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Toward the development of new standard radiation belt and space plasma models for spacecraft engineering

Jean-Marie Lauenstein
Muñiz Engineering, Inc., Lanham, Maryland, USA

Janet L. Barth and David G. Sibeck
NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

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[1] An international meeting on New Standard Radiation Belt and Space Plasma Models for Spacecraft Engineering, sponsored by NASA's Living With a Star Program, was held in 2004 to begin rebuilding the infrastructure required to develop new standard radiation belt and plasma environment models. The goal of one standard model will be accomplished in stages, including the formation of interim regional models, the calibration and incorporation of existing data sets, and the gathering of new data through future science missions. The Committee on Space Research/Panel for Radiation Belt Environment Modeling will play a central role in standardization and data archiving. Workshop attendees support the standardization of two interim models: a model of geostationary orbit electrons and a model of inner belt protons. Two future missions are planned or are being planned to provide missing measurements and to increase the scientific understanding of the particle dynamics. This information will lead to more robust modeling of the particle environment for the design and operation of spacecraft for space exploration as well as for industry and military applications.

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1. Introduction

[2] Accurate space radiation models are important to reduce risk to astronauts and design cost-effective, high-performance space systems. Exposure to radiation belt and plasma environments leads to surface and internal charging effects, degradation of instruments and the spacecraft, and to single-event effects in which electronics suffer errors or failure from a single energetic particle. In crewed missions, these effects can become life threatening. The primary radiation belt models in widespread use are AP-8 [*Sawyer and Vette*, 1976] and AE-8 [*Vette*, 1991a], released in 1976 and 1983, respectively. These standard models are esteemed for their extensive spatial coverage and user friendliness but suffer limitations and inaccuracies. As contemporary applications demand precision, functionality, and energy coverage not provided by AP-8 and AE-8, new standard radiation belt and plasma environment models are needed. The international meeting on New Standard Radiation Belt and Space Plasma Models for Spacecraft Engineering, sponsored by NASA's Living With a Star (LWS) Program, was held on 5–8 October 2004 in Adelphi, Maryland to begin rebuilding the infrastructure required to develop new models. This article provides an overview of the workshop, which was chaired by Janet Barth/NASA and was planned by the steering committee: Janet Barth, Bern Blake/Aerospace Corporation, Don Brautigam/Air Force Research Laboratory (AFRL), and Eamonn Daly/European Space Agency (ESA).

[3] The workshop successfully brought together the international community of space environment modelers with agencies and industry to identify both the current status of modeling efforts and data availability, and the needs of the end users. Over 50 people participated in the process. Since the release of AP-8 and AE-8, initiatives by both NASA's Living With a Star Targeted Research and Technology (TR&T) Program and its Space Environments and Effects (SEE) Program, ESA's Technology Research Programme, and the U.S. Air Force Space Radiation Effects Program have stimulated further analysis of data from flight instruments and model development. The purpose of the workshop was to review the results of these initiatives, define user requirements, and develop road maps for future standardized models.

2. Standard Radiation Belt Models AP-8 and AE-8

[4] In order to appreciate the need for new models and to assess their potential, the strengths and limitations of

the current standard models, AP-8 and AE-8, must be understood. Perhaps the biggest factor driving the continued use of these models lies in the number of times they have been used to successfully design spacecraft. Their spatial coverage is unmatched by recent modeling efforts. The data used to develop them come from 38 satellites [*Vette*, 1991b]; thus radiation measurements have some degree of interinstrument validation. This strength is also a source of error in the models because of the challenge of intercalibrating the instruments. The data were collected between 1958 and 1979, throughout two solar cycles. However, because of the dynamic nature of the space environment, models based on these data may no longer portray the environment that today's space systems encounter. Importantly, the inner zone electron flux data are known to be contaminated from high-altitude nuclear device detonations during the late 1950s and early 1960s [*Abel et al.*, 1994]. The models must be run with the same internal geomagnetic field models used to analyze the data [*Heynderickx*, 1996]; as a result, secular changes in the magnetic field that affect the location of the South Atlantic Anomaly (SAA) are not accounted for, resulting in incorrect positions for flux values at low altitudes. Additional low-altitude error results from the absence of east-west asymmetry in the models; while this effect averages out in nonoriented spacecraft, it is important for missions with fixed orientations such as the International Space Station. The models do not include fluxes at plasma energies, and stop far short of covering the up to 30 MeV electrons recorded by the CRRES satellite [*Blake et al.*, 1992]. AP-8 has an energy range of 100 keV to 400 MeV protons, and AE-8 covers 40 keV to 7 MeV electrons. The models are static, providing only long-term averages for solar maximum or solar minimum. In this way, they remove the effects of storm injections and solar wind on flux distributions, preventing use of the models for worst-case analysis and for missions of short duration (<6 months). The space systems of today are built using higher-performance technologies that can be more sensitive to radiation. Smaller margins of error in environment estimates will prevent costly overdesign and will aid in the decision to use or forego a particular capability.

3. User Community Needs

[5] The workshop committee presented draft model requirements, which were updated by members of industry who attended the workshop. Three design issues for which industry relies on environment models were presented. The first, endurance/wear out, is a function of the total ionizing dose and/or displacement damage received over the course of the mission. For this aspect of design, expected long-term average dose, flux energy spectra, and long-term worst-case dose information for the mission orbit must be evaluated. The second design consideration concerns outages of rate-sensitive equipment such as microprocessors or imagers. Fine temporal resolution of worst-case fluxes is required to assure that these spacecraft control or data collection electronics will function adequately. The representatives from industry indicated a desire for models that could provide estimates of the worst-case proton, electron, and heavy ion fluxes during 5-min, 1-hour, 1-day, or 1-week intervals. Finally, for the third design issue, worst-case day, week, month, 3-month, and 6-month estimates of electron flux spectra are important to determine deep charging effects.

[6] Using ''stoplight'' charts, members of industry identified their prioritized needs based upon current model and data deficits and radiation phenomena that have the greatest effect on system reliability, cost, and lifetime. The uncertainty in the 1000–10,000 km altitude environment is deemed critical for proton energies greater than 100 MeV. The resulting uncertainty in shielding requirements leads to increased mass and decreased mission lifetime. In addition, the uncertain frequency, intensity, and duration of transient proton belts in the slot region impacts single-event effect and total dose estimates in a manner seriously affecting spacecraft mission, cost, or lifetime. In the 10,000 km to geosynchronous altitudes, errors in estimates of 100 keV to 3 MeV protons critically affect sensor background levels as well as solar array and coating degradation. Greater precision in this low-energy proton range for this region in space would directly benefit several upcoming missions. In addition to these ''red light'' areas of need, the uncertainty in environment estimates significantly impacts space systems in all orbits, with one exception. The errors in model estimates of particles with energies less than 10 MeV for orbits below 1000 km were considered lower priority, having a minor impact overall.

[7] In summary, the standard AP-8 and AE-8 models fail to meet industry user needs because of their restricted energy ranges, large error estimates, and static nature. Dynamic models with fine temporal resolution are needed that provide both accurate averages and the probabilities of worst-case scenarios.

4. New Modeling Efforts

[8] Workshop attendees agreed that the Committee on Space Research (COSPAR)/Panel for Radiation Belt Environment Modeling (PRBEM) should play a central role in standardization and data archiving. The charter of the PRBEM, available at http://www.cosparhq.org/scistr/prbem.htm, is in part ''to develop a standard model of the Earth's trapped radiation belts…based on experimental data using all available space data sources,'' with ''theoretical considerations [serving] to guarantee optimal model construction and use, and internal consistency.''

[9] Attendees of the workshop support the standardization of two interim models to augment the existing radiation belt modeling capability. These models are limited in their scope, but incorporate the dynamic nature of the space environment. The first model addresses the inner belt protons. It will result from a merger of the Trapped

Proton Model (TPM-1) [*Huston*, 2002], developed at the Boeing Company with support from the NASA SEE Program, and the Solar Anomalous and Magnetospheric Particle Explorer Proton/Electron Telescope (SAMPEX/PET) data processed by the Belgian Institute for Space Aeronomy (BIRA), supported by ESA. TPM-1 combines elements of AFRL's proton model CRRESPRO [*Gussenhoven et al.*, 1993], a result of the Combined Release and Radiation Effects Satellite (CRRES) mission, and Boeing's Low Altitude Trapped Radiation Model (LATRM) [*Huston and Pfitzer*, 1998], developed under contract from the NASA SEE Program. The data sets included in TPM-1 thus span the period from 1978–1995, covering altitudes from 300 km to almost geosynchronous orbit. The 10.7 cm solar radio flux ($F_{10.7}$) is a proxy for driving solar cycle variations. Overall, TPM-1 is a dynamic model for 1.5 to 81.5 MeV protons, has a 1-month time resolution, and incorporates the secular variation of the geomagnetic field. Future versions of the model will include a statistical solar-cycle variation, providing the percentage likelihood of flux levels exceeding various estimates. Through collaboration with BIRA, the addition of SAMPEX/PET data will extend the low-altitude energy range up to 500 MeV. The result will be a new standard proton model for low Earth orbit (LEO) missions. As with AP-8, this model lacks storm effects and error estimates.

[10] The second model deemed ready for standardization is the Particle ONERA-LANL Electron (POLE) model of geostationary orbit (GEO) electrons [*Boscher et al.*, 2003]. This model is the result of a collaboration between Los Alamos National Laboratory (LANL), with support from NASA's Living with a Star (LWS) TR&T Program, and Office National d'Etudes et de Recherches Aérospatiales (ONERA). The model is based on data sets from 13 LANL geostationary satellites covering the period 1976–2001. POLE is a dynamic model of 30 keV to 2.5 MeV GEO electrons with a time resolution of 1 year. It provides mean flux, as well as worst-case and best-case fluxes possible during extreme solar cycles. The development of one unified model of the radiation belts will thus be accomplished in stages, with POLE and TPM-1 leading the way toward coverage of the GEO and LEO regions.

[11] Plasma modeling capabilities exist in a limited format for GEO and polar orbits. Maps from the LANL-GEO Magnetospheric Plasma Analyzer (MPA) [e.g., *Korth et al.*, 1999], AFRL analytic models of ATS-5 and ATS-6 geosynchronous data [see *Garrett and Spitale*, 1985, and references therein], and NASA Marshall Space Flight Center development of the Chandra Radiation Model [*Blackwell et al.*, 2000] represent some of the plasma modeling efforts presented at the workshop. The models have about a 1-year time resolution and cover an energy range on the order of 1 eV to 80 keV for surface charging climatology and 1 eV to 200 keV for surface dose climatology. Ion composition data, however, are missing for energies less than 1 keV. The models in their current implementation lack directionality information and error estimates, and only minimally represent solar cycle and storm effects. Data are available to expand the capabilities for currently covered regions.

[12] Extensive work has been done toward calibrating additional data sets, and in particular, intercalibrating multiple data sets. With funding from NASA's LWS TR&T Program, Aerospace Corporation continues to process and make available energetic particle data from Highly elliptical Earth Orbit (HEO) satellites. Aerospace Corp., LANL, and ONERA are working together toward cross calibrating Global Positioning System (GPS), Polar, HEO, LANL-GEO, and SAMPEX satellite data to use with the theoretical model Salammbô, developed at the Centre d'Etudes et de Recherches de Toulouse (CERT), ONERA, in an effort to expand space and energy coverage of radiation belt mapping. ESA is enabling similar efforts by ONERA, BIRA, QinetiQ, and the Danish Meteorological Institute (DMI) to merge European satellite data from the Project for On-Board Autonomy (PROBA), X-ray Multi mirror Mission (XMM), INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL), Ørsted, and other missions.

5. Status of Road Maps to New Standard Models

[13] Splinter groups formed to develop road maps for accomplishing the creation of new space plasma and radiation belt models of ions and electrons. The groups included sessions on ion and electron belt model development, led by Daniel Heynderickx, BIRA, and Bern Blake, Aerospace Corp., plasma model development, led by Michelle Thomsen, LANL, and a session on data set management and model standardization led by Eamonn Daly, ESA. This latter splinter group's charge was particularly important given that a significant amount of post-AP8/AE8 data and subsequent modeling has not been fully utilized due in part to a lack of a formal process to peer review data set calibration and new models.

[14] As detailed above, development of new standard radiation belt models is underway for high-energy protons in the LEO region and electrons in the GEO region. Currently available data sets will enable the construction of a LEO orbit electron model with a time resolution of 6 months that covers energies from 30 keV to 10 MeV. Furthermore, POLE can potentially be extended to altitudes as low as 12,000 km with the incorporation of existing data sets, albeit without full equatorial coverage. TPM-1 provides rudimentary modeling of medium Earth orbit (MEO) 1–80 MeV protons, but is based primarily upon less than 2 years of data. No high-energy proton data exist for the MEO region. The first steps along the road to new models are thus the creation and improvement of regional models.

[15] The expansion of current plasma models to incorporate existing data sets will result in many improvements. A time resolution as fine as 1.5 min can be

achieved; the data will enable incorporation of pitch angle distributions, solar cycle and activity variability, characterization of the charging environment, definition of spectral shape, and inclusion of statistical error bars. These upgrades necessitate many man hours for data analysis.

[16] Attendees agreed that the requirements for models meeting the needs of future space systems cannot be met without new radiation belt missions. The obstacle to robust dynamic models with high fidelity is the lack of understanding of the physical processes that govern the population distributions. Understanding can only be achieved with new missions in geospace that answer the unknowns of particle acceleration and loss processes, coupling across regions, structure of the global inner magnetospheric electric and magnetic fields, and the behavior of the ring current, among many other unanswered questions about physical phenomena.

[17] Future missions, including NASA's LWS Geospace Missions and the Canadian Space Agency's Outer Radiation Belt Injection, Transport Acceleration and Loss Satellite (ORBITALS), are planned or are being planned to collect some of this missing science required for accurate modeling. These missions will provide an opportunity for near-simultaneous multipoint data collection. The primary objective of the ORBITALS program is to understand the dynamical variation of outer belt electrons, determining their dominant acceleration and loss processes. Complementing this objective are the science priorities of the LWS Geospace program, which will in part seek to study the acceleration, global distribution, and variability of energetic electrons and ions in the inner magnetosphere. These missions will gather data in the regions of space between LEO and GEO, and expand much needed equatorial coverage of data sets. ORBITALS will provide data in the slot region, which has yet to be included in dynamic models because of a fundamental lack of understanding as to the conditions causing sudden belt formation in this region.

6. Conclusions

[18] Following workshop road maps to the completion of new standard models will require not only well-planned future missions, but also the support to analyze existing data sets and new ones as they are generated. As new models emerge, validation is critical for the interpretation of any differences from the old standards, AP-8 and AE-8. Commitment to the development of new standard models thus includes commitment to data collection, data and instrument analysis, formation of models within a framework that can accommodate additional data sets, model validation, and model and data archiving. It requires an international effort that includes scientists, modelers, and end users.

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J. L. Barth and D. G. Sibeck, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

J.-M. Lauenstein, Muñiz Engineering, Inc., Lanham, MD 20771, USA. (Jean.Marie.Lauenstein@gsfc.nasa.gov)