9 median (green) and 95th percentile (red), compared to Geostationary Operational Environmental Satellite (GOES) 10 observations (orange). As the 10-year span shown represents most of a solar cycle, the GOES data show a corresponding variation in the rate of fluence buildup, but the long term results are emulated by the overall statistics in AE9.

3. OPERATION

3.1 Application

The basic functionality of the model is a "fly-in" software function in which the user specifies an ephemeris and selected model, mode, energies, quantities, etc. and receives a time series of the requested output. This is provided in C++ with wrappers available in C and FORTRAN. In addition, the model is provided with an application tool providing access via both command line and a graphical user interface, with output in both text files and (for the GUI) simple plots. Several legacy models have been imported into the architecture and can be run, including AE8,[2] AP8,[3] CRRESPRO,[9] CRRESELE,[10] and CAMMICE/MICS.[11] The legacy SHIELDOSE2 code[12] is also included to provide basic dose estimates. Documentation of the application programming interface is provided.[13]

3.2 Options and modes

The model user's guide[14] describes options, both standard types of input and output accessible in the GUI and additional flexibility accessible in the command line program. Standard output quantities may include flux and/or fluence for requested energies (differential, fully integral, or integral over finite ranges) and dose for requested depths of aluminum-equivalent shielding. Default output is as omnidirectional-associated quantities, but requests for directional fluxes are supported, either as look directions specified in a Cartesian coordinate frame or (in forthcoming V1.20) as particle pitch angles.

AE9/AP9 has three mode options: mean, using the mean flux maps with no variance statistics; perturbed mean, run as scenarios with fluxes perturbed by uncertainties in measurements and in gap-filling/extrapolation results; and Monte Carlo, run as scenarios representing the perturbed mean uncertainties but with the addition of space weather variability,

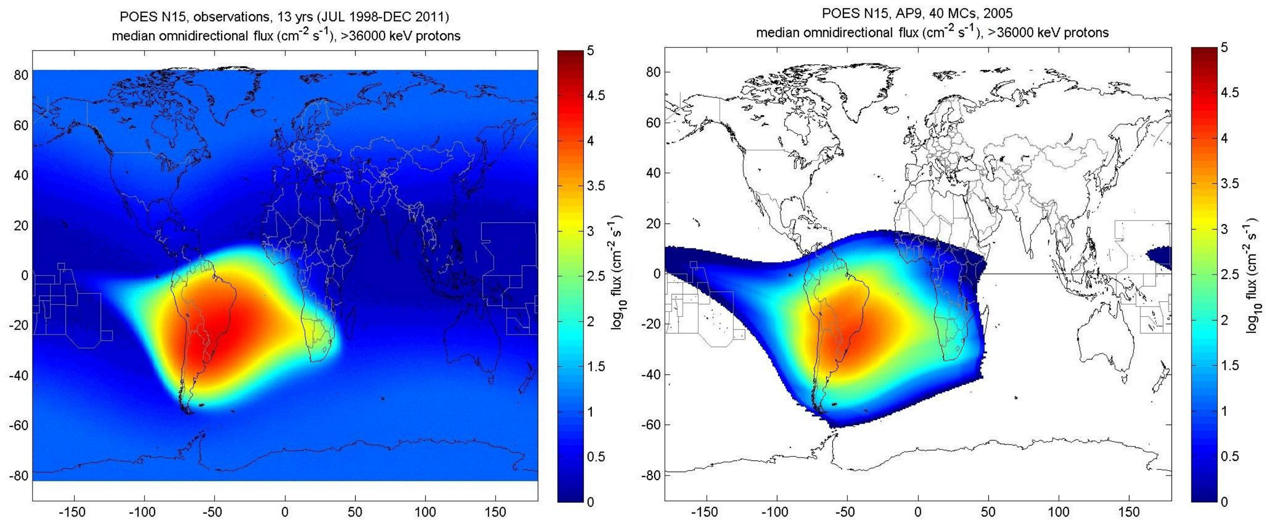

Figure 2. Validation of >36 MeV proton median fluxes vs. geographic location in LEO, (a) POES N15/SEM observations, 1998-2011, and (b) AP9 results for POES N15 orbit, 1 year run.

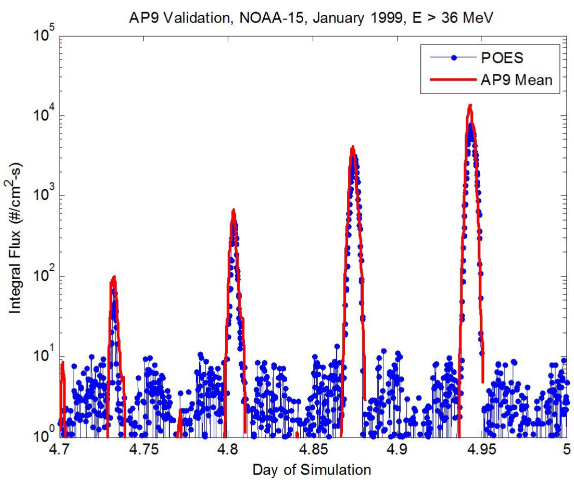

Figure 3. Validation of >36 MeV proton fluxes vs. time for POES N15, with POES data (blue) and AP9 results (red).

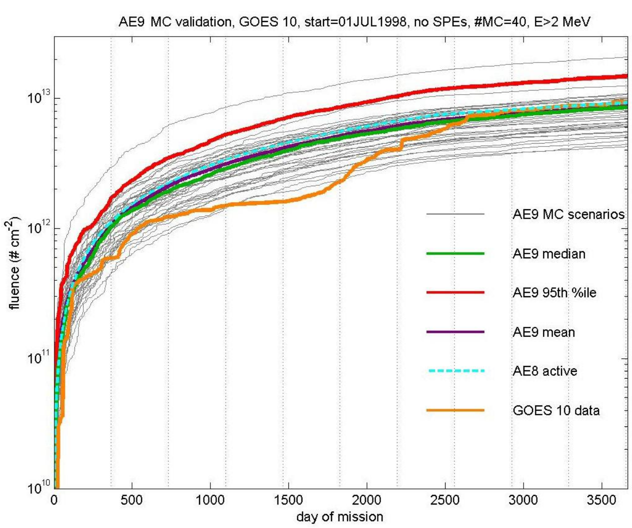

Figure 4. Validation of >2 MeV electron cumulative mission fluences, 10 years, showing 40 AE9 V1.05 MC scenarios, resulting AE9 statistics, GOES 10/MEPED observations, and AE8 active/quiet results.

including realistic temporal variability. The plasma model SPM may be run in the first two modes only. Statistics (e.g., 95th percentile) are derived by aggregating multiple scenario runs, either within the provided application for selected percentiles or by independent post-processing of model output. The documentation provides recommendations regarding run mode for desired statistics. For example, cumulative mission dose can be reasonably estimated from perturbed mean statistics extrapolated from a partial mission run. On the other hand, worst-case fluxes over short timescales require MC runs for the entire envisioned mission. Recommendations also address minimum timesteps needed for different orbital regimes, e.g., necessary sampling ranges from 10 s in LEO to 1 hr in GEO to avoid undersampling the radiation belt structures encountered in different orbits.

3.3 Illustrative output

The figures in this section illustrate types of output from AE9/AP9 relevant to spacecraft design. Figure 5 shows results for a polar LEO orbit at 800 km altitude. The first panel shows annual fluence versus energy for AP9 compared to AP8 and the CRRESPRO active model. The Combined Radiation and Release Experiment (CRRES) mission observed higher proton fluences than predicted by AP8, prompting development of the interim CRRESPRO model; AP9 predictions are more comparable to CRRESPRO. The second panel shows dose versus depth estimates from protons and electrons combined, showing higher predictions from AE9/AP9 than from AE8/AP8, and also illustrating the statistical ranges for perturbed mean scenarios provided by the new model. This is one of the important new design capabilities provided by AE9/AP9/SPM. Previously, design could only be based on AE8/AP9 with a rule-of-thumb design margin included. Now, designers can make trade space choices, e.g., designing to a chosen confidence interval weighing factors such as cost of additional shielding, mission duration, and so on.

Figure 6 shows cumulative one year electron fluence versus energy for a GEO orbit: the statistics from AE9 and SPME (plasma electrons) are shown in color along with the AE8 max estimate. The grey lines show results from the individual AE9 MC scenarios and SPME perturbed mean scenarios used to build these statistics. Note that AE9 with its MC capability shows more variability than SPME, most evident at their joint energy limit of 40 keV. This variability and associated statistics, as well as coverage of plasma energies, represent new capabilities provided by AE9/AP9/SPM.

Figure 7 shows dose/day versus depth estimates for protons and electrons separately for a GTO orbit, comparing AE9/AP9 to AE8/AP8. For this orbit, the new model predicts lower doses than the old models for both electrons and protons for shielding depths of 0.1-1 mm, but higher doses from protons for depths greater than 3 mm. Note that the AE9 median is lower than AE8 max for all depths shown.

4. UPGRADES

4.1 Recent and pending releases

AE8/AP8 suffered from the lack of follow-on updates as new observations became available and new industry needs emerged. The novel architecture of AE9/AP9/SPM includes design to support periodic updates. Since the initial release, several interim releases have included features requested by the user community. The current version V1.05 addressed a data table error in the legacy SHIELDOSE2 code. Dose calculation results from this release have been validated against other model outputs using comparable settings for AE8/AP8 in each case.[15]

The forthcoming V1.20 release, due in early 2014, will be the first with updated flux maps, including the use of new data for the AP9 proton flux maps. The AE9 V1.20 release updates the electron flux maps with results from corrected cross-calibrations for several data sets along with modifications addressing issues at high energies (>4 MeV) and at LEO altitudes. The AP9 V1.20 release updates the proton flux maps with new data from the Compact Environmental Anomaly Sensor (CEASE) instrument[16] aboard TacSat-4 regarding 10-100 MeV protons in LEO and MEO. Data from September 2011 to September 2013 for this MEO mission showed elevated hazards from low energy (<15 MeV) protons relative to historical expectations,[17] so inclusion of this data will provide more accurate statistical ranges for these energies. In addition, the new proton flux maps use templates based on Van Allen Probe Relativistic Proton Spectrometer (RPS) data,[18] allowing the energy range for protons to be extended up to 2 GeV. The SPM V1.20 release is also updated with addition of data from the Electrostatic Analyzer (ESA) aboard the five satellites of the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission, providing coverage at high L values and high pitch angles.

Version 1.20 also provides new software features requested by the user community. The new version supports a broader range of orbital elements for input as well as more options for coordinate systems used in both input and output. It also

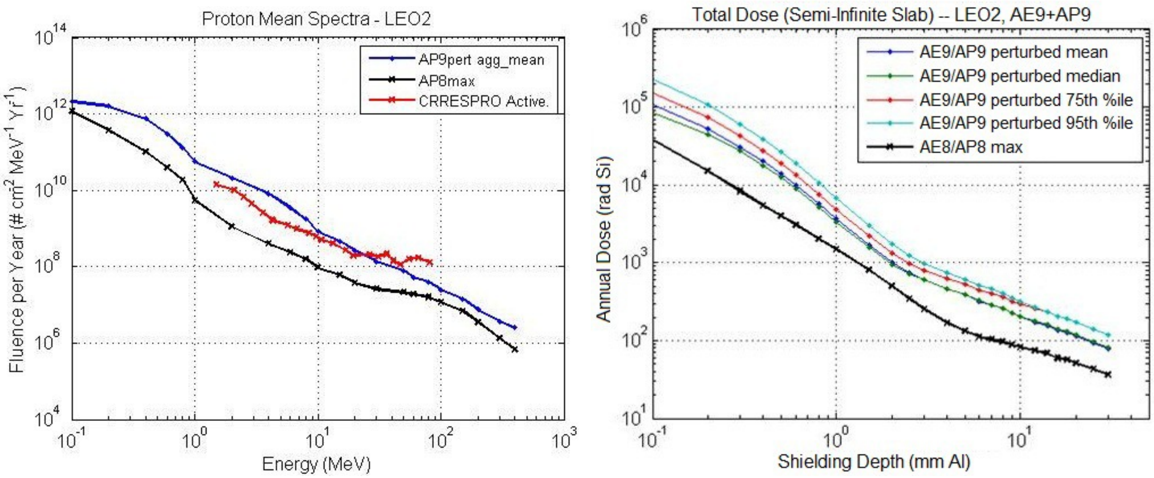

Figure 5. (a) Mean proton fluence spectra for one year in LEO orbit (800 km polar) from AP9 perturbed mean runs (blue) with same from AP8 max (black) and CRRESPRO (red). (b) Dose vs. depth curves, using AP9+AE9 and SHIELDOSE2, with results from AP8+AE8 for comparison, one year in LEO orbit (800 km polar).

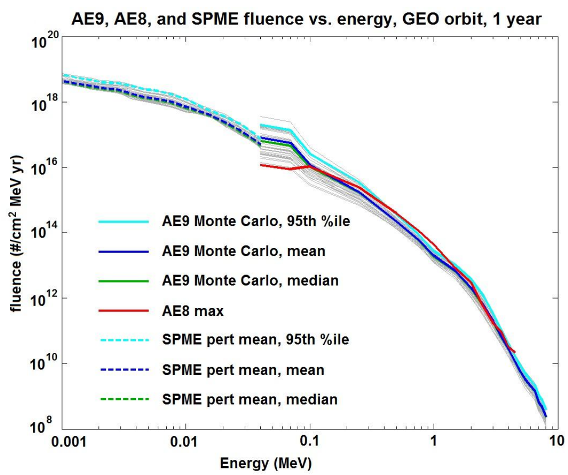

Figure 6. Fluence vs. energy for electrons, one year in GEO orbit (36000 km equatorial), from AE9 V1.05, SPME (plasma electrons), and AE8 max. Results from each of 40 MC scenarios for AE9 and 40 perturbed mean scenarios for SPME are shown by grey lines, with composite statistics shown in color.

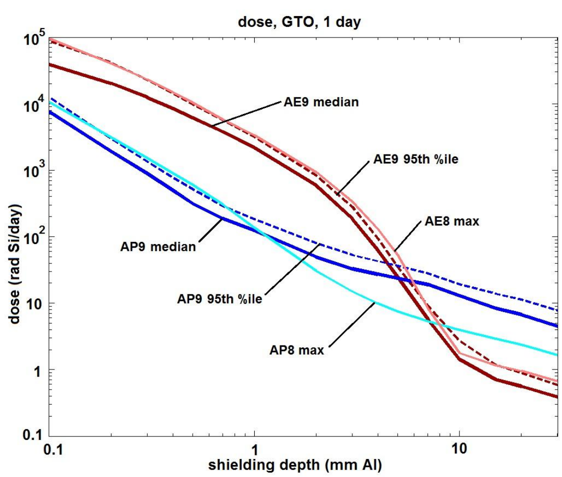

Figure 7. Dose vs. depth curves, using AE9/AP9 V1.05 or AE8/AP8 max and SHIELDOSE2, 1 day in GTO orbit (300 x 36000 km, 10° incl.), hemispherical geometry.

includes options for requesting directional fluxes specified by pitch angle (in addition to the previously supported option using Cartesian coordinate-specified look direction). While most user needs are met with the default omnidirectional flux-based quantities, support for directional flux inquiries is sometimes necessary for applications for fixed orientation spacecraft.

4.2 Future releases

Sustained upgrades of AE9/AP9/SPM in terms of improvements in both features and included data sets are planned. Features in development range from capabilities for estimating additional hazards to supporting distributed runs. Several current or near-future space missions are targeted investigations of the radiation belts, and the high-quality data from these missions will be incorporated.

A more flexible effects calculation capability is being developed that would make use of independently calculated effects kernels. Here, a kernel is a specification of the dependence of some effect (e.g., dose damage) as a function of particle species, energy, and depth, and would be the output of some independent particle simulation code for a particular material, shielding geometry, or component. When linked to AE9/AP9, the model's estimates for flux combined with the effects kernel would provide time-dependent estimates of risk. This is expected to be of particular interest to designers concerned with radiation effects on specific materials or components. To illustrate the capability, a sample kernel for estimated single event effects will be provided.

A future release will include a new mode called sample solar cycle. This will allow runs through a data-assimilative/physics-based reanalysis of the radiation belts for a full historical solar cycle. While not explicitly predictive, this will provide illustrative results for realistic time variations of hazards, e.g., authentic timescales of flux increases during geomagnetic storms, thus further informing design for worst-case conditions. A statistical model of solar particle events will be added. Various upgrades to speed performance, particularly to support parallel architecture runs, are planned in stages. Additional changes to architecture are expected to support refined hazard specification (e.g., local time dependence of plasma and east-west effect for protons) and additional hazards (e.g., auroral electrons).

NASA's twin Van Allen Probes, in orbit since September 2012, each carry five instruments for mapping radiation belt particle/plasma populations, and this data will be included in V1.50.[19] A subsequent version will incorporate data from AFRL's Demonstration and Science Experiments (DSX) satellite, scheduled for 2015 launch with five instruments to map particle/plasma populations spanning the slot region between the inner and outer radiation belts.[20] Development is also working towards inclusion of international data sets addressing LEO and other orbit regimes. With the forthcoming participation of international partners in the AE9/AP9/SPM development team, the model will be renamed the International Radiation Environment Near Earth model, or IRENE. In keeping with its goal of providing a comprehensive specification of near Earth particle hazards, AE9/AP9/SPM is being proposed as part of a new ISO standard for design to the space radiation environment.

5. SUMMARY

The new AE9/AP9/SPM trapped radiation and plasma models provide designers and mission planners with state-of-the-art capabilities for estimating particle hazards in near-Earth space. In addition to new updated data sets, the model suite implements novel architecture features providing statistics on uncertainty and environment variability. Validation results show good comparisons to independent data sets. The model is supplied with software interfaces supporting a variety of run modes and options to address a wide variety of design needs. The pending V1.20 release, with new flux maps for both AE9 and AP9, demonstrates the viability of design for sustained updates. Future versions will include data from new radiation belt science missions and introduce new features including plans for a sample solar cycle flythrough option, inclusion of untrapped solar protons, and support for calculation of effects from pre-computed effects kernels.

6. CONCLUSION

The AE9/AP9/SPM model suite meets the satellite design community's need for a state-of-the-art radiation environment specification model. It uses the most up-to-date data on the environment in an architecture that introduces quantitative statistics for use in design. Moreover, the range of features is being expanded, a result of both design and support for a sustainable, responsive tool for the modern design community.

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REFERENCES

[1] J. I. Vette, The NASA/National Space Science Data Center Trapped Radiation Environment Model Program (TREMP) (1964-1991), NSSDC/WDC-A-R&S 91-29, Natl. Space Sci. Data Center, Greenbelt, MD (1991).

[2] J. I. Vette, The AE-8 Trapped Electron Model Environment, NSSDC/WDC-A-R&S 91-24, NASA Goddard Space Flight Center, Greenbelt, MD (1991).

[3] D. M. Sawyer and J.I. Vette , AP-8 Trapped Proton Model Environment for Solar Maximum and Minimum, NSSDC/WDC-A-R&S 76-06, Natl. Space Sci. Data Cent., Greenbelt, MD (1976).

[4] G. P. Ginet, et al., "AE9, AP9 and SPM: New models for specifying the trapped energetic particle and space plasma environment," Sp. Sci. Rev., 179, 579-615 (2013) [doi:10.1007/s11214-013-9964-y].

[5] AE9/AP9 Development Team, AE9/AP9/SPM radiation environment model: Technical documentation, Air Force Research Laboratory report, in preparation (2014).

[6] International Association of Geomagnetism and Aeronomy, "Working Group V-MOD, International Geomagnetic Reference Field: The eleventh generation," Geophys. J. Int., 183, 1216-1230 (2010) [doi: 10.1111/j.1365-246X.2010.04804.x].

[7] W. P. Olson and K. A. Pfitzer, Magnetospheric magnetic field modeling, Annual Scientific Report, Air Force Office of Scientific Research contract F44620-75-C-0033, McDonnell Douglas Astronautics Co., Huntington Beach, CA (1977).

[8] T. P. O'Brien, "Documentation of C inversion library," IRBEM-LIB, 2010, <http://irbem.svn.sourceforge.net/viewvs/irbem/web/index.html> (2010).

[9] J. D. Meffert, and M. S. Gussenhoven, CRRESPRO documentation, PL-TR-94-2218, ADA 284578, Phillips Laboratory, Hanscom AFB, MA (1994).

[10] D. H. Brautigam, and J. Bell, CRRESELE documentation, PL-TR-95-2128, ADA 301770, Air Force Research Laboratory, Hanscom AFB, MA (1995).

[11] J. L. Roeder, et al., "Empirical models of the low-energy plasma in the inner magnetosphere", Sp. Weather, 3, S12B06 (2005) [doi:10.1029/2005SW000161].

[12] S. M. Seltzer, Updated calculations for routine space-shielding radiation dose estimates: SHIELDOSE-2, Gaithersburg, MD, NIST Publication HISTIR 5477 (1994).

[13] P. Whelan, AE9/AP9/SPM model application programming interface, version 1.00.000, AFRL-RV-PS-TR-2014-0018, Air Force Research Laboratory, Kirtland AFB, NM (2014).

[14] C. Roth, AE9/AP9/SPM radiation environment model: User's guide, AFRL-RV-PS-TR-2014-0013, Air Force Research Laboratory, Kirtland AFB, NM (2014).

[15] C. Roth, AE8/AP8 implementations in AE9/AP9, IRBEM, and SPENVIS, AFRL-RV-PS-TR-2014-0014, Air Force Research Laboratory, Kirtland AFB, NM (2014).

[16] B. K. Dichter, et al., "Compact Environmental Anomaly Sensor (CEASE): A novel spacecraft instrument for in situ measurements of environmental conditions," IEEE Trans. Nucl. Sci., 45(6), 2758-2764 (1998) [doi:10.1109/23.736525].

[17] S. R. Messenger, "TacSat-4 radiation environment and solar cell degradation correlations using onboard experiments," NSREC 2013 conference presentation A-1 (2013).

[18] J. Mazur, et al., "The Relativistic Proton Spectrometer (RPS) for the Radiation Belt Storm Probes Mission," Space Sci. Rev., 179, 221-261 (2013) [doi:10.1007/s11214-012-9926-9].

[19] J. M. Stratton, R. J. Harvey, and G. A. Heyler, "Mission overview for the Radiation Belt Storm Probes Mission," Space Sci. Rev., 179, 29-57 (2013) [doi:10.1007/s11214-012-9933-x].

[20] J. A. Fennelly, “Demonstrations and Science Experiment (DSX) Space Weather Experiment (SWx),” in Solar Physics and Space Weather Instrumentation III, ed. by S. Fineschi and J. A. Fennelly, Proc. Of SPIE, 7438, 743805 (2009) [doi:10.1117/12.828321].