AF-GEOSPACE 2.0

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Abstract

The capabilities of the newest AF-GEOSpace space environment software program are reviewed. Released in 2002, AF-GEOSpace Version 2.0 is a graphics-intensive software program with space environment models and applications developed and distributed by the Space Weather Center of Excellence at the Air Force Research Laboratory (AFRL). A wide range of physical domains is addressed including solar disturbance propagation, radiation belt configuration, and ionospheric auroral particle precipitation and scintillation. The software is currently being used to aid with the design, operation, and simulation of a wide variety of communications, navigation, and surveillance systems. Building on the success of previous releases, AF-GEOSpace has become a platform for the rapid prototyping of automated operational and simulation space weather visualization products and helps with a variety of tasks, including: orbit specification for radiation hazard avoidance; satellite design assessment and post-event anomaly analysis; solar disturbance effects forecasting; frequency and antenna management for radar and HF communications; determination of link outage regions for active ionospheric conditions; scientific model validation and comparison, physics research, and education. Version 2.0 provides a simplified graphical user interface, improved science and application modules, and significantly enhanced graphical performance. Common input data archive sets, application modules, and 1-D, 2-D, and 3-D visualization tools are provided to all models while FTP scripts are provided to automatically update common daily global input parameters. Dynamic capabilities permit multiple environments to be generated at user-specified time intervals while animation tools enable, for example, the display of satellite orbits and environment data together as a function of time. Documentation examples include detailed instructions for investigating phenomena that have well known effects on communications and spacecraft systems. To obtain a copy of AF-GEOSpace Version 2.0 for Windows NT/2000/XP, please contact the first author.

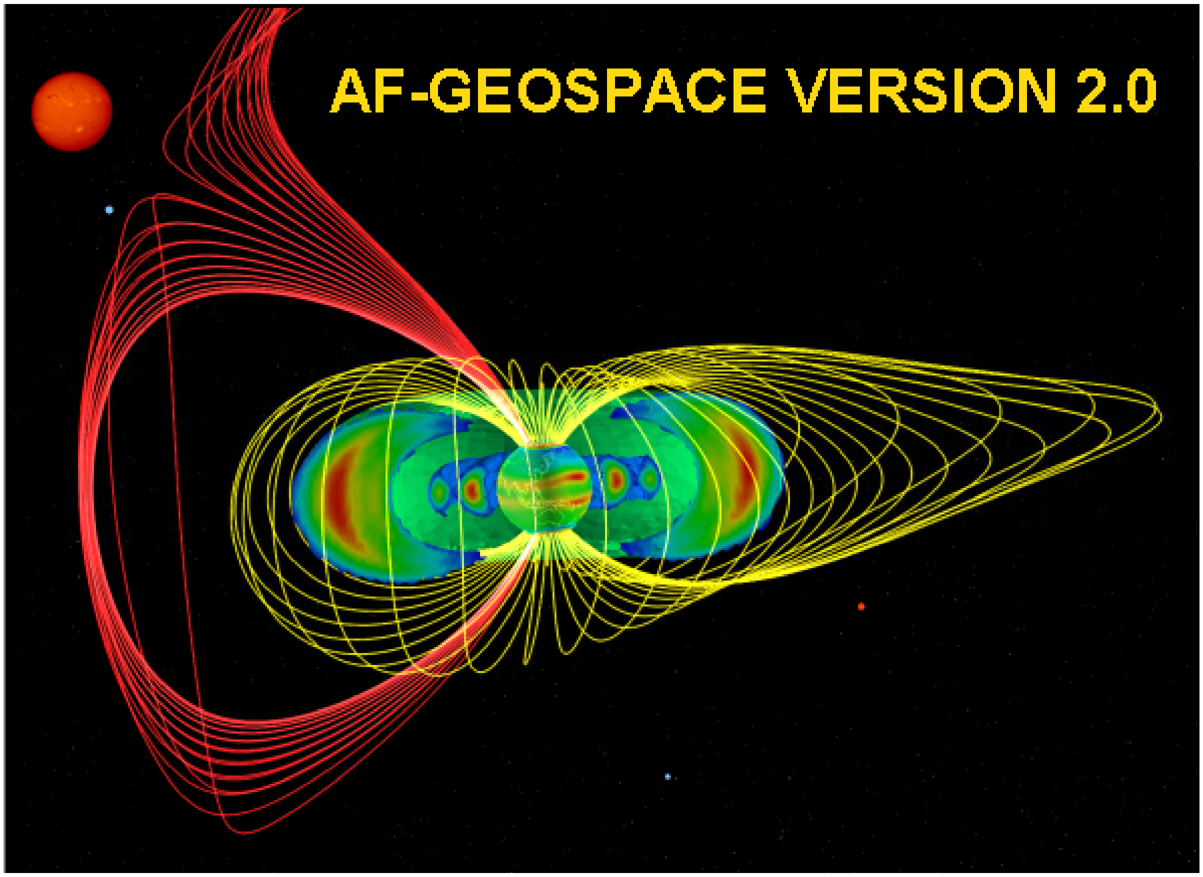

Figure 1. AF-GEOSpace Version 2.0 for Windows NT/2000/XP was developed by the Space Weather Center of Excellence at the Air Force Research Laboratory. With the Sun to the left, (yellow) geomagnetic field lines originating from constant magnetic latitude envelop the radiation belts and are stretched anti-sunward (to the right). Originating at higher latitude, the magnetic field lines of the northern dayside magnetic cusp (red) help to define the shape of the dayside magnetopause. Ionospheric electron densities are shown with peak bands at latitudes both above and below the Earth's geomagnetic equator.

Introduction

Space systems experience environmental effects ranging from intermittent communication outages caused by ionospheric scintillation to total satellite system failures caused by energetic magnetospheric particles. Motivated by the need to mitigate the impact of these hazards, space environment models are employed during the spacecraft design process and operations and provide environmental simulations for a wide variety of communication, navigation, and surveillance systems operating at altitudes between 100 km and geosynchronous orbit (6.6 Earth Radii). While our understanding of fundamental physical processes is still limited, useful empirical, statistical, and theoretical models have been developed to address topics ranging from solar coronal mass ejections to the Earth's trapped radiation belts to auroral particle precipitation.

AFRL is constantly expanding its space environment modeling capabilities and has integrated a collection of scientific codes and related applications into the AF-GEOSpace software program. A sample of the program's output is shown in Figure 1. The program has grown and evolved steadily in an effort to address the concerns of the space weather community. While some models may not be considered state-of-the-art, they are included to provide valuable historical validation baselines and the ability to easily relate output from models covering similar domains, e.g., to directly compare results from the CRRES and AE-8 electron radiation belt models. The flexibility to simultaneously view science model results and real-time data with a common set of visualization tools has allowed AF-GEOSpace to serve AFRL as a development platform for some of the automated visualization products required of the operational community. With all models running on a common platform, AF-GEOSpace becomes a vehicle for rapid model prototyping, model validation, environment specification for spacecraft design, mission planning, and anomaly resolution. In short, AF-GEOSpace becomes the backbone for an integrated space environment model.

This paper describes the software program AF-GEOSpace Version 2.0 released in 2002. We begin by highlighting the program's development history then provide a summary of current capabilities by reviewing the Windows pull-down menu functions, and the content of the science, application, data, and graphics modules. A complete reference list detailing model and application sources is provided.

Development Overview

The first public release of AF-GEOSpace (Version 1.21, 1996/IRIX on SGI) contained radiation belt particle flux and dose models derived from CRRES satellite data, an aurora model, an ionospheric model, and ionospheric HF ray tracing capabilities. The next public release (Version 1.4, 1999/IRIX on SGI)[1] added science modules related to the cosmic ray and solar proton environment, low-Earth orbit radiation dosages, single event effects probability maps, and ionospheric scintillation, solar proton, and shock propagation models. New application modules for estimating linear energy transfer (LET) and single event upset (SEU) rates in solid-state devices, and modules for visualizing radar fans, communication domes, and satellite detector cones and links were added. Automated FTP scripts permitted users to automatically update their global input parameter data set directly from NOAA/SEC (Space Environment Center). Real-time DMSP data modules for displaying auroral particle data and identifying enhanced outer zone electron belt populations remain exclusive to Version 1.4.

What's New? AF-GEOSpace Version 2.0 (for WindowsNT/2000/XP) includes the first true dynamic run capabilities and offers new and enhanced graphical and data visualization tools such as 3-D volume rendering and eclipse umbra and penumbra determination. The dynamic run capability enables the animation of all model results, in all dimensions, as a function of time. Version 2.0 also contains a new realistic day-to-day ionospheric scintillation simulation generator (IONSCINT), an upgrade to the WBMOD scintillation code, a simplified HF ionospheric ray tracing module, and applications built on the NASA AE-8 and AP-8 radiation belt models. User-generated satellite data sets can now be visualized along with their orbital ephemerides. A tool for visualizing MHD model results stored in structured grids provides a hint of where future space weather model development efforts are headed. A new graphical user interface with improved module tracking and renaming features greatly simplifies software operation. Finally, a major restructuring of the code to an open architecture has greatly increased the code's portability and made it easier in integrate new modules.

AF-GEOSpace Version 2.0 is written in C++ for Windows NT, 2000, and XP. It is rigorously object oriented and contains separate user interface, kernel, and graphics libraries. Environment modules provide interfaces to the science models and related applications needed to investigate the solar, interplanetary, magnetospheric, auroral, and ionospheric environments and their effects on communications and spacecraft systems.

The software is divided into five explicit module classes to simplify the integration of new algorithms and increase portability. *Science Modules* control individual science models and produce output data sets on user-specified grids. *Application Modules* typically manipulate these data sets, e.g., by integrating dose calculated by a radiation belt model or tracing HF rays through a model ionosphere. They also provide capabilities like orbit generation and magnetic field line tracing. *Data Modules* read and assist with the analysis of user-generated data sets. *Graphics Modules* control the one, two, and three-dimensional viewport windows and enable display features such as isocontours, plane slices, magnetic field lines, line plots, axes, the Earth, stars, and satellites. *Worksheet Modules* provide transformations between the GEOC, GSM, SM, and GEI systems in spherical, cylindrical, and Cartesian coordinates and also provide calendar system conversion tools. This separation of modules by function permits the use of common inputs and visualization tools by all modules. Next we look at the new dynamic run capability.

Dynamic Run Environments

AF-GEOSpace Version 2.0 supports two basic environment module types: *static* and *dynamic*. Note that previous releases of AF-GEOSpace supported only *static* environments. Science or application module runs are called *static* if they produce output representing a single Universal Time. All environment models and applications are run using a fixed set of geophysical parameters, e.g., the geomagnetic activity index Kp. With the exception of the new ionospheric scintillation module and the satellite orbit generator and its associated applications, all environment models and applications are run for a fixed Universal Time. Runs are called *dynamic* if they produce output at more than one Universal Time. This dynamic run capability allows the user to animate results in all dimensions, e.g., simultaneously view a satellite's path through a generated data set in 3-D, view a 2-D projection on Earth of data slaved to a satellite's altitude, and view a 1-D plot of the time history of data values encountered by the satellite. Figure 2 shows 3-D and 2-D graphic frames for a single time from a dynamic run sequence representing a 2001 geomagnetic storm. A common set of global parameters was the key to generating this coordinated set of environments over the storm time interval.

Global Parameters

The purpose of the global parameter concept is to provide consistent inputs to the multiple models that can be created within a single static or dynamic environment. Global parameters are the date, time, and geophysical indices shared between many of the models, i.e., the geomagnetic activity index Kp, daily sunspot number (SSN), solar radio flux at 10.7 cm (F10.7), planetary magnetic index Ap, geomagnetic activity index Dst, and the equatorward boundary of the diffuse aurora at midnight (AB). Most models have additional parameter inputs that are entered by the user when initializing a module. The last two parameters are included for reference purposes, i.e., Dst is useful when constructing magnetic field models and the AB values are useful as manual inputs to the aurora science module equatorward edge-mapping algorithm. A data archive covering 1932 to 2001 includes the indices Kp and Dst as well as DMSP-derived auroral boundaries. These data enable the user to run models over a wide variety of activity levels and space weather events. FTP scripts enable automated updates of some common parameters.

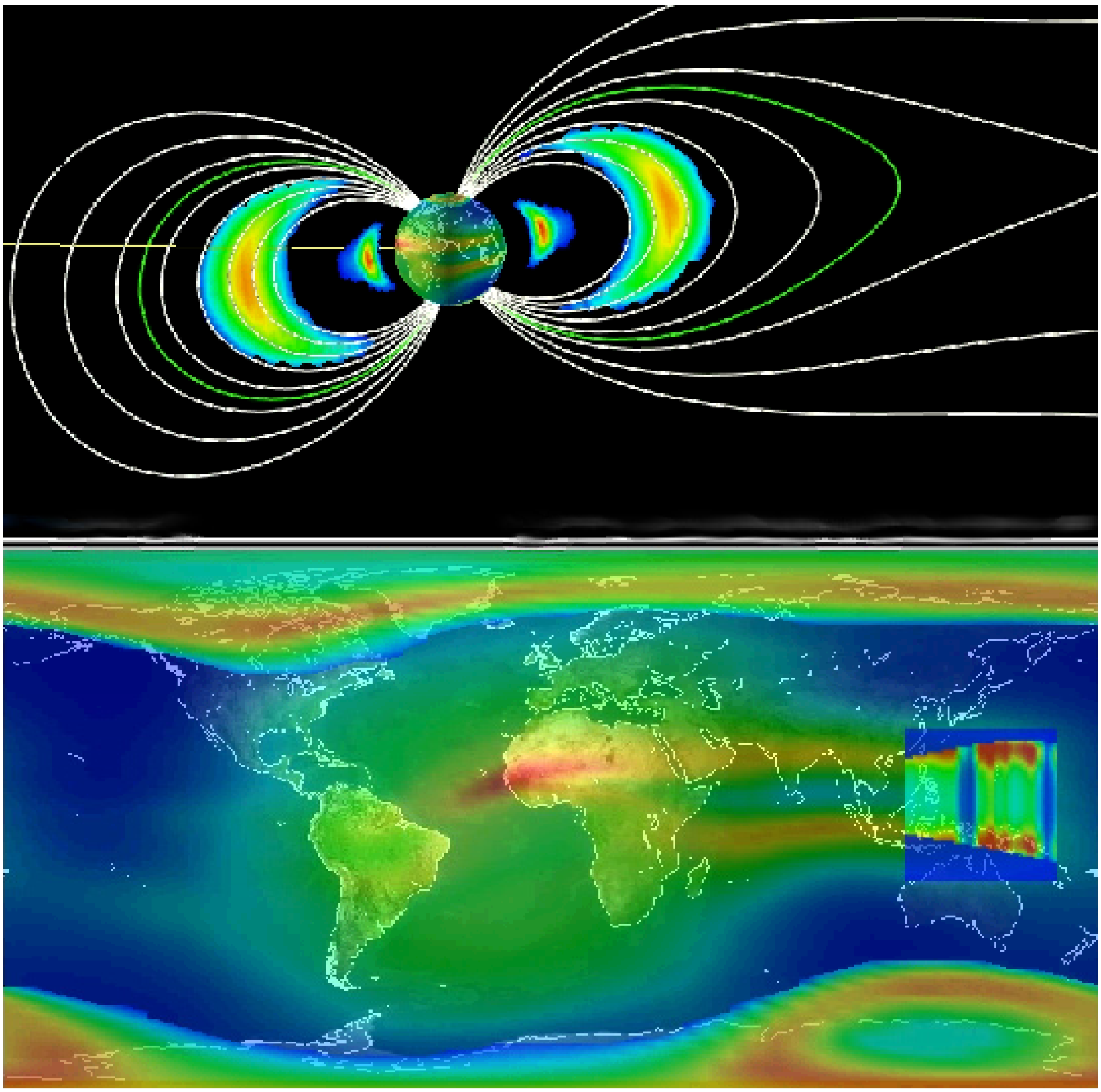

Figure 2. AF-GEOSpace 2.0 environment models representing 30 March 2001 at 1400 UT. *Lower*: Earth map with precipitating auroral electron flux at high latitudes, total electron content (TEC) in the ionosphere with peak over East Africa, and S4 scintillation index (inset) north of Australia. *Upper*: Earth with Sun axis to left, inner

proton belt (9.7 MeV), outer electron belt (1.6 MeV), and magnetic field lines in the noon-midnight meridians. Auroral and TEC from lower frame are also visible.

Menus

The functions of the AF-GEOSpace pull-down menus illustrate the software's capabilities.

The *File* menu provides options to load Environment Window inputs and run results of previously saved science and application modules. Module settings and output are saved as single Common Data Format (CDF) files. The contents of the active windows can be captured in Tagged Image File Format (TIFF) or Joint Photographic Experts Group (JPEG) format.

The *Edit* menu provides access to features enabling the user to run models, delete models, rename entries in the active modules lists, examine text representations of module produced data, setup computation grids, set dynamic run mode time step values and output parameter selection, and animate results from dynamic module runs (including satellite orbits in static mode).

The *Module* menu provides access to the five basic module classes: (1) *Science Modules* control individual science models and produce output data sets on user-specified grids, (2) *Application Modules* typically manipulate these data sets, e.g., by integrating dose calculated by a radiation belt model or tracing HF rays through a model ionosphere. Application modules also provide orbit generation and magnetic field line tracing capabilities, (3) *Data Modules* read and assist with the analysis of user-generated data sets, (4) *Graphics Modules* control the one, two, and three-dimensional windows and enable display features such as plane slices, magnetic field lines, line plots, axes, the Earth, stars, and satellites, and (5) *Worksheet Modules* provide commonly requested coordinate transformations and a calendar system conversion tools.

The *Windows* menu provides access to functions for creating, adjusting, and arranging graphics windows, i.e., create 1D, 2D, 3D or special 3-D Heliospace viewports, set background color, switch to full screen, or arrange windows in cascading or tile patterns.

The *Viewport* menu contains options for splitting the active viewport horizontally or vertically, transforming a viewport's dimensionality from 2D to 3D while retaining the displayed data, and fixing the viewer's position relative to a selected coordinate system.

In dynamic mode, the *Globals* menu provides read, write, and save access to the global parameters appropriate to the selected time period. A *Globals* popup window will appear showing the parameters Date, Time, Kp, Ap, SSN, F10.7, Dst, and AB. These values can be edited and line entries can be added or deleted directly in the text window. All science and application modules run will utilize using this same set of global input values. In static mode the global parameters used to represent the single selected time are contained in the Kp, SSN, F10.7, and Ap text boxes at the top of the Environment window.

The *Help* menu connects the user to a PDF version of the user's manual. The manual includes an extensive examples section with click-by-click instructions allowing the user to recreate the graphics presented.

Science Modules

Science modules provide methods for generating data sets from various space environment models. The following science modules are supported by AF-GEOSpace:

APEXRAD: The Advanced Photovoltaic and Electronics Experiment (APEX) space radiation dose model[2] specifies the location and intensity of the radiation dose rate behind four different thicknesses of aluminum shielding for five geomagnetic activity levels as specified by Ap15. It covers the Low Earth Orbit (LEO) altitude region (360-2400 km) and was developed to supplement the CRRESRAD model (see below) which has limited resolution in the LEO regime.

AURORA: Auroral precipitation models[3, 4] specify the location and intensity of electron number and energy flux, ion number and energy flux, Pederson and Hall conductivities, and the equatorward boundary at 110 km altitude. This module also provides the capability to map flux, conductivity, and equatorial boundary values up magnetic field lines into the three-dimensional magnetospheric grid.

CHIME: The CRRES/SPACERAD Heavy Ion Model of the Environment[5] (CHIME) specifies the location and intensity of galactic cosmic rays and/or solar energetic particle fluxes and/or anomalous cosmic ray fluxes.

CRRESELE: The Combined Radiation and Release Effects Satellite (CRRES) electron flux model[6] specifies the location and intensity of electron omni-directional flux over the energy range 0.5-6.6 MeV for a range of geomagnetic activity levels.

CRRESPRO: The Combined Radiation and Release Effects Satellite (CRRES) proton flux model[7] specifies the location and intensity of proton omni-directional flux over the energy range 1-100 MeV for quiet, average, or active geophysical conditions.

CRRESRAD: The Combined Radiation and Release Effects Satellite (CRRES) space radiation dose model[8] specifies the location and intensity of the radiation dose rate behind four different thicknesses of aluminum shielding for active or quiet geophysical activity levels.

IONSCINT: The High Fidelity Ionospheric Scintillation Simulation Algorithm (IONSCINT) model[9] provides realistic scenarios of disruptions in trans-ionospheric radio wave communications with spacecraft due to equatorial scintillation. IONSCINT addresses only intensity (or amplitude) scintillation of 244 MHz signals from geosynchronous satellites and represents statistically realistic climatology as well as the day-to-day variability of equatorial scintillations.

ISPM: The Interplanetary Shock Propagation Model[10] predicts the transit time of interplanetary shocks from the sun to the Earth and the shock strength upon arrival.

NASAELE: The NASA AE-8 radiation belt model[11] is used to compute the intensity and location of differential omni-directional electron flux for ten energy intervals between 0.5 and 6.6 MeV that correspond to the ranges of the CRRES HEEF instrument.
NASAPRO: The NASA AP-8 radiation belt model[11] is used to compute the intensity and location of differential omni-directional proton flux for 22 energy intervals between 1 and 100 MeV, which correspond to the ranges of the CRRES PROTEL instrument.

PIM: The Parameterized Ionospheric Model[12] (PIM) is a global ionosphere model that generates electron number density as well as maps of total electron content (TEC), Height of E and F2 peaks, and plasma frequencies at the E and F2 peaks as a function of a variety of geophysical activity indices.

PPS: The Proton Prediction System[13] (PPS) provides forecasts of the intensity and duration of solar proton events.

SEEMAPS: Single Event Effects Maps[14] (SEEMAPS) uses normalized flux and dose data for protons with energy > 50 MeV from the APEX and CRRES satellites to produce contour maps of relative probabilities of experiencing SEE in the Earth's inner radiation belts.

STOA: The Shock Time-of-Arrival Model[15] (STOA) predicts the transit time of interplanetary shocks from the sun to the Earth. STOA is a predecessor of ISPM.

WBMOD: The WideBand Model[16] (WBMOD) is an RF ionospheric scintillation model specifying S4, SI, and other scintillation parameters between any location on the globe and a satellite above 100 km altitude at any frequency above 100 MHz as a function of a variety of geophysical activity indices. A year 2000 update improves high latitude output.

Application Modules

Application modules provide orbit creation/prediction, dataset integration along orbits, magnetic field model generation, and access to specialized ionospheric ray-tracing, graphics, and scintillation products. The following applications are supported by AF-GEOSpace:

APEXRAD-APP: Advanced Photovoltaic and Electronics Experiments (APEX) radiation dose model[2] calculates expected accumulated yearly dose (in units of rads silicon/year) for four thicknesses of aluminum shielding during four levels of magnetic activity. For orbits with apogees greater than 2500 km, use CRRESRAD-APP described below.

BFIELD-APP: The B-Field application allows the generation of datasets representing the magnetic field in the near-Earth space environment. A variety of internal (dipole, IGRF) and external magnetic field models[17, 18, 19, 20] are used to generate gridded data set, and trace field lines and flux tubes.

CRRESELE-APP: The Combined Radiation and Release Effects Satellite (CRRES) electron flux model[6] is used to estimate of electron fluence, over the energy range 0.5-6.6 MeV, received along a user-specified satellite orbit under a wide range of magnetospheric conditions.

CRRESPRO-APP: The Combined Radiation and Release Effects Satellite (CRRES) proton flux model[7] is used to calculate proton omni-directional fluence (integral and differential) over the range 1 to 100 MeV for user specified orbits and quiet, active, or average geophysical activity levels.

CRRESRAD-APP: Combined Radiation and Release Effects Satellite (CRRES) space radiation dose model[8] is used to calculate the expected satellite dose accumulation behind four different thicknesses of aluminum shielding for user-specified orbits for active or quiet geophysical activity levels.

LET-APP: Calculates the linear energy transfer (LET) spectrum and its associated single event upset (SEU) rate in a microelectronic device resulting from the penetration of energetic space particles. Effects from both cosmic rays and the trapped protons are estimated by using the CHIME[5] and CRRESPRO[7] models.

NASAELE-APP: Calculates electron omni-directional fluence (differential and integral) for ten energy intervals in the range 0.65-5.75 MeV. A user-specified orbit is traced through the NASA AE-8 trapped electron model[11] to provide an estimate of electron fluence received by the satellite under a wide range of magnetospheric conditions.

NASAPRO-APP: Calculates proton omni-directional fluence (differential and integral) over the energy range 1.5-81.3 MeV for user specified orbits and quiet or active geophysical conditions using the NASA AP-8 trapped proton model[11].

RAYTRACE-APP: Calculates the behavior of MHz rays in an ionosphere specified by a Parameterized Ionosphere Model (PIM) data set generated using the PIM module.

SATEL-APP: Calculates orbital trajectories for satellites from a variety of user specified orbital element input sets.

WBPROD-APP: Gives a 24hr WBMOD[16] climatology prediction of the dB fade levels due to ionospheric scintillation effects for specific ground-to-satellite communication links.

Data Modules

Data modules provide methods for reading and displaying externally generated data sets. The following data modules are supported by AF-GEOSpace:

EPHEMERIS: Allows user-generated time-ordered data and satellite ephemeris to be loaded into AF-GEOSpace. Data and satellite trajectory can then be displayed using the ORBIT-PROBE (1D) and SATELLITE (3D) graphical modules, respectively. This feature enables data/model comparisons as the user-provided satellite trajectory can be used to sample other AF-GEOSpace environment models.

PARAMESH: Allows the user to load MHD simulation run results produced externally using the large-scale parallel grid meshing package called *Paramesh* and MHD science codes developed by the Navel Research Laboratory. Loaded data is then displayed within the special Heliospace viewport using the *Paramesh* related graphics modules described below. Details about the *Paramesh* package can be found at the NRL website (http://www.lcp.nrl.navy.mil/hpcc-ess/amrmhd3d.10.html). This module was a product of a CHSSI collaboration between NRL and AFRL. (Note that this module is actually accessed with the *File* menu option *Open Paramesh*.)

Graphics Modules

Graphics modules are used to visualize the data sets created through the Application, Data, and Science modules. The following graphics are supported by AF-GEOSpace:

ANNOTATION: Create and display descriptive text or time labels for viewports.

AXES: Plot a set of axes or sun vector.

COORD-PROBE: Provides a method for probing data along lines defined in user-specified coordinate systems.

COORD-SLICE: Slice the data set along a constant coordinate surface.

DETECTOR: Define and associate fixed or tracking detector cones with satellites or station locations.

EARTH: Plot an outlined or solid Earth. A variety of additional features are available including geographic, magnetic, and corrected geomagnetic latitude-longitude grids.

EMITTER: Define and associate fixed or tracking emitters, e.g., radar fan structures, with satellites or stations.

FIELD-LINES: Plot magnetic field lines and surfaces, flux tubes, and location of the auroral equatorward boundaries.

GLOBAL INPUTS: Produce a line plot of the global input data values, e.g., Kp or Dst, as a function of time.

GRID: Plot the 3-D grid associated with a data set.

ISOCONTOUR: Calculate an isocontour of a data set and plot the resulting surface.

LINK: View a line-of-sight link between stations and satellites or between satellites.

ORBIT-PROBE: Plot data sets from along satellite orbits.

ORBIT-SLICE: Cut the data set with a plane placed at the orbital plane of a satellite (or a plane perpendicular to or containing the satellite velocity vector) and plot the resulting slice.

PLANE-SLICE: Cut the data set with an arbitrary plane and plot the resulting slice.

RAY TRACE: Produce a depiction of the ionospheric rays traced through the PIM science model data sets.

SATELLITE: Provides a means of viewing satellite trajectories.

STARS: Plot the celestial background including stars, planets, and the moon.

STATION: Plot a labeled location on or above the surface of the Earth.

VOLUME: View the entire volume of a data set as a single three-dimensional object.

PARAMESH-COORDSLICE: Produce a slice or constant coordinate surface through a data set written using the *Paramesh* parallel meshing software.

PARAMESH-FIELDLINES: Produce field lines through a *Paramesh* data set.

PARAMESH-GRID: Display the grid, block structure (e.g., leaf and parent block), and overall domain of a *Paramesh* data set.

PARAMESH-ISOCONTOUR: Produce a surface of constant value through a *Paramesh* data set.

PARAMESH-VOLUME: View the entire volume of a *Paramesh* data set as a single three-dimensional object.

Graphical Module Options

Graphical option controls appear in the environment window of each active graphics module. The *Display* option is used to place or display a graphics object in an active viewport. The *Use Texture* mapping option improves the appearance of color data contours. An *Interactive* option controls whether or not graphical renderings are updated immediately as changes are made to the graphic inputs. The appearance of a graphical object can be manipulated using the *Clipping* (multiple planes with rotation and translation), *Transparency*, *Lighting* (e.g., ambient, specular), *Material* (e.g., emission and shininess), and *Color* (Red-Green-Blue and Hue-Saturation-Value slider) options. The *Color Map* option enables tailored modifications to the mapping of colors assigned to data values represented in the viewport color bar. The *Data Map* option controls the range and linear/log scale used to display data, e.g., to examine a subset of the data range.

Worksheet Modules

Worksheet modules provide auxiliary tools that are helpful in AF-GEOSpace calculations. The following worksheet modules are supported by AF-GEOSpace:

CALENDAR: A calendar showing month and day, day of year, and modified Julian day.
COORD_TRANSFORM: Perform coordinate transformations on point locations using different coordinate systems (GEOC, GSM, SM, GEI) and coordinate geometries (Cartesian, Cylindrical, Spherical) at a given Year, Day, and UT.

Final Comments

The AF-GEOSpace software suite provides the scientific community with a number of empirical, statistical, and physics-based models that address concerns about environmental hazards affecting real-world space systems. Recent improvements to the software have greatly increased its utility and portability. The authors encourage the community to make suggestions regarding the addition of new models and applications. AF-GEOSpace Version 2.0 software is distributed exclusively by AFRL and can be obtained by contacting the first author.

Acknowledgements

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References

1. Hilmer, R V (Ed.), AF-GEOSpace User's Manual, Version 1.4 and Version 1.4P, AFRL-VS-TR-1999-1551, Air Force Research Laboratory, Hanscom AFB, MA, 1999

2. Bell, J T, and M S Gussenhoven, APEXRAD Documentation, PL-TR-97-2117, Phillips Laboratory, Hanscom AFB, MA, 1997

3. Hardy, D A, W McNeil, M S Gussenhoven, and D Brautigam, A statistical model of auroral ion precipitation, J. Geophys. Res., 94, 370, 1989.

4. Hardy, D A, M S Gussenhoven, and E Holeman, A statistical model of aurora electron precipitation, J. Geophys. Res., 90, 4229, 1985

5. Chenette, D L, J D Tobin, and S P Geller, CRRES/SPACERAD Heavy Ion Model of the Environment, CHIME, PL-TR-95-2152, Phillips Laboratory, Hanscom AFB, MA, 1995

6. Brautigam, D H, and J T Bell, CRRESELE Documentation, PL-TR-95-2128, Phillips Laboratory, Hanscom AFB, MA, 1995

7. Meffert, J D, and M S Gussenhoven, CRRESPRO Documentation, PL-TR-94-2218, Phillips Laboratory, Hanscom AFB, MA, 1994

8. Kearns, K J, and M S Gussenhoven, CRRESRAD Documentation, PL-TR-92-2201, Phillips Laboratory, Hanscom AFB, MA, 1992

9. McNeil, W, User’s Guide for the High Fidelity Ionospheric Scintillation Simulation Algorithm, Prepared for AFRL/VSB by Radex, Inc., March 8, 2000

10. Smith, Z, and M Dryer, The Interplanetary Shock Propagation Model: A model for predicting solar-flare-caused geomagnetic storms, based on the 2 1/2 D, MHD numerical simulation results from the Interplanetary-Global Model (2D IGM) NOAA Tech. Mem., NOAA/ERL 89, 1995

11. Vette, J I, The NASA/NSSDC Trapped Radiation Environment Model Program (1964-1991), NSSDC/WDC-A-RS 91-29, 1991

12. Daniell, R E, Jr., L D Brown, D N Anderson, M W Fox, P H Doherty, D T Decker, J J Sojka, and R W Schunk, Parameterized Ionospheric Model: A global ionospheric parameterization based on first principles models, Radio Sci., 30, 1499, 1995

13. Smart, D F, and M A Shea, Modeling the time-intensity profile of solar flare generated particle fluxes in the inner heliosphere, Adv. Space Res., 12, No. 2-3, (2) 303, 1992

14. Mullen, E G, G Ginet, M S Gussenhoven, and D Madden, SEE relative probability maps for space operations, IEEE Trans. Nuc. Sci., 45, 2954, 1998

15. Smart, D F, and M A Shea, A simplified model for timing the arrival of solar flare-initiated shocks, J. Geophys. Res., 90, 183, 1985

16. Secan, J A, and R M Bussey, An improved model of high-latitude F-region scintillation (WBMOD version 13), PL-TR-94-2254, 1994

17. Hilmer, R V, and G -H Voigt, A Magnetospheric Magnetic Field Model with Flexible Current Systems Driven by Independent Physical Parameters, J. Geophys. Res., 100, 5613, 1995

18. Olson, W P , 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

19. Tsyganenko, N A, Global Quantitative Models of the Geomagnetic Field in the Cislunar Magnetosphere for Different Disturbance Levels, Planet. Space Sci., 35, 1347-1358, 1987

20. Tsyganenko, N A, A Magnetospheric Magnetic Field Model with a Warped Tail Current Sheet, Planet. Space Sci., 37, 5-20, 1989