TREND
Trapped Radiation Environment Model Development

Technical Note 10
UNIRAD Improvements and Subroutine Library

ESTEC Contract No. 10725/94/NL/JG(SC)\(^1\)

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\(^1\)ESA Technical Management: E.J. Daly (WMA)
# Contents

<table>
<thead>
<tr>
<th>Preface</th>
<th>vii</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgments</td>
<td>ix</td>
</tr>
<tr>
<td><strong>Introduction</strong></td>
<td>xi</td>
</tr>
<tr>
<td>Implementation of new models in UNIRAD</td>
<td>xi</td>
</tr>
<tr>
<td>The UNIRAD library</td>
<td>xi</td>
</tr>
</tbody>
</table>

## 1 Implementation of new trapped particle models in UNIRAD 1

1.1 The UNIRAD program suite | 1
1.2 The TREP program | 3
1.3 New trapped particle models | 4
  1.3.1 The ESA-SEE1 model | 5
  1.3.2 The CRRESPRO and CRRESELE models | 5
    1.3.2.1 The CRRESPRO model | 6
    The PROTEL instrument | 7
    Proton flux models | 7
    1.3.2.2 The CRRESELE model | 7
    The HEEF instrument | 7
    Electron flux models | 8
  1.3.3 Structure of the model data files | 9
  1.3.4 Interpolation in flux maps | 10
  1.3.5 Conversion to omnidirectional fluxes | 11
  1.3.6 Modifications to TREP | 13

## 2 The UNIRAD library 15

2.1 Portability | 15
2.2 Sources | 15
2.3 Functionality of the library ........................................... 16
2.4 Conventions used in the UNIRAD library ......................... 17
  2.4.1 Units ................................................................. 17
  2.4.2 Coordinate systems .............................................. 17
  2.4.3 Component identifiers ......................................... 18
    2.4.3.1 Error trapping ............................................. 18
2.5 Library documentation ............................................... 18
2.6 Installation and usage ............................................... 21
  2.6.1 Initialization ................................................... 22
  2.6.2 Main subroutines ............................................... 22
2.7 Models included in the library ..................................... 23
  2.7.1 Magnetic field models ........................................ 23
  2.7.2 Atmospheric models ........................................... 24
  2.7.3 Collisional cross section models ............................. 25
2.8 Magnetic drift shell ................................................. 25
  2.8.1 Field line tracing ............................................. 25
  2.8.2 Drift shell tracing ............................................ 26
2.9 Content of the library ............................................... 29

References ............................................................... 31

A HTML Help pages for the UNIRAD library .......................... 35
List of Figures

1.1 Flow diagram of UNIRAD .............................................. 2
2.1 Sample of a FORTRAN programme using the library ................ 19
2.2 Sample of an IDL programme using the library ....................... 20
2.2 (continued) ............................................................... 21
## List of Tables

1.1  List of the new flux models implemented in TREP .......................... 4
1.2  Integration parameters (MeV) for integral omnidirectional PROTEL flux [from Meffert & Gussenhoven (1994)] ................................. 6
1.3  Channel energies (MeV) for CRRES/HEEF [from Brautigam & Bell (1995)] .. 8
1.4  Summary of CRRES \(A_{p15}\) model separation and statistics [from Brautigam & Bell (1995)] .................................................. 9
1.5  Record structure of the flux map data files ...................................... 10
1.6  New or modified NAMELIST parameters for TREP .......................... 12

2.1  Physical units used in the UNIRAD library ................................. 17
2.2  URLs Of the main pages of the UNIRAD library documentation .......... 18
2.3  Subroutines implemented in the UNIRAD library .......................... 27
2.3  (continued) ............................................................................. 28
2.3  (continued) ............................................................................. 29
Preface

The aim of the TREND-3 study was to update or replace existing models of the Earth’s trapped radiation environment. To this effect, several satellite data bases have been acquired and analysed: the AZUR/EI-88, SAMPEX/PET, and UARS/PEM energetic proton data, and the CR-RES/MEA and ISEE/WAPS electron data. From these data, new \( (E, L, \alpha_0) \) flux maps have been constructed, which constitute the basis of the new trapped radiation models. The analysis of the proton data sets is described in detail in Technical Note 5 of this study, while the CR-RES/MEA and ISEE/WAPS analysis form the subject of Technical Notes 2 and 3, respectively.

The second aspect of a trapped radiation model is its interface to, in general, an orbit generator, so that for each orbital point the trapped radiation fluxes can be evaluated. The UNIRAD software suite provides such an interface. Up to now, it only contained the standard NASA models AP-8 and AE-8. The new flux maps developed in this study have been added to UNIRAD, so that all its subsidiary programs (estimation of mission dose and damage equivalent fluences for solar cells) can use the fluxes and fluences predicted by the new models.

Besides the models developed in the framework of TREND-3, the ESA-SEE1 (Vampola 1996) model and the CRRESPRO (Meffert & Gussenhoven 1994) and CRRESELE (Brautigam & Bell 1995) models have also been adapted to and integrated in UNIRAD.

The interface between the orbit generator and the flux maps contains a module to calculate the magnetic coordinates \((B, L)\), in which the flux maps are organised. In addition, in order to study the feasibility of using other coordinate systems than \((B, L)\) for organising trapped particle measurements, software had to be developed to derive these coordinates. These coordinates are defined in terms of drift shell averages, so that drift shell tracing had to be implemented as well. The result of this programming effort is a new software library containing a fully developed set of routines for magnetic field line and drift shell tracing.
Acknowledgments

We thank E.G. Mullen, D.H. Brautigam, and M.S. Gussenhoven of Phillips Laboratory for providing us with copies of the CRRESPRO and CRRESELE models and for giving their permission to include them in UNIRAD. Their assistance is greatly appreciated, as well as many discussions which proved invaluable in the correct interpretation of the models.

We thank A.L. Vampola for providing copies of the ESA-SEE1 model and documentation, and for his assistance in the implementation of the model.

The AZUR radiation belt model for trapped protons could never have been developed without the cooperation of D. Hovestadt, Max Planck Institut für Extraterrestrische Physik, Garching, who was the PI of the EI-88 directional detectors. He provided D. Heynderickx with the necessary documentation for the analysis of the AZUR data and granted permission to use the data set. We wish to acknowledge also the Director of NSSDC, J. King, who has unearthed this historical data set from the archives of the NSSDC, at GSFC, Greenbelt.

We wish to address our special thanks to J.B. Blake, Aerospace Corporation, Los Angeles, and R.A. Mewaldt, CALTECH, Pasadena, for offering the TREND project manager to make use of the proton flux measurements of the Proton Electron Telescope (PET) obtained onboard of the SAMPEX satellite, in order to build a new trapped proton environment model. R.A. Mewaldt and J.B. Blake are PI’s for this comprehensive experiment. We thank also M.D. Looper, research assistant at Aerospace Corporation for implementing the unique PET dataset during two visits at BIRA/IASB, and for many long and fruitful discussions.

The TREND team at BIRA/IASB has also been given access to the PEM proton flux measurements obtained onboard of the UARS satellite. We are very grateful to J.D. Winningham and J.R. Sharber, South West Research Institute, San Antonio, PI and Co-I of PEM, for allowing M. Kruglanski to visit SwRI, and to use the PEM observations to build a database for trapped energetic protons. The TREND project manager also thanks the SwRI personnel, especially R.A. Frahm, for allowing us to retrieve and partly process these data on their computer facilities. This database has been used by M. Kruglanski, with the assistance of M.M. Echim (visiting BIRA/IASB from the Institute of Gravitation and Space Sciences, Bucharest), to build the PEM/UARS proton environment model.

During the TREND-3 modelling effort the ESA Technical Manager E.J. Daly has closely followed the progress of the project. His experience and advise have been very stimulating and greatly appreciated by all TREND team members. We also benefited from H. Evans’ useful suggestions and comments.
J.-M. Vandenberge has assisted with part of the UNILIB coding and with the writing of the HTML documentation, which he has also patiently and carefully read and corrected.

We thank J. Lemaire, the TREND-3 project manager, for carefully reading the manuscript and providing many helpful comments and suggestions.

The technical support of our system manager L. Fedullo has been invaluable throughout the TREND programme. He has installed and maintained the VMS cluster and software that constitute the platform on which the BIRA/IASB part of the TREND work has been performed.

Finally, we acknowledge P. Simon, Director of BIRA/IASB, and his predecessor, Baron M. Ackerman, who gave full support to the TREND study and who facilitated its realisation. The logistic and administrative personnel of BIRA/IASB is also generally acknowledged for its efficient help and good collaboration.
Introduction

This Technical Note describes the modifications to the UNIRAD package resulting from the TREND-3 study (WO 3 to ESA/ESTEC TRP Contract No. 11711/95/NL/JG), entitled *Radiation Environments of Astronomy Missions and LEO Missions*.

Two types of modifications have been made to the existing UNIRAD model suite:

1. the addition of new flux maps from five satellite data sets: AZUR/EI-88, SAMPEX/PET, UARS/PEM, CRRES/MEA, and ISEE/WAPS, and the addition of the ESA-SEE1, CRSRESPRO, and CRRESELE models;
2. the development of a library of subroutines.

Implementation of new trapped particle models in UNIRAD

New flux maps from five satellite data sets have been added to UNIRAD: AZUR/EI-88, SAMPEX/PET, UARS/PEM, CRRES/MEA, and ISEE/WAPS. The data sets and their analysis have been described in Technical Notes 2, 3, and 5.

Besides the models developed in the framework of TREND-3, the ESA-SEE1 (Vampola 1996) model and the CRSRESPRO (Meffert & Gussenhoven 1994) and CRRESELE (Brautigam & Bell 1995) models have also been adapted to and integrated in UNIRAD.

In Chapter 1 of this Technical Note we describe the software developed for converting flux maps into BLOCK_DATA files, and the modifications to TREP to incorporate the new models.

The UNIRAD library

A library of subroutines has been developed to compute the magnetic field vector, to trace magnetic field lines and drift shells, and to average physical quantities over a drift shell. This new library is described in Chapter 2. Appendix A contains a compilation of the HTML help pages developed for the library.

The new library is an output of WP 3.2R. The aim of this WP was to combine various utility subroutines to trace magnetic field lines (including foot points and mirror points), trace drift
shells (including the geographic locations of the lowest mirror point), compute adiabatic invariants, perform coordinate transformations, and integrate physical quantities over drift shells. Note that various software packages (including UNIRAD) contain implementations of (part of) these functionalities, but are not always well documented or easily integrated with other programs.
Chapter 1

Implementation of new trapped particle models in UNIRAD

1.1 The UNIRAD program suite

The UNIRAD suite of programs provides information about the radiation environment in an arbitrary Earth orbit, predicting satellite exposures to particle fluxes, the resulting radiation dose, and the resulting damage-equivalent fluences for solar cell degradation calculations (Heynderickx et al. 1996d).

From the orbit parameters, the system will generate a detailed trajectory, magnetic coordinates, integral and differential proton and electron fluences, doses for three shield geometries in four detector materials, and solar cell degradation information, in both printed and graphical form.

The UNIRAD package consists of the following programs:

- **SAPRE**: orbit generator which produces a data file used by the next two programs in the package;
- **BLXTRA**: calculates the geomagnetic coordinates \((B, L)\) from the geographic coordinates generated by SAPRE;
- **TREP**: determines the radiation flux for the geographic coordinates generated by SAPRE from the NASA trapped radiation models AP-8 and AE-8 and determines the solar proton flux over the mission. It produces a data file with the energy spectra of trapped protons and electrons and of solar protons;
- **TREPPOS**: calculates the trapped radiation flux for pairs of \((B, L)\) or \((B/B_0, L)\) coordinates interactively input by the user. It produces a data file with the energy spectra of trapped protons and electrons;
- **TREPAVE**: averages the spectra generated by TREP or TREPPOS for different orbits;
- **ANISO**: transforms the trapped proton omnidirectional integral flux produced by TREP into unidirectional integral and differential fluxes, taking into account pitch angle and azimuthal dependence. The user can define a set of look directions with respect to a satellite reference frame. The resulting fluxes are averaged over the orbit.

- **ANISOPOS**: provides the angular distribution (i.e. pitch angle and azimuthal dependence) of the unidirectional integral or differential flux at a given geographic location.

- **SHIELDOSE**: reads the energy spectra resulting from TREP, TREPave, or TREPPOS and converts them to radiation dose-depth curves for different detector materials and simple shielding geometries;
1.2. The TREP program

TREP calculates orbital radiation environment fluxes for a spacecraft trajectory generated by SAPRE. It estimates fluxes of trapped particles in function of \((B, L)\) coordinates, and computes solar proton event probabilities to estimate solar proton fluences. The output consists of:

1. the time dependent fluxes of trapped protons, solar protons, and trapped electrons;
2. trajectory-averaged spectra for trapped protons and electrons;
3. solar flare fluence spectra, taking into account geomagnetic shielding.

TREP accesses the NASA trapped particle models AP-8 (Sawyer & Vette 1976) and AE-8 (Vette 1991) at each orbital point contained in the common interface file produced by SAPRE. The NASA trapped radiation models AP-8 and AE-8 are distributed as tables of omnidirectional fluxes in function of particle energy \(E\) and \((B/B_0, L)\), where

\[
B_0 = \frac{0.311653}{L^3}.
\]

The NASA models AP-8 and AE-8 are static models built with data obtained in the sixties and seventies. There are two sets of models: AP-8 MAX and AE-8 MAX for solar maximum conditions, and AP-8 MIN and AE-8 MIN for solar minimum conditions. Since these models were built with specific magnetic field models, the same magnetic field models should be used to calculate the \((B/B_0, L)\) values that serve as input to AP-8 and AE-8. The appropriate magnetic field models are: Jensen & Cain (1962) for AE-8 MIN, AP-8 MIN, and AE-8 MAX, and GSFC 12/66 (Cain et al. 1967) updated to epoch 1970 for AP-8 MAX (Heynderickx et al. 1996ab). Two coordinate pairs \((B, L)\) are written to the common interface file PROJECT.INT, corresponding to the field models used with the proton and electron model, respectively.

The position of the SAA in the old magnetic field models to be used with AP-8 and AE-8 is different from its actual position due to the secular variation on the geomagnetic field (Fraser-Smith 1987). This has important effects on the prediction of trapped particle fluxes for low altitude orbits. Therefore, a correction has been built into TREP: when the NAMESLIST parameter SAAROT is set to 1 (the default value), a correction term \(\Delta \phi(t)\) is added to the
geodetic longitude before the calculation of $(B, L)$ (the actual value of the longitude on the interface file is not changed):

$$\Delta \phi(t) = 0.3^\circ \left( t - \text{EPOCH} \right).$$ \hspace{1cm} (1.2)

where $t$ is the orbit epoch as written in the header of the common interface, and $\text{EPOCH}$ is the epoch of the geomagnetic field model. This correction is also made for the new trapped particle models. The new models were constructed with the IGRF magnetic field model for the epoch of the observations and external magnetic field models for the models that extend beyond the inner radiation belt.

### 1.3 New trapped particle models

Several new proton and electron models have been developed during the TREND-3 study. They are listed in Table 1.1, with their epoch and number of submodels. The models are described in the references given in Table 1.1. The ESA-SEE1 model developed by Vampola (1996) has been implemented as well as the CRRESPRO (Meffert & Gussenhoven 1994) and CRRESELE (Brautigam & Bell 1995) models developed by Phillips Laboratory.

The naming convention for the new models is as follows:

1. the first character of the name indicates whether it is a proton (P) or an electron (E) model;
2. the second character identifies the spacecraft which collected the data (‘A’ stands for AZUR, ‘S’ for SAMPEX, ‘U’ for UARS, ‘C’ for CRRES, and ‘I’ for ISEE);
1.3. NEW TRAPPED PARTICLE MODELS

3. the third character identifies the institute where the model was developed (‘B’ stands for BIRA/IASB, ‘M’ for MSSL or MPA, ‘P’ for PLGD, and ‘S’ for SEE);

4. the last two characters form the year in which the model was developed (not the epoch of the model!).

1.3.1 The ESA-SEE1 model

The ESA-SEE1 model developed by Vampola (1996) is meant to be a replacement of AE-8 MIN, and therefore has the same structure as the NASA model. The model data file ESA-SEE1.DAT provided by Vampola (1996) is not in the same BLOCK DATA format as the version of the NASA models used in TREP. The program VAMPOLA.FOR was developed to rewrite the ESA-SEE1.DAT file in the format used by TREP. The resulting BLOCK DATA file ECS96BD.FOR is linked to TREP, and makes use of the TRARAP subroutine developed by Daly & Evans (1993) to interpolate in the flux map.

1.3.2 The CRRESPRO and CRRESELE models

The CRRESPRO and CRRESELE software packages developed by Phillips Laboratory determine omnidirectional energetic proton and electron fluences for user-defined orbits. The flux models used in these software packages are based on measurements made with the PROTEL (Violet et al. 1993) and HEEF (Hunerwadel et al. 1987) instruments onboard the Combined Release and Radiation Effects Satellite (CRRES), which flew from 25 July 1990 to 12 October 1991 during solar maximum. CRRES was in a geosynchronous transfer orbit with an inclination of 18°, a perigee of 350 km, and an apogee of 33 000 km. It traversed the radiation belts twice per orbit with a period of 9^h5^m2^s.

Both flux models are provided in a series of binary files containing omnidirectional differential flux maps in (L, B/B0) space. In order to implement these flux maps in TREP, we first converted the binary files to ASCII format. Then, new flux map files were created for omnidirectional integral fluxes, which were obtained by integrating the differential fluxes in accordance with the guidelines of Meffert & Gussenhoven (1994) and Brautigam & Bell (1995). Finally, the new flux maps were converted into BLOCK DATA format using the procedure outlined in Sect. 1.3.3.

The conversion from differential flux \( j \) to integral flux \( J \) is defined as:

\[
J(> E_i) = \int_{E_i}^{\infty} j(E) \, dE, \tag{1.3}
\]

where \( E_i \) is the lower energy boundary of channel \( i \). The integration is approximated by a summation:

\[
J(> E_i) = \sum_{k=i}^{N} j(E_k) \Delta E_k, \tag{1.4}
\]
Table 1.2. Integration parameters (MeV) for integral omnidirectional PROTEL flux [from Meffert & Gussenhoven (1994)]

<table>
<thead>
<tr>
<th>Channel</th>
<th>$E_{lo}$</th>
<th>$E_{mid}$</th>
<th>$E_{hi}$</th>
<th>$\Delta E$</th>
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</table>

with $\Delta E_k$ the width of channel $k$ and $N$ the number of channels. The summation for channel $i$ begins at the lower boundary of that channel and ends at the upper boundary of the highest energy channel.

1.3.2.1 The CRRESPRO model

During the TREND-2 study, the CRRESPRO model maps have been converted to the AP-8 model format (Heynderickx 1995), in an attempt to facilitate the implementation of CRRESPRO in TREP, as this approach used the interpolation routine TRARA developed for AP-8 and AE-8. However, this approach required interpolating the pitch angle dependence of the CRRESPRO flux maps in order to convert them to the AP-8 format, which means that the converted flux maps did not contain the original flux values of the model. Therefore, it was decided not to release the UNIRAD version that contained this implementation of CRRESPRO.
1.3. NEW TRAPPED PARTICLE MODELS

The PROTEL instrument  The CRRESPRO flux models are based on in situ flux measurements made by the PROton TELEscope (PROTEL) onboard CRRES. PROTEL had two detector heads which together measured protons from 1 to 100 MeV in 24 energy steps, giving a complete spectrum every 1.024 s. The angular resolution of the detector low (high) energy head was $\pm 10^\circ \times \pm 10^\circ$ ($\pm 12^\circ \times \pm 17^\circ$). A full description of PROTEL is available in Violet et al. (1993) and Lynch et al. (1989).

The PROTEL detectors comprised detector stacks and a logic system that required single or double coincidence to verify that the proper energy particle is counted. In addition, both active and passive shielding were used around much of the detector stack. The detectors were extensively calibrated prior to launch. During calibration, it was found that energetic protons ($> 60$ MeV) incident over a large angular angle with respect to the detector axis could degrade sufficiently in the shielding, pass through the necessary angle in the detector stack, and be counted. This contamination was found to be significant enough for very hard spectra, such as occurs for $L$ values between 1.1 and 1.7, to require correction. A correction scheme was devised based on the assumption of an empty atmospheric loss cone (Gussenhoven et al. 1993).

One channel (15.2 MeV) had significantly lower sensitivity than the other channels and one channel was an overlap channel at 8.5 MeV. To avoid both redundancy and the appearance of discontinuities in differential and integral spectra at certain $L$ values, the 8.5 MeV and 15.2 MeV channels were not used.

Proton flux models  In March 1991, a magnetic storm caused a reconfiguration of the inner magnetosphere, resulting in, among other features, the formation of a second proton belt over a certain energy range. Because of this change, two CRRES models were created. The “quiet” model uses data from July 1990 to March 1991, and the “active” model uses data from March 1991 to October 1991. Note that the terms “quiet” and “active” have no correspondence to quiet and active as determined by the index $K_p$. The channel characteristics of the PROTEL integral flux maps are given in Table 1.2.

The CRRESPRO models are in the form of omnidirectional differential flux maps organised in $(E, L, B/B_0)$ coordinates. The bin widths of the $L$ range are 0.05 $R_E$, while for $B/B_0$ the bin limits are chosen such that they cover approximately $\pm 68^\circ$ magnetic latitude in a dipole field with steps of $2^\circ$.

The CRRESPRO models have been implemented in UNIRAD as one model, called PCP94, containing 2 submodels.

1.3.2.2 The CRRESELE model

The HEEF instrument  The flux models used by CRRESELE are based on in situ flux measurements made by the High Energy Electron Fluxmeter (HEEF) onboard CRRES (Brautigam & Bell 1995). HEEF was designed to measure the flux of 1–10 MeV electrons in 10 differential number flux channels and to return a complete spectrum every 0.512 s. The telescope consists of a well collimated stack of three particle detection elements, the top two being solid state detectors, and the third a bismuth germanate (BGO) crystal. A passive beryllium shield is placed
Table 1.3. Channel energies (MeV) for CRRES/HEEF [from Brautigam & Bell (1995)]

<table>
<thead>
<tr>
<th>Channel</th>
<th>$E_{lo}$</th>
<th>$E_{mid}$</th>
<th>$E_{hi}$</th>
<th>$\Delta E$</th>
</tr>
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<td>0.40</td>
</tr>
<tr>
<td>6</td>
<td>2.90</td>
<td>3.15</td>
<td>3.30</td>
<td>0.40</td>
</tr>
<tr>
<td>7</td>
<td>3.30</td>
<td>3.75</td>
<td>4.10</td>
<td>0.80</td>
</tr>
<tr>
<td>8</td>
<td>4.10</td>
<td>4.55</td>
<td>4.95</td>
<td>0.85</td>
</tr>
<tr>
<td>9</td>
<td>4.95</td>
<td>5.75</td>
<td>6.60</td>
<td>1.65</td>
</tr>
</tbody>
</table>

at the entrance of the telescope to stop lower energy (<0.3 MeV) electrons. A plastic scintillator surrounds the BGO crystal to veto particles that penetrate it from the sides and would otherwise trigger accidental counts.

As the result of extensive post-launch analysis of the actual flight and test data of the HEEF replica, the spectrum energies were revised. The lowest energy differential channel was omitted because of the large uncertainty in its geometric factor, and the highest energy differential channel was omitted because its counting efficiency was so low that it rendered little statistically meaningful data for modelling purposes. The final set of energy channels is listed in Table 1.3.

To facilitate the determination of the integral flux, the fictitious channels 0.a and 1.a have been introduced to fill the gaps in the energy spectrum between channels 0 and 1 and between channels 1 and 2, respectively. The omnidirectional flux at these two fictitious channels is determined by interpolating between the adjacent channels in each case. This procedure is followed to provide a stepwise continuous spectrum, which can then be summed over a discrete set of energies to give the integral omnidirectional flux.

**Electron flux models** The potential problem of energetic proton contamination of HEEF in the inner zone has not been addressed in the construction of the CRRESELE model. The slot region, populated by the temporary third electron belt during the second half of the CRRES mission, would require special treatment in comparison to the outer belt. Therefore, the CRRESELE models are developed for the outer zone electron belts only, and are limited to the interval $2.5 \leq L \leq 6.8$.

The CRRESELE models are in the form of omnidirectional differential flux maps organised in $(E, L, B/B_0)$ coordinates. The bin widths of the $L$ range are 0.05 $R_E$, while for $B/B_0$ the
Table 1.4. Summary of CRRES $A_{p15}$ model separation and statistics [from Brautigam & Bell (1995)]

<table>
<thead>
<tr>
<th>Model Nr.</th>
<th>$A_{p15}$ Range</th>
<th>Average $A_{p15}$</th>
<th>Days/model</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.0–7.5</td>
<td>6.8</td>
<td>13</td>
<td>3.2</td>
</tr>
<tr>
<td>1</td>
<td>7.5–10.0</td>
<td>8.7</td>
<td>83</td>
<td>20.7</td>
</tr>
<tr>
<td>2</td>
<td>10.0–15.0</td>
<td>12.5</td>
<td>69</td>
<td>17.1</td>
</tr>
<tr>
<td>3</td>
<td>15.0–20.0</td>
<td>17.1</td>
<td>82</td>
<td>20.6</td>
</tr>
<tr>
<td>4</td>
<td>20.0–25.0</td>
<td>22.4</td>
<td>72</td>
<td>17.7</td>
</tr>
<tr>
<td>5</td>
<td>25.0–55.0</td>
<td>35.7</td>
<td>83</td>
<td>20.7</td>
</tr>
</tbody>
</table>

bin limits are chosen such that they cover approximately ±68° magnetic latitude in a dipole field with steps of 2°.

Eight models are available. Six of these models are parametrized by geomagnetic activity, i.e. in terms of the $A_{p15}$ index which is defined as the average of the preceding 15 daily values of $A_p$. Six ranges of $A_{p15}$ were defined, for each of which a full electron model was constructed. The statistics of the six $A_{p15}$ ranges are given in Table 1.4. Two additional models, independent of $A_{p15}$, are available as well. For model 6, the entire data base was averaged, providing a mission average model. Model 7 was constructed from the maximum flux found at each $L$ bin of the daily averaged data base.

The CRRESELE models have been implemented in UNIRAD as one model, called ECP95, containing 8 submodels.

1.3.3 Structure of the model data files

For all the models listed in Table 1.1, except the ESA-SEE1 model, a new model format and a set of interpolation routines were developed. The flux maps are stored in data files, one for each model, which are transformed into BLOCK DATA files by the program MODTOBD.FOR. The format of the data files is common to all models and is given in Table 1.5. The number of submodels in this table refers to the number of flux maps in a model corresponding to, for instance, different geomagnetic conditions. For each submodel, the external magnetic field parameters have to be specified.

The BLOCK DATA files generated by MODTOBD.FOR must be linked to TREP, as well as the program file MODINT.FOR, which contains the new interpolation routines for the models that are not in AP-8 format.

The flux maps are given on a three-dimensional rectangular grid in $E$, $L$, and a third coordinate $x$ which is either $B$, $B/B_0$, or the equatorial pitch angle $\alpha_0$. The third coordinate is identified in the third record of the flux map data file as 1, 2, or 3, corresponding to the above coordinates. The directionality of the flux map is given by a flag: 0 for unidirectional, 1 for omnidirectional. The fluxes are considered to be integral fluxes.
Table 1.5. Record structure of the flux map data files. All records except the first two are free-format.

<table>
<thead>
<tr>
<th>Record</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Model name (1X, A5, right justified)</td>
</tr>
<tr>
<td>2</td>
<td>Description label (1X, A8, right justified)</td>
</tr>
<tr>
<td>3</td>
<td>Number of submodels (N), number of energy, L, and coordinate bins, flag (omni- or unidirectional), third coordinate identification, lower flux limit</td>
</tr>
<tr>
<td>4</td>
<td>Model number and epoch for internal magnetic field model, external model number</td>
</tr>
<tr>
<td>5–4+(N)</td>
<td>(K_p), Range number, solar wind density and velocity, (D_{st})</td>
</tr>
<tr>
<td>5+(N)</td>
<td>Bin limits of the energy grid</td>
</tr>
<tr>
<td>6+(N)</td>
<td>Reference values of the energy grid</td>
</tr>
<tr>
<td>7+(N)</td>
<td>Bin limits of the (L) grid</td>
</tr>
<tr>
<td>8+(N)</td>
<td>Reference values of the (L) grid</td>
</tr>
<tr>
<td>9+(N)</td>
<td>Bin limits of the third coordinate grid</td>
</tr>
<tr>
<td>10+(N)</td>
<td>Reference values of the third coordinate grid</td>
</tr>
<tr>
<td>11+(N)</td>
<td>Fluxes for first energy and (L) bin</td>
</tr>
<tr>
<td>(\vdots)</td>
<td></td>
</tr>
</tbody>
</table>

1.3.4 Interpolation in flux maps

The interpolation in the flux maps is performed tri-linearly in \((E, L, x)\) space over the parallelepiped containing the point for which the flux \(f(E, L, x)\) is required. The vertices of this parallelepiped are \((E_1, L_1, x_1)\), \((E_1, L_1, x_2)\), \((E_1, L_2, x_1)\), \((E_1, L_2, x_2)\), \((E_2, L_1, x_1)\), \((E_2, L_1, x_2)\), \((E_2, L_2, x_1)\), and \((E_2, L_2, x_2)\), where \(E \in [E_1, E_2]\), \(L \in [L_1, L_2]\), and \(x \in [x_1, x_2]\). The interpolation function has the form:

\[
   f(E, L, x) = (1 - p)(1 - q)(1 - r)f(E_1, L_1, x_1) + (1 - p)(1 - q)r f(E_1, L_1, x_2) \\
   + (1 - p)q(1 - r)f(E_1, L_2, x_1) + (1 - p)q r f(E_1, L_2, x_2) \\
   + p(1 - q)(1 - r)f(E_2, L_1, x_1) + p(1 - q)r f(E_2, L_1, x_2) \\
   + pq(1 - r)f(E_2, L_2, x_1) + pq r f(E_2, L_2, x_2),
\]

(1.5)
with
\[
\begin{align*}
    p &= \frac{E - E_1}{E_2 - E_1}, \\
    q &= \frac{L - L_1}{L_2 - L_1}, \\
    r &= \frac{x - x_1}{x_2 - x_1}
\end{align*}
\]  

(1.6)

Interpolation of the flux maps between grid values is handled by the subroutine MODINT, which is contained in the program file MODINT.FOR. This subroutine takes as input the number of grid bins in each dimension, the grid limits and reference values, a vector containing the flux values over the grid, and a vector of energies (and its length) plus a pair of \( L \) and third coordinate for which the flux is required. The subroutine returns a vector of fluxes of the same size as the vector of input energies.

The flux maps can cover regions where no measurements were available when building the map. The corresponding value in these bins has to be set to \(-1\). The interpolation program MODINT uses the value \(-1\) as a flag: if a value of \(-1\) is encountered during interpolation, the procedure is stopped and a flux value of \(-1\) is returned. In turn, TREP interprets a flux value of \(-1\) as a sign that the geographic point in question is outside the region covered by the model map, and will issue a warning. The same warning is issued when the geographic point or the energy is completely outside of the model map.

MODINT Can be called directly by TREP, or by the routine that converts unidirectional to omnidirectional fluxes.

### 1.3.5 Conversion to omnidirectional fluxes

The omnidirectional flux \( J \) at a given location \( P \) and energy \( E \) can be expressed in terms of the unidirectional flux \( j \) as:
\[
    J(E) = \int_0^{2\pi} \int_0^\pi j[E, L(\alpha), \alpha, \phi] \sin \alpha \, d\alpha \, d\phi
\]

(Roederer, 1970). Using the relation between the local pitch angle \( \alpha \), the local magnetic field strength \( B \), and the equatorial pitch angle \( \alpha_0 \):
\[
    \frac{\sin^2 \alpha}{B} = \frac{\sin^2 \alpha_0}{B_0},
\]

(1.8)

and assuming that the dependence of the flux on \( \alpha \) is symmetric around \( \pi/2 \), Eq. (1.7) can be rewritten as:
\[
    J(E) = 2 \frac{B}{B_0} \int_0^{2\pi} \int_0^1 j_0[E, L(\alpha_0), \alpha_0, \phi] \cos \alpha_0 \, d\cos \alpha_0 \, d\phi,
\]

(1.9)
Table 1.6. New or modified NAMELIST parameters for TREP

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data Type</th>
<th>Default</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRPMOD</td>
<td>INTEGER</td>
<td>1</td>
<td>Proton model selection:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1: AP-8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2: PAB97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3: PSB97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4: PUB97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5: PCP94</td>
</tr>
<tr>
<td>TREMOD</td>
<td>INTEGER</td>
<td>1</td>
<td>Electron model selection:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1: AE-8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2: ECS96</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3: LANL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4: ECM97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5: EIM97</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6: ECP95</td>
</tr>
<tr>
<td>IMODP</td>
<td>INTEGER</td>
<td>1</td>
<td>Index of proton submodel</td>
</tr>
<tr>
<td>IMODE</td>
<td>INTEGER</td>
<td>1</td>
<td>Index of electron submodel</td>
</tr>
<tr>
<td>OMNIP</td>
<td>INTEGER</td>
<td>1</td>
<td>Flag for conversion to omnidirectional proton fluxes</td>
</tr>
<tr>
<td>OMNIE</td>
<td>INTEGER</td>
<td>1</td>
<td>Flag for conversion to omnidirectional electron fluxes</td>
</tr>
</tbody>
</table>

with

$$\mu_0 = \sqrt{1 - \frac{B_0}{B}}.$$  

Equation (1.10)

The subroutine UNIOMN, contained in MODINT.FOR, uses Eq. (1.9) to derive omnidirectional fluxes from a unidirectional flux map parametrised in terms of \(E\), \(L\), and \(\alpha_0\), and which does not depend on \(\phi\) (the azimuthal dependence of the flux will be implemented later). The integration is carried out using the trapezoid method, so that

$$J(E) = 2\pi \frac{B}{B_0} \sum_{i=1}^{n} \left\{ j_{0,i} \left[ 1 - \frac{B}{B_0} \left( 1 - \cos^2 \alpha_{0,i} \right) \right]^{-1/2} + j_{0,i+1} \left[ 1 - \frac{B}{B_0} \left( 1 - \cos^2 \alpha_{0,i+1} \right) \right]^{-1/2} \right\} \times (\cos \alpha_{0,i+1} - \cos \alpha_{0,i})$$

$$+ 2\pi \frac{B}{B_0} \left\{ j_{0,n} \left[ 1 - \frac{B}{B_0} \left( 1 - \cos^2 \alpha_{0,n} \right) \right]^{-1/2} + j_{0,n+1} \left[ 1 - \frac{B}{B_0} \left( 1 - \cos^2 \alpha_{0} \right) \right]^{-1/2} \right\} \times (\cos \alpha_{0} - \cos \alpha_{0,n}),$$

Equation (1.11)

where \(j_{0,i}\) represents the flux map entry \(j_0[E, L(\alpha_{0i}), \alpha_{0i}]\), and \(n\) is the index of the \(\alpha_0\) grid value preceding \(\alpha_0\).
The integration in Eq. (1.9) can be rewritten in terms of $B$ or $B_0$ to accommodate the flux maps organised in these coordinates. This extension to UNIOMN will be added later.

### 1.3.6 Modifications to TREP

In order to add the new flux models, the TREP program had to be modified in several ways:

1. addition of models in the same format as the NASA models AP-8 and AE-8;
2. addition of models in a different format, including the development of new interpolation routines;
3. addition of a routine for converting unidirectional fluxes to omnidirectional fluxes;
4. modification and extension of the TREP NAMELIST parameters to accommodate the preceding modifications.

The addition of new models has been described in Sects. 1.3.3 and 1.3.4, and flux conversion in Sect. 1.3.5, respectively. The NAMELIST parameters added or modified are listed in Table 1.6. The new version of TREP has been used to produce the spectra used in Part IV of Technical Note 5.
Chapter 2

The UNIRAD library

The development of the UNIRAD library was the task of WP 3.2R of the TREND-3 project. The main objectives of the WP are to improve the software used to build radiation belt models and to predict the radiation experienced by spacecraft in orbit around the Earth. To this effect, other coordinates than \((B, L)\) have been investigated to organise trapped particle fluxes, especially at low altitude. The UNIRAD library provides tools to evaluate these new coordinates, which are related to interactions of particles with the environment, such as the atmospheric material encountered or the energy loss experienced by the trapped particles. The software library therefore implements tools to compute the geomagnetic field, to trace magnetic field lines and drift shells, to determine the minimum altitude of mirror points and to evaluate quantities averaged along a drift trajectory.

2.1 Portability

The library has been developed on a DEC/AXP platform under the operating system OpenVMS. The modules of the library have been written conformably to standard FORTRAN 77, extended by the use of STRUCTURE and RECORD statements. These statements (suggested to us by H. Evans) greatly increase the user friendliness of the library and are generally supported by all FORTRAN 77 compilers.

Machine specific code has been avoided so that the library can be ported on VAX, AXP, HP, Sun, and PC platforms, under different operating systems. Under the operating systems VAX/VMS and OpenVMS/AXP, the library is callable directly from IDL routines, to allow graphical representation and data analysis.

2.2 Sources

The UNIRAD library has been partially derived from the UNIRAD software [programme BLX–TRA, see Heynderickx et al. (1996d)] and from the code developed by Hassitt (1965) at the
University of California (San Diego) provided to BIRA/IASB by C.E. McIlwain. The UNIRAD library subroutines which evaluate the geomagnetic field intensity and McIlwain’s (1961) parameter $L$ are those developed earlier at BIRA/IASB for BLXTRA.

The Hassitt code calculates averages of the atmospheric density over a drift shell. In this code, the Jensen and Cain (1962) magnetic field model and the atmosphere model of Anderson & Francis (1964) are used, respectively, to trace the drift shell and to evaluate the atmospheric number densities. Hassitt (1965) deduced the averaged atmospheric density over a drift shell by weighting the atmospheric number densities with proton cross sections for charge exchange, ionisation and excitation. The Hassitt code has been extended during the course of the TREND-2 project to incorporate additional magnetic field models and the latest atmosphere and ionosphere models (Heynderickx et al. 1995, 1996c). The new version of drift shell tracing programme differs significantly from that of Hassitt. Both codes have been tested for a number of case studies and give comparable results.

Note that similar codes have been developed in the sixties by Cornwall et al. (1965).

2.3 Functionality of the library

A main goal of the UNIRAD library is to evaluate the effects of the interaction of trapped protons with the atmosphere. These effects are usually described with the help of effective scale heights. Different scale heights are obtained from the averages of different physical quantities over one complete longitudinal drift period of the trapped particles. The different physical quantities are, for instance:

- the amount of atmospheric material encountered by the particle;
- the number of charge-exchange collisions;
- the number of ionisation or excitation interactions;
- the energy lost by the trapped particle;
- the pitch angle deviation experienced by the trapped particle.

These quantities are generally expressed per unit of time.

Another main goal of the library is to compute specific coordinates for the geomagnetically trapped particles, for instance:

- the magnetic field intensity $B_m$ at the mirror points;
- the equatorial pitch angle $\alpha_0$;
- the McIlwain (1961) parameter $L$;
- the second and third adiabatic invariants $J, \Phi$;
2.4. **Conventions used in the UNIRAD library**

### 2.4.1 Units

The SI units are used in the UNIRAD library except for the quantities listed in Table 2.1. Angles are given in degrees.

### 2.4.2 Coordinate systems

Geographic positions are generally given in the Geocentric Equatorial (GEO) coordinate system in the form of longitude, colatitude and radial distance from the centre of the Earth. The vector attached to a geographic position is given by its spherical components (e.g. $V_\rho$, $V_\theta$, $V_\phi$, where the subscripts $\rho$, $\theta$ and $\phi$ indicate the radial distance, the colatitude and the longitude in GEO, respectively). The spherical components of a vector are related to its cartesian components by the transformation

\[
\begin{bmatrix}
V_\rho \\
V_\theta \\
V_\phi
\end{bmatrix} =
\begin{bmatrix}
\sin \theta \cos \phi & \sin \theta \sin \phi & \cos \theta \\
\cos \theta \cos \phi & \cos \theta \sin \phi & -\sin \theta \\
-\sin \phi & \cos \phi & 0
\end{bmatrix}
\begin{bmatrix}
V_x \\
V_y \\
V_z
\end{bmatrix}.
\]

One should note that the GEO spherical components and the Geocentric Inertial (GEI) spherical components of any vector are identical.

The library includes several subroutines to convert GEO coordinates to other coordinate systems, and inversely (Russell, 1971).
Table 2.2. URLs of the main pages of the UNIRAD library documentation, relative to the root locator http://www.magnet.oma.be/home/unilib/

<table>
<thead>
<tr>
<th>URL</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>home.htm</td>
<td>Home page of the library</td>
</tr>
<tr>
<td>toc.htm</td>
<td>List of the library components</td>
</tr>
<tr>
<td>faq.htm</td>
<td>Frequently asked questions</td>
</tr>
<tr>
<td>index.htm</td>
<td>Set of links to other pages ordered by keywords</td>
</tr>
<tr>
<td>structure.htm</td>
<td>Description of the FORTRAN structures used by the library</td>
</tr>
</tbody>
</table>

2.4.3 Component identifiers

Each component has a unique identifier in the UNIRAD library.

The FORTRAN COMMON BLOCK components of the library are identified by the two characters UC followed by three digits. The FORTRAN subroutine components of the library are identified by two characters, related to the functionality of the component, followed by three digits. The characters UL, UF, UD, UM, UA, and UT correspond to geomagnetic labels, field line tracing, drift shell tracing, magnetic models, atmospheric models, and general tools, respectively. Each component of the library is uniquely defined by its 3-digit code.

For the variables used in the library, the first character of the identifier indicates the type of the variable. The correspondences between the first character of the identifier and the FORTRAN type of the field are: A–H, P–Y for REAL*8; I, J, K and N for INTEGER*4; L for CHARACTER*(*); M for structure record; and Z for EXTERNAL.

2.4.3.1 Error trapping

When an error occurs in a subroutine of the library, the error diagnostic is returned by way of a negative integer value of the form /BnZr dddii. The first three digits (ddd) are set to the three digits of the name of the subroutine where the error occurs. The last two digits (ii) are used to differentiate between errors inside a same subroutine.

2.5 Library documentation

The documentation of the UNIRAD library is provided in the form of HTML pages. The documentation contains a list of Frequently Asked Questions, a list of all the components of the library, and a detailed description of each component. Some examples are provided as well. The complete set of HTML pages is provided in Appendix A. The Universal Resource Locator (URL) of the main pages of the documentation are listed in Table 2.2.
PROGRAM  sample
 C
 INCLUDE 'structure.h'
 INTEGER*4  kunit, kinit, ifail, kint, kext, nfbm
 CHARACTER*32  lbint, lbext
 REAL*8  year, para(10), amjd, fbm(10), falt
 RECORD /zgeo/  mpos

 DATA kunit, kinit, kint, year/6, 1, 0, 1995.0/
 DATA kext, amjd, para/0., 0., 10*0.0/
 DATA nfbm, falt, fbm/1, -999., 0.4, 9*0./

 C  Initialization
 C
 CALL UT990(kunit, kinit, ifail)
 IF( ifail .LT. 0 )STOP
 CALL UM510(kint, year, lbint, kunit, ifail)
 IF( ifail .LT. 0 )STOP
 CALL UM520(kext, amjd, para, lbext, kunit, ifail)
 IF( ifail .LT. 0 )STOP

 C  Body part
 C
 mpos.radius = 8371.2
 mpos.colat = 50.
 mpos.elong = 30.
 CALL UF420(mpos, fbm, nfbm, falt, ifail)
 IF( ifail .LT. 0 )STOP

 C  Result Printing
 C
 CALL UT991(kunit, ifail)
 IF( ifail .LT. 0 )STOP

 C  END

Figure 2.1. Sample of a FORTRAN programme using the library. It traces the magnetic field line segment passing through a geographic position and limited by a mirror-point magnetic field intensity.
testdef = TRNLOG( 'unilib', content) mod 2
IF NOT testdef THEN $
    MESSAGE, 'The logical UNILIB has to be defined' +$
    ' before running idl'
MESSAGE, 'File ' + strtrim( content, 2) + ' linked' ,$
    /informational

; Data
;
kunit= 6L & kinit= 1L & kint= 0L & year= 1995.0D0
kext= 0L & amjd= 0.0D0 & para= DBLARR(10)
nfbm= 1L & falt= -999.0D0
fbm= DBLARR(nfbm) & fbm(*)= [ 0.4D0 ]
;
; Initialization
;
version = 0L
status = CALL_EXTERNAL( 'unilib', 'ut990', -6L, 1L, version)
IF version LT 0 THEN MESSAGE, 'Unable to initialize' +$
    ' the Unirad Library'
MESSAGE, 'Unirad Library v' + STRCOMPRESS( $ 
    STRING( version*0.01, format= '(f10.2)'), $ 
    /remove_all), /informational
lbint = '12345678901234567890123456789012'
ifail = 0L
status = CALL_EXTERNAL( 'unilib', 'um510', kint, year, $ 
    lbint, kunit, ifail)
IF ifail LT 0 THEN MESSAGE, 'Error' + STRING(ifail) + $ 
    ' in UM510'
lbext = '12345678901234567890123456789012'
ifail = 0L
status = CALL_EXTERNAL( 'unilib', 'um520', kext, amjd, $ 
    para, lbext, kunit, ifail)
IF ifail LT 0 THEN MESSAGE, 'Error' + STRING(ifail) + $ 
    ' in UM520'

Figure 2.2. Sample of an IDL programme using the library. It traces the magnetic field line segment passing through a geographic position and limited by a mirror-point magnetic field intensity.
2.6 Installation and usage

The UNIRAD library contains two items:

1. an object library file (unilib.lib, unilib.olb, or libunilib.a, depending on the operating system);

2. an include file (structure.h).

The object library file is intended to be used by the linker. It includes the object code of all the subroutines contained in the UNIRAD library. The include file contains the definition of all the structures defined in the library. The include file can be called in user source code by the statement INCLUDE ‘STRUCTURE.H’. Both files can be downloaded from the HTML page http://www.magnet.oma.be/home/unilib/hreg.htm.

The functionality of the library has to be accessed with the help of a FORTRAN programme or an IDL routine. Note that except under the operating systems VAX/VMS and OpenVMS/AXP, additional C codes have to be produced to interface the library with the IDL software. A sample FORTRAN programme is given in Fig 2.1. In the programme of Fig 2.1, a magnetic field line segment —passing through the GEO location [2,000 km, 40°N, 30°E] and limited by a magnetic field intensity of 0.4 Gauss— is computed and printed. In this sample, the library has been initialized with the IGRF-95 geomagnetic field model. Note that the
HTML documentation (see Appendix A) contains help for each subroutine, including synopsis, description, dependencies and a list of reported bugs.

The IDL programme corresponding to the FORTRAN programme of Fig 2.1 is listed in Fig 2.2. One should remember that the implementation displayed in Fig 2.2 is specific to the OpenVMS operating system. Further information on the IDL routine \texttt{CALL\_EXTERNAL} can be found in Chapter 18 of the \textit{IDL user’s guide}.

### 2.6.1 Initialization

Before most of the library subroutines can be used, the different \texttt{COMMON BLOCK}s of the \texttt{UNIRAD} library have to be initialized. The following initialisation subroutines are provided inside the library:

- \texttt{UT990}: to initialize the different \texttt{COMMON BLOCK}s of the \texttt{UNIRAD} library;
- \texttt{UM510}: to select a geomagnetic field model;
- \texttt{UM520}: to select an external magnetic field model;
- \texttt{UA610}: to select an atmospheric, ionospheric and/or plasmaspheric model.

### 2.6.2 Main subroutines

The subroutines of the \texttt{UNIRAD} library can be divided into three sets:

1. the main subroutines;
2. the internal subroutines;
3. the miscellaneous subroutines.

The internal subroutines are subroutines called by other subroutines of the library and as such, are not directly accessed by the user. The main subroutines are top-level subroutines, they include:

- \texttt{UL220}: to evaluate $B_m$, $L$, $K = I \sqrt{B_m}$ for a set of field line segments passing through a given position where $I$ is the integral invariant function;
- \texttt{UD310}: to trace a magnetic drift shell;
- \texttt{UD320}: to average physical quantities over a drift shell;
- \texttt{UD330}: to evaluate the third invariant;
- \texttt{UF420}: to trace a magnetic field line segment passing through a given position;


2.7. MODELS INCLUDED IN THE LIBRARY

- UM530: to evaluate the magnetic field vector;
- UA630: to evaluate the atmospheric number and mass densities;
- UA636: to evaluate the atmospheric number or mass densities weighted by cross sections;
- UT980: to print the library error messages.

The miscellaneous subroutines are subroutines called by other subroutines of the library but that users can also use directly (e.g. UM539, UT540, UT541, UT550).

The HTML pages relative to the main subroutines are a good starting point to learn about the UNIRAD library. Another starting point to understand the philosophy of the library are the examples provided in the HTML documentation.

2.7 Models included in the library

2.7.1 Magnetic field models

The library includes some internal and external magnetic field models. The set of internal magnetic field models is composed of:

1. the International Geomagnetic Reference Field (IGRF) model;
2. the Jensen & Cain (1962) model;
3. the GSFC12/66 model (Cain et al., 1967);
4. a simple centred tilted dipole magnetic field.

The IGRF model is the empirical representation of the Earth’s magnetic field recommended for scientific use by the International Association of Geomagnetism and Aeronomy (IAGA). The Jensen & Cain (1962) model and the GSFC12/66 model (Cain et al. 1967) are included in the library since they have been used to produce the NASA trapped radiation belt models AP-8 and AE-8 (Heynderickx et al. 1996ab). The simple dipole magnetic field model is deduced from a truncation to the second order of the expansion of the IGRF geomagnetic field models.

Eight external magnetic field models are included in the library:

1. Mead & Fairfield (1975) model;
2. Tsyganenko (1987) short model;
3. Tsyganenko (1987) long model;
4. Tsyganenko (1989) model;
5. Olson & Pfitzer (1977) quiet model;
6. Olson & Pfitzer (Olson et al. 1988) dynamic model;
7. model T96 (Tsyganenko & Stern 1996);

The Mead & Fairfield (1975) and Tsyganenko (1987, 1989) magnetic field models depend on levels of magnetic disturbance parameterized by $K_p$. The Tsyganenko (1989) model is tilt dependent and was primarily developed as a tail model. The Olson & Pfitzer (1977) model is an average models fit to quiet conditions without parameter. The dynamic model (Olson et al. 1988) is a scalable model depending upon the activity level but without a tilt dependence. The scale factors are determined by the activity index $D_{st}$ and the standoff distance of the magnetopause determined by the solar wind density and velocity. The model T96 (Tsyganenko & Stern 1996) depends on the solar wind pressure and the $B_Z$ and $B_Y$ components of the interplanetary magnetic field. The Ostapenko-Maltsev (1997) model was obtained by a least-square fit of fourth order polynomials to 14,000 vector field measurements from the data base of Fairfield et al. (1994). The model depends on the $D_{st}$ and $K_p$ indices, as well as on the solar wind dynamic pressure and the $z$ component of the interplanetary magnetic field.

The different magnetic field models are accessible through subroutines UM510, UM520 and UM530.

2.7.2 Atmospheric models

Some atmospheric models as well as ionospheric and plasmaspheric extensions are accessible from the library. The library includes:

1. the neutral atmosphere empirical model MSISE-90 (Hedin 1991), improved by Chabrillat (1995);
2. the Anderson and Francis (1964) atmosphere and ionosphere model;
3. the international reference ionosphere IRI-90 (Bilitza 1990);
4. a plasmaspheric extension of IRI-90 (Carpenter & Anderson 1992);
5. a simple atmospheric model based on a table of Allen (1985);
6. the atmospheric model used by Pfitzer (1990).

The MSISE-90 atmospheric model is a very comprehensive reference model for the upper atmosphere based on measurements from several rockets, satellites and incoherent scatter radars. It is extended to the middle and lower atmosphere on the base of a tabulation of zonal average temperature and pressure. The IRI-90 ionospheric model is a reference model for the ionospheric densities and temperatures. Although outdated and obsolete, the Anderson and Francis
2.8. Magnetic drift shell

(1964) model is included in the library since it had been originally used by Hassitt (1965). The last two models are simplified models which provide only the total atmospheric mass density.

The atmospheric models and their ionospheric and plasmaspheric extensions are accessible through the use of the subroutines UA610 and UA630.

2.7.3 Collisional cross section models

Two models to evaluate the cross sections for collisions between protons and atmospheric particles are included in the library:

1. the Hassitt (1965) cross sections;
2. a collection of cross sections compiled by Pierrard (1994).

The Hassitt model is included for historical reason and includes cross sections from unreferenced origin. Pierrard’s (1994) compilation includes cross sections of charge exchange, ionisation, excitation and nuclear collision from several sources. Both models are accessible through the use of the subroutines UA636 and UA637.

2.8 Magnetic drift shell

The tracing of magnetic drift shells is the central part of the UNIRAD library: when a drift shell is traced with the help of the library, more than twenty subroutines of the library are used. The tracing of a drift shell is mainly controlled by the subroutines UD310, UF410 and UF420. The algorithm is separated in two parts, the magnetic field line tracing and the drift shell tracing.

2.8.1 Field line tracing

A segment of a magnetic field line is described as a set of elementary segments. Each segments is characterized by its GEO location, arc length, radius of curvature, . . . (see the definition of the FORTRAN structure /zseg/). The field line segments are traced by the subroutine UF420 and its dependencies. The algorithm has been derived from Pfitzer’s (1991) one and is still based on Gill’s (1951) 4-order Runge-Kutta integration method. The subroutine UF420 gets, as input arguments, the GEO coordinates of a point on the magnetic field line, a set of mirror-point magnetic field intensities and, eventually, an altitude boundary. As result, the subroutine traces the segment of the magnetic field line that includes all the pair of mirror points and eventually the foot points of the magnetic field line when an altitude boundary has been provided. Note that the resulting field segment does not necessarily include the starting point.

When the subroutine UF420 is called, it checks first that the starting point is located inside the most external boundary conditions (the boundary conditions are defined by the mirror-point magnetic field intensities and the altitude boundary). If it is not the case, the field line is traced in
the direction of decreasing field intensity until a boundary condition is reached. The field line segment is then firstly traced in the increasing field intensity direction until all the boundary conditions have been reached. Afterwards, this first part of the field line segment is reversed and the rest of the field line segment is traced in the opposite direction. During this process, each time when a boundary condition is overstepped, the field line tracing is suspended and the exact location on the field line corresponding to the boundary condition is calculated by an iterative search. Such an iterative search is also applied when an extremum of the magnetic field line intensity is overreached.

Note that the integral invariant function $I$ is not evaluated during the field line tracing, but that the intermediate $B$ value of the Runge-Kutta integration step are stored in order to calculate the value of $I$ afterwards (see subroutine UL230).

### 2.8.2 Drift shell tracing

Magnetic drift shells are defined by their mirror-point magnetic field intensity $B_m$ and McIlwain shell parameter $L$: the drift shell $(B_m, L)$ consists of a family of magnetic field line segments

- which are bounded by the magnetic field intensity $B_m$, and,
- the integral invariant function $I$ which corresponds to the requested $L$ value.

Drift shells can be traced by subroutine UD310. The input arguments of the subroutine are $B_m$, $L$ and the number $n$ of field line segments to be traced. As output the subroutine returns the set of field line segments such that the longitudes of the points with the lowest magnetic field intensity along each field line segment are equidistant. The subroutine UD310 calls the subroutine UF410, $n$ times, to find and trace the different field line segments.

The arguments of the subroutine UF410 are $B_m$, $L$, a longitude and an altitude range. When the subroutine is entered, it seeks first a magnetic field line for which the point $P_{min}$ with the lowest magnetic field intensity has the requested longitude and lies in the given altitude range. If the magnetic field intensity at $P_{min}$ is greater than $B_m$, the lower limit of the altitude range is set to the altitude of the current $P_{min}$ and the programme seeks for another magnetic field line.

When a field line which satisfied all conditions on $P_{min}$ is obtained, the $I$ value of the field line segment (delimited by the magnetic field intensity $B_m$) is evaluated and compared to the expected value. According to the value obtained for the integral invariant function, the altitude range of the point $P_{min}$ is adapted:

- when the invariant function is larger than the requested $I$, the upper limit of the altitude range is set to the altitude of the current $P_{min}$;
- when the invariant function is lower than the requested $I$, the lower limit of the altitude range is set to the altitude of the current $P_{min}$.

Afterwards, a new magnetic field line is sought again.
### 2.8. Magnetic drift shell

#### Table 2.3. Subroutines implemented in the UNIRAD library

<table>
<thead>
<tr>
<th>Name</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>UL220</td>
<td>get information on a magnetic field line segment</td>
</tr>
<tr>
<td>UL230</td>
<td>evaluate the integral invariant coordinate $I$</td>
</tr>
<tr>
<td>UL240</td>
<td>evaluate the Hilton's function</td>
</tr>
<tr>
<td>UL242</td>
<td>inverse the Hilton function</td>
</tr>
<tr>
<td>UL245</td>
<td>equatorial pitch angle</td>
</tr>
<tr>
<td>UD310</td>
<td>trace a magnetic drift shell</td>
</tr>
<tr>
<td>UD315</td>
<td>search the mirror point with the lowest altitude</td>
</tr>
<tr>
<td>UD316</td>
<td>search the equatorial point with the lowest magnetic field intensity</td>
</tr>
<tr>
<td>UD319</td>
<td>transfer a field line segment from common block UC170 to UC130</td>
</tr>
<tr>
<td>UD320</td>
<td>evaluate a double time integral over a drift shell</td>
</tr>
<tr>
<td>UD321</td>
<td>evaluate a time integral over a magnetic field line</td>
</tr>
<tr>
<td>UD327</td>
<td>search an extremum</td>
</tr>
<tr>
<td>UD328</td>
<td>evaluate the second derivative of $B$</td>
</tr>
<tr>
<td>UD329</td>
<td>interpolate between two or three points</td>
</tr>
<tr>
<td>UD330</td>
<td>evaluate the third invariant</td>
</tr>
<tr>
<td>UD331</td>
<td>evaluate the magnetic flux through a spherical cap</td>
</tr>
<tr>
<td>UD332</td>
<td>evaluate the magnetic flux through a spherical pie</td>
</tr>
<tr>
<td>UF410</td>
<td>search the geographic position of a magnetic field line</td>
</tr>
<tr>
<td>UF411</td>
<td>search a local magnetic equator</td>
</tr>
<tr>
<td>UF415</td>
<td>rebuild the labels of the field line</td>
</tr>
<tr>
<td>UF420</td>
<td>trace a magnetic field line segment passing through a given position</td>
</tr>
<tr>
<td>UF421</td>
<td>initialize and close a field line segment</td>
</tr>
<tr>
<td>UF422</td>
<td>follow a field line until a boundary condition is reached</td>
</tr>
<tr>
<td>UF423</td>
<td>Runge Kutta step</td>
</tr>
<tr>
<td>UF424</td>
<td>search the lowest $B$ value</td>
</tr>
<tr>
<td>UF425</td>
<td>evaluate the curvature of the field lines</td>
</tr>
<tr>
<td>UF426</td>
<td>interpolating an extremum of $B$</td>
</tr>
<tr>
<td>UF427</td>
<td>interpolating a value of $B$</td>
</tr>
<tr>
<td>UF428</td>
<td>interpolating an altitude</td>
</tr>
<tr>
<td>UF429</td>
<td>transpose a field line segment</td>
</tr>
<tr>
<td>UM510</td>
<td>select a geomagnetic field model</td>
</tr>
<tr>
<td>UM511</td>
<td>set the Jensen &amp; Cain model coefficients</td>
</tr>
<tr>
<td>UM512</td>
<td>set the GSFC 12/66 model coefficients</td>
</tr>
<tr>
<td>UM513</td>
<td>set the DGRF/IGRF model coefficients</td>
</tr>
<tr>
<td>UM515</td>
<td>perform a Schmidt normalisation</td>
</tr>
<tr>
<td>UM517</td>
<td>transform from Schmidt to Kluge normalisation</td>
</tr>
<tr>
<td>UM520</td>
<td>select an external magnetic field model</td>
</tr>
<tr>
<td>UM521</td>
<td>ground disturbances from $K_p$</td>
</tr>
<tr>
<td>UM522</td>
<td>position of the Sun</td>
</tr>
</tbody>
</table>
Table 2.3. (continued)

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UM523</td>
<td>GEO to GSM transformation</td>
</tr>
<tr>
<td>UM524</td>
<td>GEO to SM transformation</td>
</tr>
<tr>
<td>UM530</td>
<td>evaluate the magnetic field vector</td>
</tr>
<tr>
<td>UM531</td>
<td>geomagnetic field</td>
</tr>
<tr>
<td>UM532</td>
<td>external magnetic field</td>
</tr>
<tr>
<td>UM533</td>
<td>distance to the magnetopause</td>
</tr>
<tr>
<td>UM535</td>
<td>geocentric to geodetic transformation</td>
</tr>
<tr>
<td>UM536</td>
<td>geodetic to geocentric transformation</td>
</tr>
<tr>
<td>UM537</td>
<td>Kluge evaluation of the geomagnetic field</td>
</tr>
<tr>
<td>UM539</td>
<td>evaluate the magnetic field</td>
</tr>
<tr>
<td>UT540</td>
<td>compute modified Julian Day from date</td>
</tr>
<tr>
<td>UT541</td>
<td>convert spherical coordinates to cartesian coordinates</td>
</tr>
<tr>
<td>UT542</td>
<td>convert spherical vector components to cartesian components</td>
</tr>
<tr>
<td>UT545</td>
<td>compute date from modified Julian Day</td>
</tr>
<tr>
<td>UT546</td>
<td>convert cartesian coordinates to spherical coordinates</td>
</tr>
<tr>
<td>UT547</td>
<td>convert cartesian vector components to spherical components</td>
</tr>
<tr>
<td>UT550</td>
<td>select a coordinate transformation</td>
</tr>
<tr>
<td>UT551</td>
<td>initialize an Euler rotation matrix</td>
</tr>
<tr>
<td>UT552</td>
<td>initialize a quaternion rotation matrix</td>
</tr>
<tr>
<td>UT555</td>
<td>coordinate conversion</td>
</tr>
<tr>
<td>UT556</td>
<td>vector conversion</td>
</tr>
<tr>
<td>UA610</td>
<td>select an atmospheric, ionospheric and/or plasmaspheric model</td>
</tr>
<tr>
<td>UA612</td>
<td>provide a list of atmospheric constituents</td>
</tr>
<tr>
<td>UA630</td>
<td>evaluate the density numbers and mass densities</td>
</tr>
<tr>
<td>UA631</td>
<td>Anderson and Francis atmosphere</td>
</tr>
<tr>
<td>UA632</td>
<td>MSISE-90 atmosphere</td>
</tr>
<tr>
<td>UA633</td>
<td>IRI-90 ionosphere</td>
</tr>
<tr>
<td>UA634</td>
<td>compute mass density from number density</td>
</tr>
<tr>
<td>UA635</td>
<td>evaluate the Debye length</td>
</tr>
<tr>
<td>UA636</td>
<td>evaluate a weighted atmospheric mass</td>
</tr>
<tr>
<td>UA637</td>
<td>proton cross sections</td>
</tr>
<tr>
<td>UA638</td>
<td>Hassitt proton cross sections</td>
</tr>
<tr>
<td>UA639</td>
<td>equatorial electron density</td>
</tr>
<tr>
<td>UT980</td>
<td>print the error messages</td>
</tr>
<tr>
<td>UT981</td>
<td>search information on a subroutine</td>
</tr>
<tr>
<td>UT982</td>
<td>print the link between two subroutines</td>
</tr>
<tr>
<td>UT985</td>
<td>transfer a field line of the drift shell to IDL</td>
</tr>
<tr>
<td>UT986</td>
<td>pass general variables to IDL</td>
</tr>
<tr>
<td>UT990</td>
<td>initialize the UNIRAD library</td>
</tr>
<tr>
<td>UT991</td>
<td>print the magnetic field line</td>
</tr>
</tbody>
</table>
2.9. **Content of the library**

The complete set of subroutines implemented in the library is listed in Table 2.3.

<table>
<thead>
<tr>
<th>UT992</th>
<th>print the magnetic drift shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>UT993</td>
<td>store a magnetic field drift shell</td>
</tr>
<tr>
<td>UT998</td>
<td>evaluate the magnetic field vector and the normal to the field line</td>
</tr>
<tr>
<td>UT999</td>
<td>radius of curvature in a dipolar magnetic field</td>
</tr>
</tbody>
</table>

This iterative process is repeated until the integral invariant function is found to be equal to the expected $I$ within a tolerance specified in the common block UC190. During the iterations, the programme is aborted when

1. the number of iterations exceeds 20;
2. the upper and lower limits of the altitude range become equal;
3. an unrecoverable error occurs during the field line tracing.

In that case, the subroutine UF410 returns with a specific error diagnostic.

The subroutine UD310 succeeds only when all the magnetic field line segments of the drift shell have been successfully traced.
References


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Appendix A

HTML Help pages for the UNIRAD library

The user documentation for the UNIRAD library has been written in the HyperText Mark-up Language (HTML). The documentation consists of:

- Frequently Asked Questions (FAQs) and their answers, available at:

- a set of pages with a detailed description of the subroutines making up the library, one HTML page per subroutine. These HTML pages are made up of the following sections: Name, Synopsis, Arguments, Description, Dependencies, See Also, and Examples. The pages can be accessed directly from a Table of Contents (TOC) page. In addition, links are provided between related pages. The URL of the TOC page is http://www.magnet.oma.be/home/unilib/toc.htm.

A hardcopy of the complete set of HTML pages is provided in this Appendix.