Radiation Belt Studies and Development of Space Environment Tools

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ABSTRACT

The Earth's trapped radiation belts were discovered at the beginning of the space age and were immediately recognised as a considerable hazard to space missions. Consequently, considerable effort was invested in building models of the trapped proton and electron populations, culminating in the NASA AP-8 and AE-8 models which have been de facto standards since the seventies. The CRRES mission has demonstrated that the trapped radiation environment is much more complex than the static environment described by the old models. Spatial and especially temporal variations were shown to be much more important than previously thought, and to require more complex models than those in use at that time.

In the framework of a number of ESA/ESTEC contracts, the institute has worked on improvements of existing radiation belt models and on constructing new ones. The main results of this work are:

- guidelines for the correct use of old models for contemporary applications have been established (Heynderickx et al., 1996);
- a low altitude trapped proton model has been developed using data of the PET instrument onboard SAMPEX (Heynderickx et al., 1999);
- a new method for modelling the East-West asymmetry in the low altitude trapped proton environment has been developed (Kruglanski and Heynderickx, 1999);
- a new trapped electron model has been built from data of the MEA instrument onboard CRRES;
- the feasibility of modelling the storm time electron population in the radiation belts with the numerical model Salammbô has been investigated (Kruglanski et al., 2000).

A byproduct of these studies is a Fortran library of magnetic field routines, UNILIB, which has been made available to the general community with full documentation on the WWW.

Another major project taken on by our group is the development of the Space ENVironment Information System (SPENVIS) in the framework of a GSTP contract. SPENVIS is a WWW interface to models of the space environment and its effects on spacecraft components. It is widely used by the international community for a variety of applications.

KEYWORDS

Radiation belts, radiation effects, magnetic field

MODELLING THE LOW ALTITUDE TRAPPED PROTON ENVIRONMENT

A new solar minimum model

The models of the Earth's trapped radiation environment still in common use are the NASA models AP-8 and AE-8 [Vette, 1991], which represent the trapped particle environment as measured by a series of instruments on satellites that flew in the sixties and early seventies. The NASA models have been used-more or less exclusively-for more than twenty years now and have become a generally accepted de facto standard.

The interest in the trapped radiation environment has been rekindled since the Combined Release and Radiation Effects (CRRES) mission, which has emphasized that the AP-8 and AE-8 trapped radiation models are in need of updating or replacement. In the framework of the TREND contract, we made an analysis (Heynderickx et al., 1999) of low altitude trapped proton flux measurements made by the Proton/Electron Telescope (PET) onboard the Solar, Anomalous, and Magnetospheric Particle EXplorer (SAMPEX) satellite http://surya.umd.edu/www/sampex.html. One year of SAMPEX/PET data has been processed to produce a model map of the directional trapped proton distribution below 600 km, for epoch 1995. The energy range of the measurements, and hence of the model, is 18.5-500 MeV, which extends the high energy range of the AP-8 models. Figure 1 shows the SAMPEX/PET model flux of protons with energy above 20 MeV, at 500 km altitude.

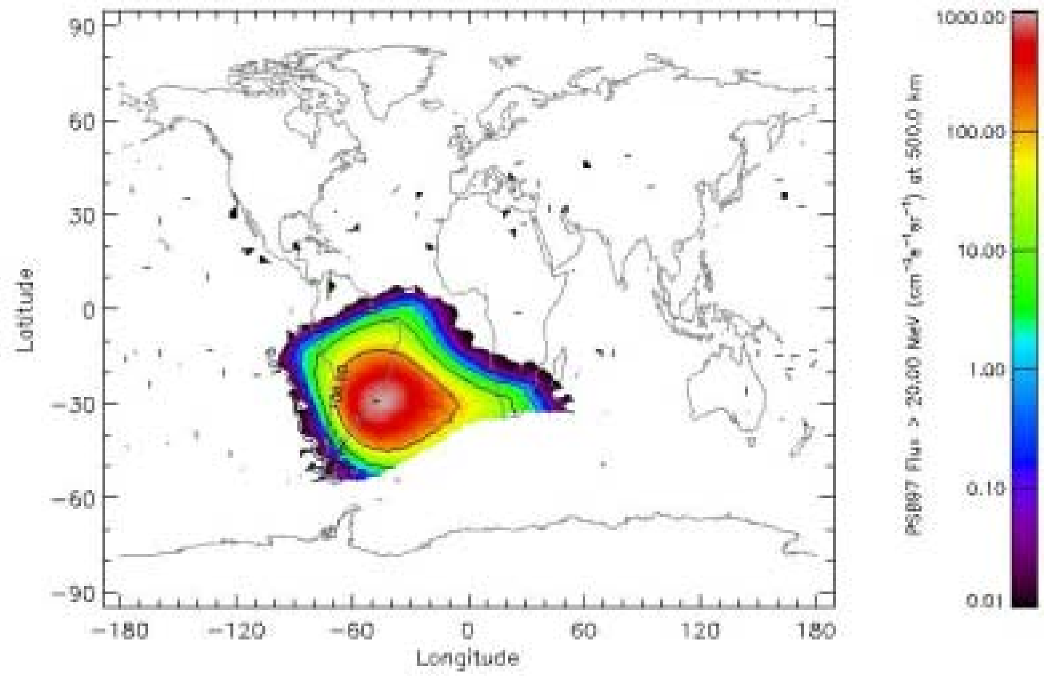

Figure 1: World map at 500 km of the SAMPEX/PET model proton flux above 20 MeV

The production of a flux map based on one year of PET data is only an intermediate step in the development of a complete low altitude trapped proton model which takes into account the effects of the solar cycle variation, seasonal changes in the neutral atmosphere, the secular variation of the geomagnetic field, and the East-West effect. Such a model is now under development.

A new model for the East-West asymmetry

At the inner edge of the radiation belts, the trapped proton fluxes are highly anisotropic due to the interaction of the particles with the Earth's atmosphere. An important part of the flux anisotropy consists of a steep pitch-angle distribution related to the atmospheric loss cone. An additional azimuthal anisotropy appears for the high-energy trapped proton fluxes. This anisotropy is observable at particle energies for which the scale length of the radiation flux is comparable to or shorter than the size of the proton gyration radius. The azimuthal anisotropy results in an East-West asymmetry effect where, in general, the fluxes of protons coming-for a given position-from the East are higher than the fluxes of proton coming from the West. This East-West effect observed experimentally is explained by the fact that protons viewed with the same pitch angle but in different azimuthal directions have their guiding centres on different magnetic field lines and thus belong to different drift shells, where the fluxes are rather different from each other.

Generally, for spacecraft shielding calculations, omnidirectional radiation fluxes are assumed since large variations in spacecraft attitudes tend to average out any anisotropies. However, when the spacecraft attitude is stabilized, the anisotropies in the radiation distribution cannot be ignored, and a complex shielding analysis has to be performed. Such circumstances are met with the International Space Station, the attitude of which will be approximately stabilized along its velocity vector. Using only omnidirectional models could result in errors in the shielding analysis and an erroneous estimation of the hazard to the crew and electronics.

One purpose of modelling the flux anisotropy is to deduce angular dependent proton flux spectra from standard omnidirectional flux data bases which were, until recently, the only ones available. These models depend more or less on the assumption that the energetic proton fluxes at low altitudes are directly controlled by the density distribution of the Earth's atmosphere over a particle drift. Since, in these models, the proton fluxes also depend explicitly on the local value of the magnetic dip angle and of the atmospheric scale height, a new trapped radiation belt model based on this type of description of the anisotropy would probably poorly satisfy the constraints imposed on the angular flux distribution by Liouville's theorem, which introduces a compulsive constraint on all models depending on local values.

In order to obtain a more general description of the trapped proton anisotropy, we introduced (Kruglanski and Heynderickx, 1999) an alternative approach based only on the use of a coordinate system attached to the magnetic field lines. It resulted in a model which does not include parameters depending explicitly on the geographic location where the model is evaluated. This kind of approach is not original: it corresponds to the use of action variables, i.e. the adiabatic invariants μ, J and Φ. However, to our knowledge, it has never been applied to the modelling of the trapped particle anisotropy. Figure 2 compares the angular distribution predicted by the new model to two older models, for a point on the drift shell (B=1.24,L=1.24). The anisotropy predicted by the new model is much more pronounced.

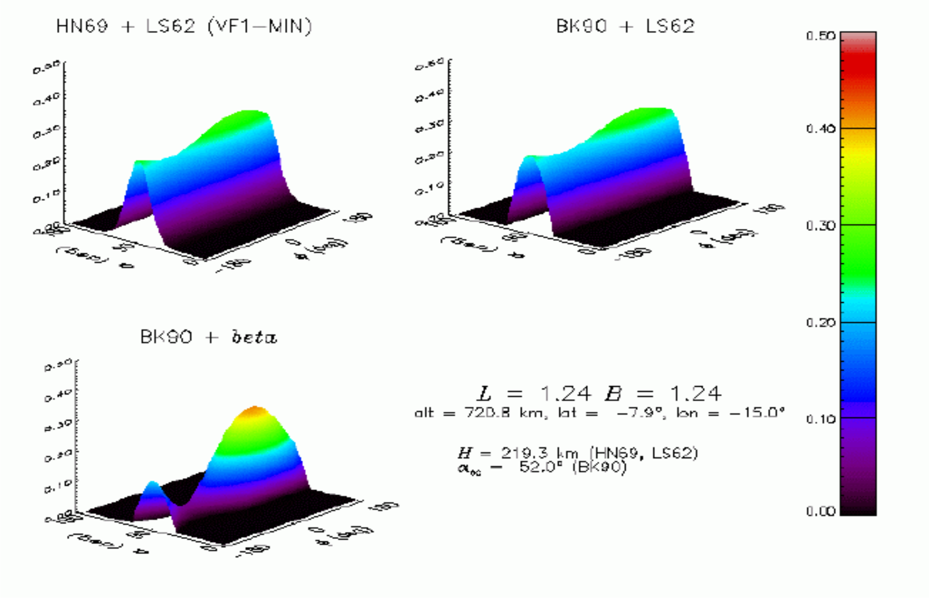

Figure 2: Comparison of the new proton asymmetry model (bottom left hand picture) to two older models.

MODELLING THE STORM TIME ELECTRON BELT POPULATION

The prediction of the radiation electron belt dynamics during storm periods is an important cornerstone of space weather forecasting. The Radiation Environment Monitor (REM) (*Bühler et al.,1996*) aboard the STRV-1B satellite in GTO orbit provides a wealth of data for studying the radiation environment and evaluation of empirical or theoretical models of the radiation belts. Both shielded silicon diodes of the REM detector allow the determination of electron fluxes in the energy range from 2 to 10 MeV in a typical time base of 100 seconds. We confronted (Kruglanski et al., 2000) the STRV/REM measurements with the results of the Salammbô-3D code developed by DESP to simulate the high energy charged particle transport (*Beutier and Boscher, 1995*) by solving a Fokker-Planck diffusion equation in (E, α_0, L) space. In order to better describe the wave-particle interaction during the storm event, a dependence on Kp for both the radial diffusion coefficients and the plasmapause location has been added to the Salammbô code. The time evolution of the boundary conditions is based on geostationary electron flux measurements of the SEM-2 detector aboard the Meteosat-3 spacecraft. We limited the comparison to two conjunction periods for which good data coverage is available from the Meteosat-3, STRV and Wind spacecraft. During the first period, from 5 to 18 April 95, the solar wind velocity was nearly constant during 4 days, corresponding to a coronal hole, and the GOES fluxes nearly reach the value 105 $cm^{-2}s^{-1}sr^{-1}MeV^{-1}$ during 7 days. The second period extends from 28 May to 14 June 95 and corresponds to a shock followed by 3 days of high wind velocity and a long decrease of the magnetic activity. The Salammbô simulations are in qualitative agreement with the STRV data. Salammbô reproduces quite well the first event, indicating that most of the physical phenomena are modelled. But some discrepancies remain, especially during the recovery phase and for the second event for which the magnetic activity is less intense. The discordance is related to shortcomings in some parts of the current physical modelling, such as the loss processes.

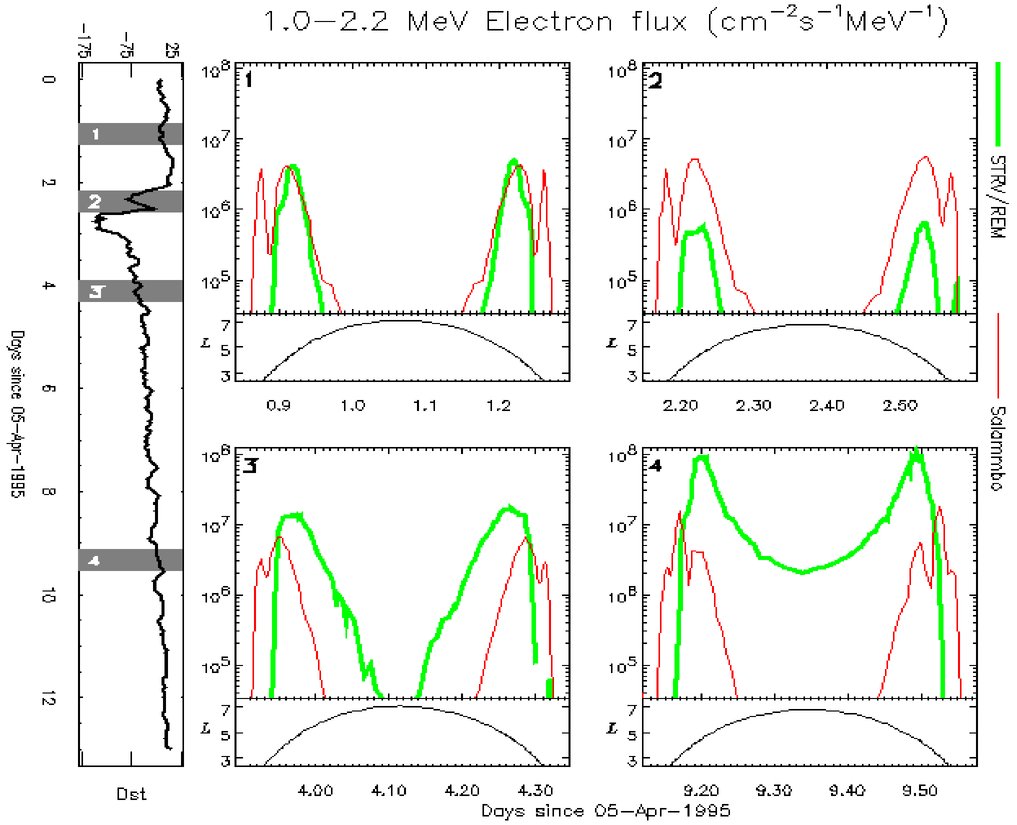

Figure 3: Comparison of 1.0–2.2 MeV electron flux observed by Strv-1b/REM (thick green curves) with the Salammbô-3D simulation of these measurements (thin red curves) along four orbits: one before the storm, one during the main phase and two during the recovery phase.

In order to directly compare the Strv-1b/REM measurements and the Salammbô simulation, the Salammbô results have been integrated in energy and pitch angle to predict the REM measurements along the Strv-1b orbit. The Salammbô predictions and Strv-1b/REM measurements are shown in Figure 3 for four Strv-1b orbits: one orbit before the storm, one orbit during the main phase and two orbits during the recovery phase. Before the storm, the measurements and predictions look similar in spite of Salammbô initial conditions being based on data from a different epoch. During the storm, the predicted electron fluxes do not decrease during the growth phase, and Salammbô overestimates the REM flux by a factor 10. This can be partly due to the effect of L as the Strv-1b/REM measurements were plotted using a McIlwain L and a static magnetic field while the Salammbô results are obtained in (M, J, L^*) space. During the recovery phase, the differences between measurements and predictions become even more significant. Both measured and simulated fluxes increase in the outer belt region, but the shape, the growth rate and the amplitude are very different. For large L values the discrepancies are probably due to boundary conditions.

THE SPACE ENVIRONMENT INFORMATION SYSTEM (SPENVIS)

The ESA SPace ENVironment Information System (SPENVIS) provides standardized access to models of the hazardous space environment through a user-friendly WWW interface. The interface includes parameter input with extensive defaulting, definition of user environments, streamlined production of results (both in graphical and textual form), background information, and on-line help. It is available on-line at http://www.spenvis.oma.be/spenvis/. Intranet versions are also available. SPENVIS has been operational for about three years, with a continuously expanding user community and set of functions. SPENVIS Is designed to help spacecraft engineers perform rapid analyses of environmental problems and, with extensive documentation and tutorial information, allows engineers with relatively little familiarity with the models to produce reliable results. It has been developed in response to the increasing pressure for rapid-response tools for system engineering, especially in low-cost commercial and educational programmes. It is very useful in conjunction with radiation effects and electrostatic charging testing in the context of hardness assurance. SPENVIS is based on internationally recognised standard models and methods in many domains. It uses an ESA-developed orbit generator to produce orbital point files necessary for many different types of problem. It has various reporting and graphical utilities, and extensive help facilities. SPENVIS includes models of the radiation environment and effects, including NIEL and internal charging. It also contains an active, integrated version of the ECSS Space Environment Standard, and access to in-flight data. Apart from radiation and plasma environments, SPENVIS includes meteoroid and debris models, atmospheric models (including atomic oxygen), and magnetic field models implemented by means of the UNILIB library.

The planning of space missions requires an analysis of the space environment and its impact on space systems. The space environment includes the following hazardous environments:

- radiation environment due to the radiation belts, solar particles, and cosmic rays;
- the plasma environments of the ionosphere and geomagnetic substorms;
- neutral gaseous environments, including atmospheric atomic oxygen;
- micro-meteoroids and space debris;
- magnetic fields;
- solar emissions.

Empirical or quasi-empirical models of these hazardous environments have been developed by different organizations, often independently of one another. As a consequence, the availability of existing models is not always known to potential users. In addition, the issue of updating models and acquiring up-to-date versions is not straightforward.

The SPace ENVironment Information System (SPENVIS) developed for ESA/ESTEC provides easy access to most of the recent models of the hazardous space environment, in combination with an orbit generator, via an integrated user-friendly World-Wide Web (WWW) interface. The interface includes parameter input with extensive defaulting, definition of user environments, streamlined production of results (both in graphical and textual form), background information and on-line help. The tools are harmonised with the European standard on the space environment, currently under parallel development. In the framework of a separate ESA/ESTEC contract (TREND, Trapped Radiation ENvironment Development, see http://www.magnet.oma.be/trend4/), a Fortran library (UNILIB) of magnetic field routines and utilities has been developed. The magnetic field calculations in SPENVIS use function calls to this library.

SPENVIS GENERAL FUNCTIONALITY

The SPENVIS system makes full use of the WWW facilities through the following features:

- access via computer networks to a centralized system;
- easy-to-use input facilities making extensive use of default values for the various input parameters, hierarchical structuring of input, and input validation;
- identification of users allowing for the creation of personalized environments, in which previous results and inputs are retained, even when leaving the system;
- automatic and/or user-specified generation of output, both plots and tables, as in-line images or downloadable graphical formats;
- extensive on-line help and links to in-depth documentation.

The URL of the SPENVIS system is http://www.spenvis.oma.be/spenvis/.

SPENVIS is based on internationally recognised standard models and methods in many domains. It uses an ESA-developed orbit generator to produce orbital point files necessary for many different aspects of mission analysis, and can also generate maps and profiles to study the geographical distribution of model parameters.

The results of a SPENVIS model run are presented in the form of reports and data files that can be downloaded by the user, and as a variety of plot types (line plots, maps and 3-D plots) in different graphics formats (GIF, PS, JPG, VRML, ...).

Extensive help facilities are provided in SPENVIS: context-sensitive help pages provide information on the model parameters and usage, background pages contain in-depth material on the space environment and models, and a user guide and links to other sites are available as well. The help pages are cross-referenced for fast navigation, which is further enhanced by a search engine.

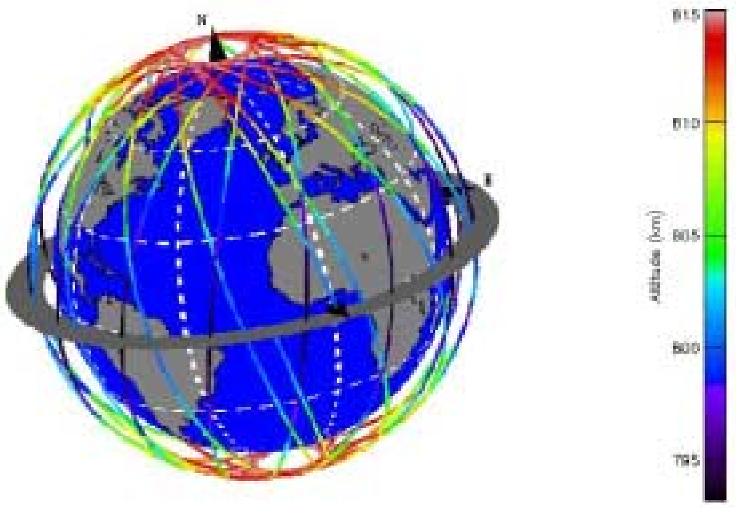

Figure 4: Three dimensional representation of an 800 km heliosynchronous orbit

MODELS IMPLEMENTED IN SPENVIS

Most of the models implemented in SPENVIS require as input a set of points on a spacecraft trajectory or a user-defined set of geographic points. These sets of points are produced by two tools: the orbit generator and the coordinate grid generator (Fig. 4 shows a three dimensional representation of a heliosynchronous orbit at 800 km altitude). When running the orbit or grid generator, all outputs previously obtained with models that use the respective coordinate tool, are deleted. This is to ensure consistency between results, and to avoid errors in the plotting routines that produce the graphical output. The input parameters for the models are not deleted, so that they can be run again in the same way. The models in SPENVIS have been organised in packages, which are described in the sections below

RADIATION ANALYSIS

The radiation tools include:

- radiation belt models: the NASA models AP-8 and AE-8 [1], the AFRL models CRRESPRO [2] and CRRESELE [3], and models developed in the framework of ESA TRP contracts [4] with data sets including SAMPEX [5] and CRRES/MEA [6], and a model of the low-altitude trapped proton anisotropy [8].
- solar proton models: JPL-85 [9], JPL-91 [10] (see Fig. 5), King [11];
- CREME [12] for cosmic rays.

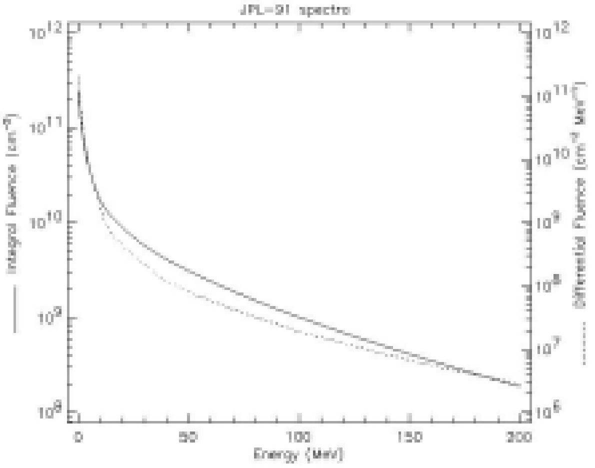

Figure 5: Integral and differential solar proton spectrum for an 800 km heliosynchronous orbit

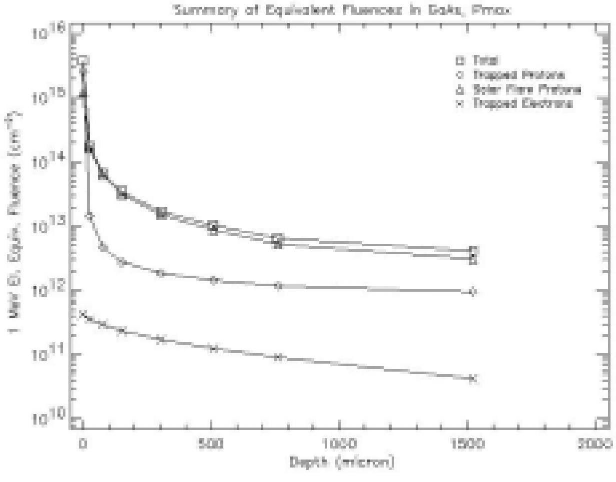

Figure 6: Equivalent fluences in a GaAs solar cell for an 800 km heliosynchronous orbit

The conversion of geographic to magnetic coordinates is done internally without interference from the user, ensuring consistency in the application of magnetic field models, often a source of confusion and error [13]. Internal and external magnetic field models can also be run separately to study the distribution of the magnetic field and related parameters over an orbit or a grid of geographic coordinates, or to generate and visualise magnetic drift shells (see section on magnetic fields).

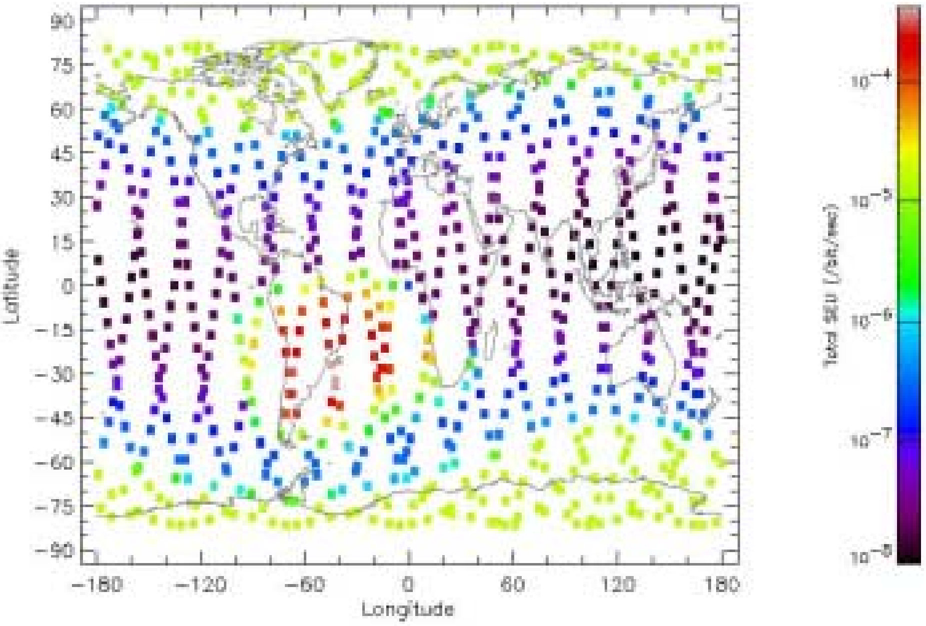

Figure 7: Single event upset rates along an 800 km heliosynchronous orbit

SPENVIS contains the SHIELDOSE [14] and SHIELDOSE-2 codes for total dose assessment and the EQFRUX [15] and EQFRUXGA codes for solar cell damage-equivalent fluences (1 MeV electron equivalent). Figure 6 shows the equivalent fluences of trapped protons and electrons and solar protons in a GaAs solar cell for an 800 km heliosynchronous orbit. These tools have been augmented by a code for computing the Non-Ionizing Energy Loss (NIEL) or non-ionizing dose [16]. This parameter is gaining importance since it represents the best way to quantify the environment for assessing displacement damage effects such as charge transfer efficiency degradation of CCDs, and is now proposed as a better parameter for solar cell damage assessment. In conjunction with CREME and the trapped and solar proton models, the user can compute single event upset rates from cosmic and solar ions and trapped and solar protons (shown in Fig. 7 for an 800 km heliosynchronous orbit).

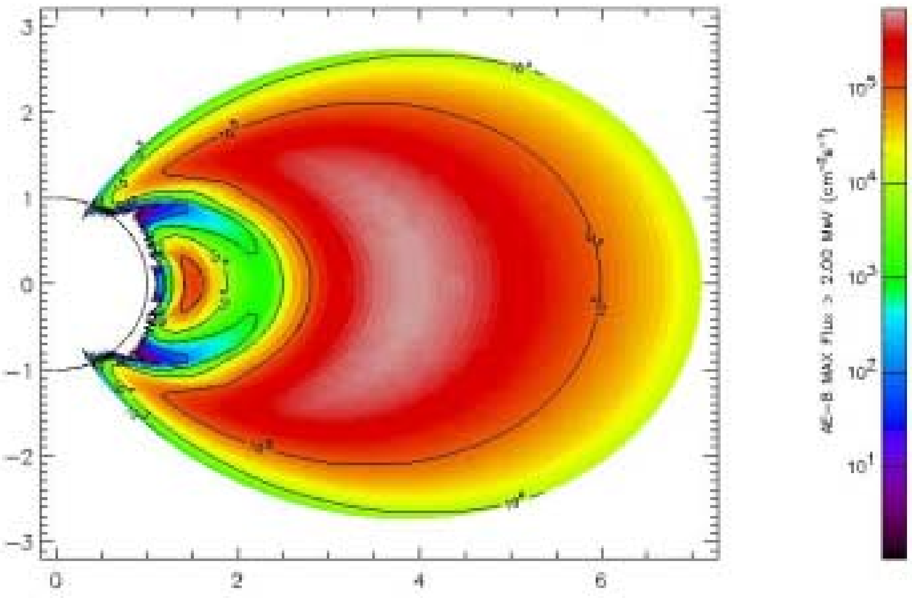

Figure 8: Invariant coordinate map of the AE-8 MAX electron flux >2 MeV

In computing all these parameters, spacecraft or solar cell coverglass shielding is taken into account. In addition, a geometric tool to calculate shielding distributions for simple spacecraft geometries is available. A tool to fold the shielding distribution with ionising and non-ionising dose curves is under development. The trapped particle models can also be run on a coordinate grid. Figure 8 shows the AE-8 MAX electron flux >2 MeV on an invariant coordinate grid.

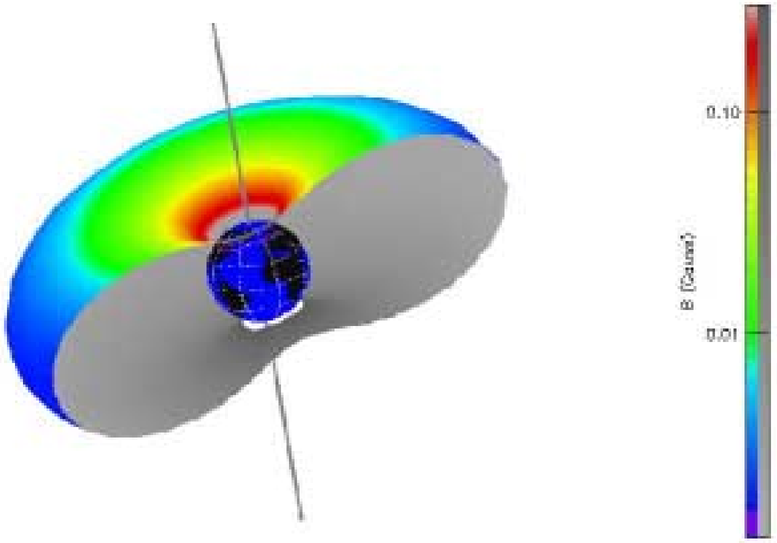

Figure 9. Three dimensional representation of the drift shell L=5,B=0.3

Magnetic field

The most commonly used internal and external magnetic field models have been implemented in SPENVIS through the UNILIB library (see section on UNILIB). The magnetic field models can be evaluated over a spacecraft trajectory or a coordinate grid. The output from the SPENVIS implementation of the models contains the (*B*,*L*) coordinates, the invariant coordinates (*R*,Λ), magnetic longitude and latitude, the magnetic field vector components, and the location of the footpoints. In addition, field line traces are plotted, and three-dimensional plots of drift shells are available. Figure 9 shows a three dimensional representation of the drift shell (*L*=5,*B*=0.3).

Atmosphere and ionosphere

The following neutral atmosphere and ionosphere models have been implemented in SPENVIS: MSISE-90 [18], MET [19], DTM78 [20], HWM93 [21], IRI-90 [22]. These models can be evaluated over a grid of points to produce world maps of densities or temperatures (see Fig 10), over a coordinate range to produce density profiles, or over a range of one of the model parameters for one geographic point (see Fig. 10). In addition, number densities can be calculated along a spacecraft trajectory, and particle fluxes and fluences on an oriented surface can be determined (see Fig. 12).

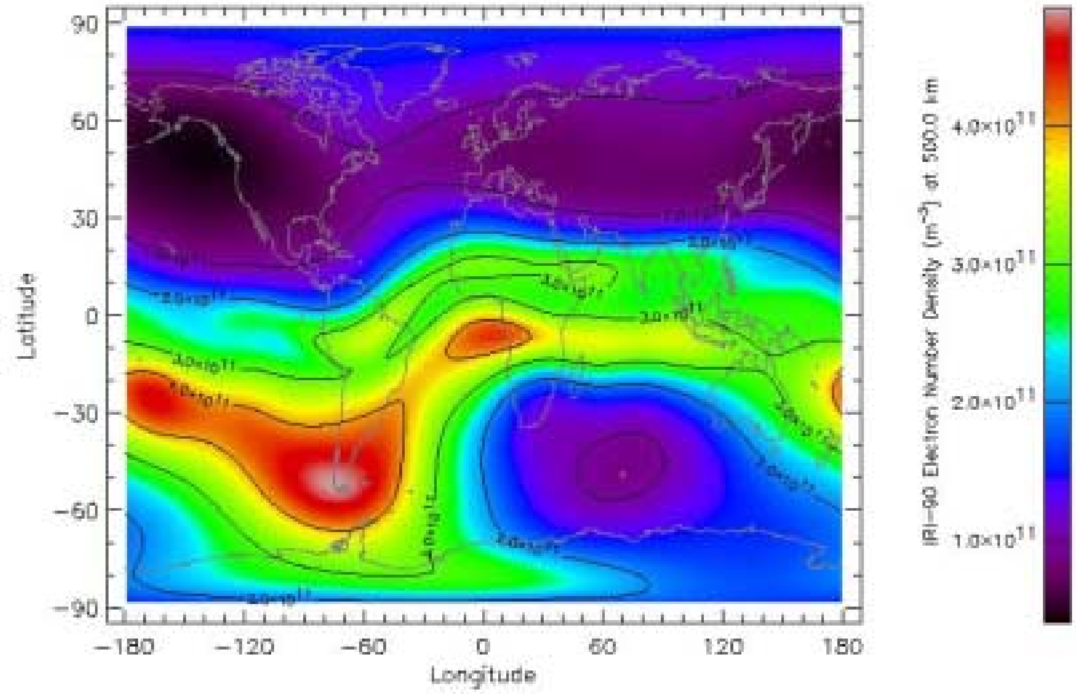

Figure 10: IRI-90 Electron density at 500 km altitude

Spacecraft charging

There has long been a lack of a tool for engineering level evaluation of the internal charging problem. This has recently been addressed by the development of the DICTAT [23] tool by DERA for ESA. Not only is there a lack of analysis tools but also of a method for specifying the hazard, which is addressed by DICTAT. DICTAT calculates the electron current that passes through a conductive shield and becomes deposited inside a dielectric. It has an integrated electron environment model. From the deposited charge, the maximum electric field within the dielectric is found. This field is compared with the breakdown field for that dielectric to see if the material is at risk of an electrostatic discharge. The breakdown field can be a field deduced from beam irradiations, also with the help of the tool.

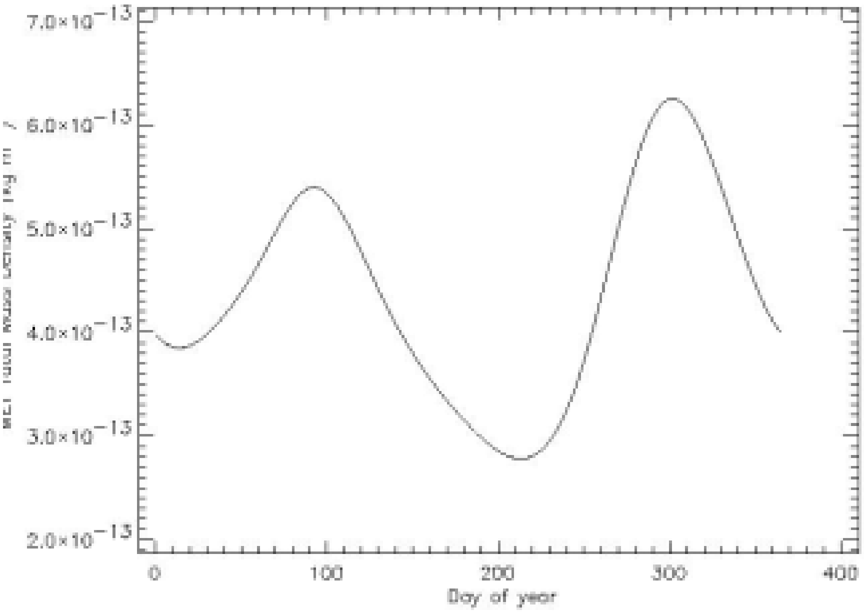

Figure 11: MET Total mass density at 500 km as a function of day number

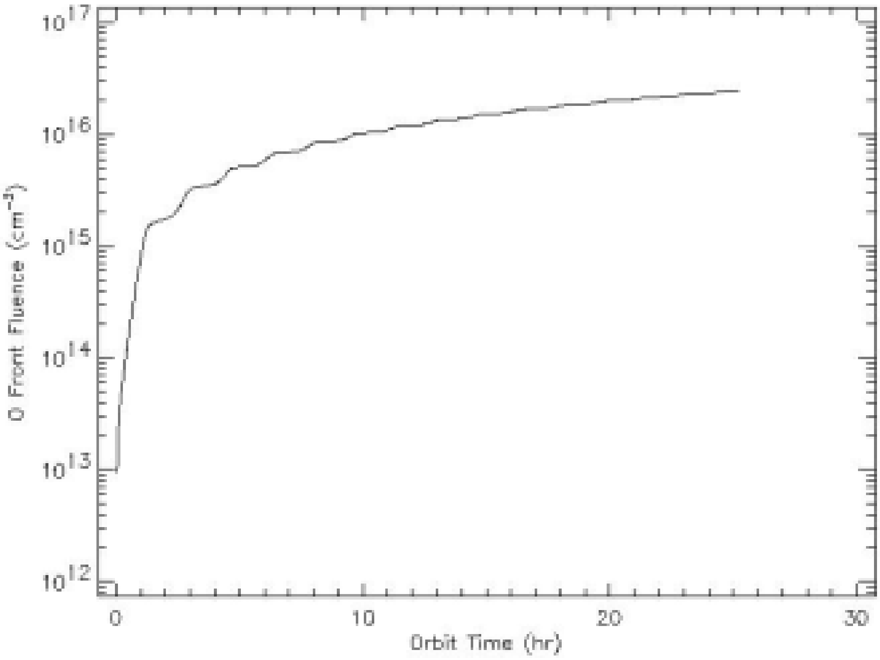

Figure 12: MSISE-90 Atomic oxygen fluence on a plate perpendicular to the spacecraft velocity vector for an 800 km heliosynchronous orbit

While the standard tool for spacecraft charging assessment is the 3-D NASCAP code [24], SPENVIS has implemented the DERA EQUIPOT [25] non-geometrical tool for assessing material susceptibility to charging in typical orbital environments, including polar and GEO environments. While it does not treat geometry explicitly, it does model the charging behaviour of a patch-on-a-sphere model which is useful for investigating differential charging. SPENVIS Also includes SOLARC [26], for assessment of the current collection and the floating potential of solar arrays in LEO (see Fig. 13).

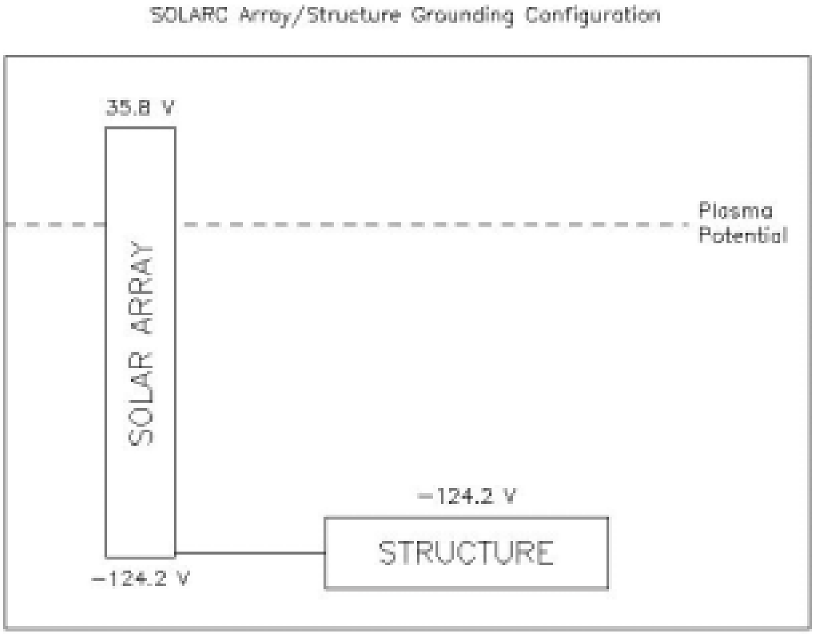

Figure 13: SOLARC Solar array/structure grounding configuration

The system features access to data from surface charging events on the CRRES and the Gorizont spacecraft, in the form of spectrograms and double Maxwellian fit parameters.

Meteoroids and debris

The Grün [27] meteoroid model and the NASA90 [28] debris model have been added to the system. The implementation of the NASA96 [29] debris model as well as particle/wall penetration models for damage risk analysis are in progress.

Access to space environment data bases

One of the latest developments is a feature to produce survey plots of satellite data bases, in combination with geomagnetic indices and related parameters. Data from Meteosat, GOES, SAMPEX, UARS, AZUR, CRRES, and ISEE have been implemented, as well as radiation environment data from the REM instruments on MIR and STRV. Figure 14 shows a sample multi-panel plot obtained with the data base interface.

Integration with a standard on the space environment

The European Cooperation on Space Standards (ECSS) is a system of harmonized standards for the management and engineering of space projects. One of the standards is on Space Environment. SPENVIS Has allowed this standard to be made “active" so that it links to SPENVIS utilities when an engineer wishes to make use of a model or method referred to in the standard, and sits alongside the models so that the engineer can consult the standard in an efficient way for information. As further standards are prepared by ECSS in the areas of radiation effects and spacecraft charging, these will be similarly integrated.

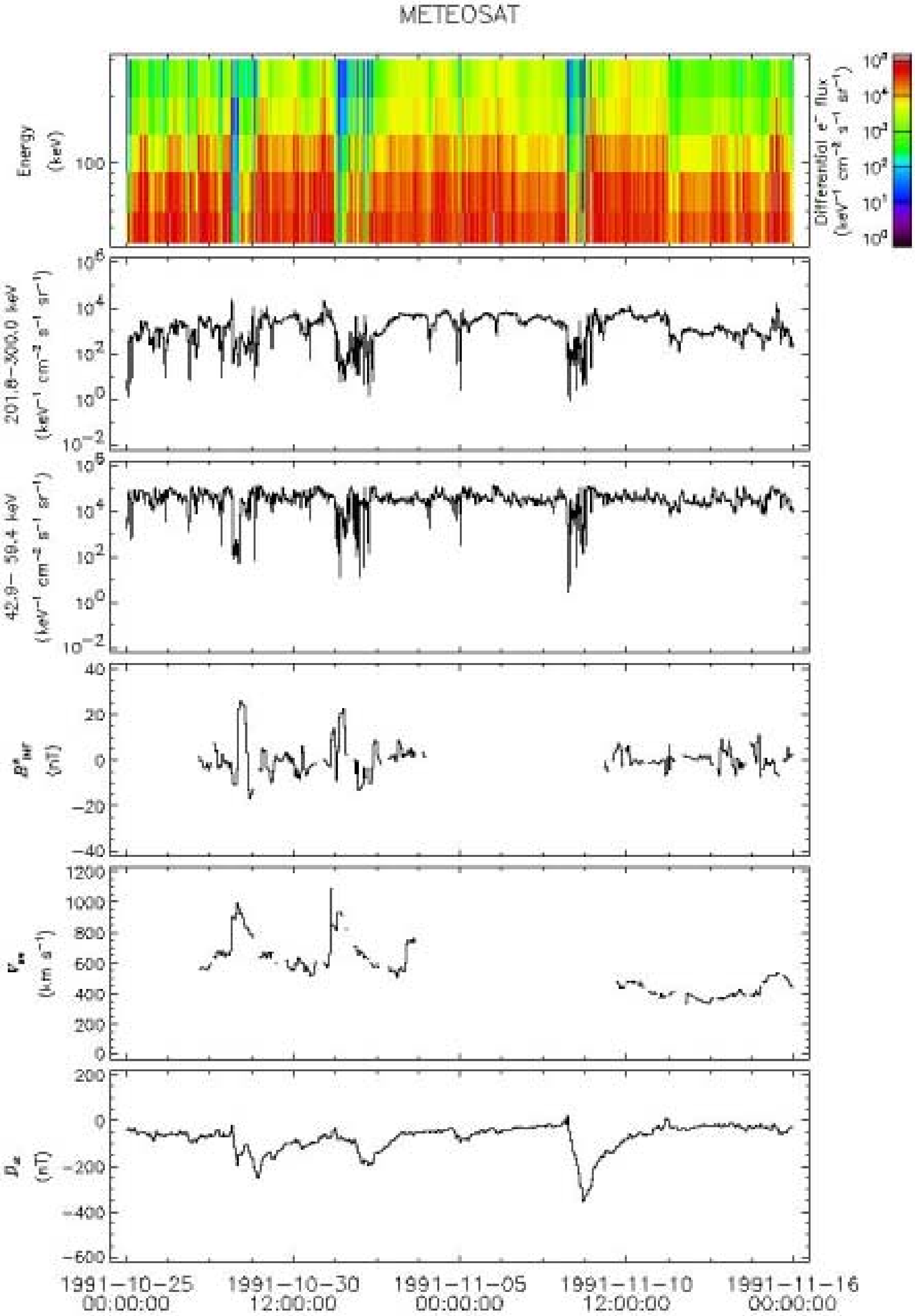

Figure 14: Sample output of the data base interface

The UNILIB library

The UNILIB library implements a series of tools for coordinate transformations, magnetic field computations, magnetic coordinate evaluation, magnetic field line tracing and drift shell tracing. The UNILIB library was originally designed as a tool for the ESA/ESTEC TREND project (Trapped Radiation ENvironment Development) to investigate new coordinates to organise trapped particle fluxes, but can be applied to other fields of magnetospheric research. For instance, UNILIB determines mirror point and footpoint locations and evaluates adiabatic invariants. The UNILIB library is freely accessible from the Web (http://www.magnet.oma.be/unilib/) for downloading in the form of a Fortran object library for different platforms (DecAlpha, SunOS, HPUX and PC/MS-Windows). An interface for the Interactive Data Language (IDL) is included in the distribution. The Web site features extensive documentation including installation instructions, a reference guide, programme examples, and frequently asked questions. A news group has been established at news://news-ae.oma.be/unilib.

The UNILIB library has been designed as a tool for the TREND project. The UNILIB library is a collection of FORTRAN modules that implements a series of tools for coordinate transformations, magnetic field computation, magnetic coordinate evaluation, magnetic field line and drift shell tracing, etc. These modules can be applied through the use of a FORTRAN programme or by the use of IDL/RSInc external calls for which a specific interface is provided. The library has been developed conform to Standard FORTRAN 77, extended to the use of STRUCTURE and RECORD statements which greatly increase the user friendliness of the library and are supported by most FORTRAN 77 compilers. Machine specific code has been avoided so that the library can be installed on different platforms and operating systems. The UNILIB library is freely accessible from the Web (http://www.magnet.oma.be/unilib/) for downloading in the form of a Fortran object library for the supported platforms (DecAlpha, SunOS, HPUX and PC/MS-Windows). The documentation of the library is provided in the form of HTML pages. It includes a cross-referenced list of all the components of the library with a detailed description of each component. A list of frequently asked questions and some examples are provided as well.

Currently, the library includes most of the common geomagnetic and external magnetic field models: DGRF/IGRF 45-95, Jensen and Cain [31], GSFC 12/66 [32], Mead and Fairfield [33], four Tsyganenko models (1987 short and long [34], 1989c [35] and 1996 [36]), Olson and Pfitzer quiet [17] and dynamic [37], Ostapenko and Maltsev [38].

Inside the UNILIB library, geographic locations are expressed in the Geocentric Equatorial (GEO) coordinate system and vectors are specified by their GEO spherical components. Other coordinate systems and representations can be used by applying conversion routines included in the library. These conversion routines allow transformations between GEO, Geocentric Equatorial Inertial (GEI), Geomagnetic (MAG), Solar Magnetic (SM) and Geocentric Solar Magnetospheric (GSM) coordinates. They allow also conversions between cartesian and spherical representations of coordinates as well as of vector components.

Magnetic field line segments are traced by means of a fourth-order Runge-Kutta integration [39] with a step size proportional to the radius of the field line curvature. The segments are defined by conditions on the magnetic field intensity, e.g. the intensity B_m at a trapped particle mirror point, or on the geographic altitude, e.g. to determine foot points. Parameters like the integral invariant coordinate I [40], the Kaufman K parameter or the McIlwain [41] L parameter can be obtained for each evaluated magnetic field segment. The field line tracing is also used to compute magnetic drift shells defined by a pair of (B_m,I) values: for a number of longitudes, the magnetic field line segments that yield the user-defined (B_m,I) values are sought by iterations. In addition to the drift shell, the library provides information such as the foot print of the drift shell, the mirror point with the lowest altitude, the magnetic flux enclosed by the drift shell and the Roederer [40] L^* shell parameter.

The MSISE-90 [18] atmospheric and IRI-90 [22] ionospheric models are also implemented into the library. These models can be evaluated at any geographical location and be integrated along a field line segment or a drift shell for specific applications.

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