Chapter 1

General overview and results

In this chapter, we present an overview of the results obtained during this study and the development of new tools and models for the radiation belt environment. The main results and output produced during this ESA/ESTEC contract are presented following the order of the chapters in this final report.

The present study is the follow-up of the TREND-2 study (ESA/ESTEC TRP Contract No. 9828/92/NL/FM), the final report of which was issued in February 1995 (copies are available from E.J. Daly at ESTEC/WMA, Keplerlaan 1, PO Box 299, 2200 AG Noordwijk, The Netherlands, or from J. Lemaire, BIRA/IASB, Ringlaan 3, 1180 Brussel, Belgium). This final report contains an introductory description of the radiation belts and the physical processes in the magnetosphere. Other review papers can be found in AGU Monograph **97**, *Radiation Belts: Models and Standards*, eds. J.F. Lemaire, D. Heynderickx, and D.N. Baker (1996).

Figure 1.1 lists the WP numbers and content, the initials of the contributors and their institutes, the type, format, and identification number of the deliverables associated with each WP, and their status in October 1997 and in March 1998, when the TREND-3 project was terminated.

1.1 Improvements of UNIRAD

The `UNIRAD` software package is used by ESA to evaluate fluxes and fluences of energetic particles for space missions, as well as mission doses and damage equivalent fluences. A number of improvements of this package has already been made by BIRA/IASB during the TREND (1989–1992) and TREND-2 (1993–1995) studies. In the course of the present TREND-3 study, BIRA/IASB has added further features:

- new trapped particle models;
- two new modules to derive directional fluxes from omnidirectional models;
- a Fortran library of routines related to magnetic coordinates;

WP	Content	Authors	Institutes	Type of document	Format	Delivery date	Status Oct. 97	Status March 98
1.1;1.1R	Analysis of ISEE Data	EK;RF;GL	MPAe	TN1	LATEX	Jun 97	6hc delivered	Done
1.2; 1.2R	Improved MEA-3 MSSL model	DR; SS	MSSL	TN2	LATEX	March 96	2hc delivered	Done
1.3	Model unification MEA3-ISEE		MSSL	TN3			Not available	Not done
1.4	Analysis of Hipparcos			TN4			Cancelled	Cancelled
2.1; 2.1R; 2.2R	Flight Data Comparisons	DH; MK	BIRA-IASB	TN5(1;2;3)	LATEX	June 97	partly done	Done
2.2	Trapped proton anisotropy at low altitudes	MK;JL	BIRA-IASB	TN6	LATEX	April 66	6hc delivered @ ESTEC	Done
2.3R	Improved trapped proton anisotropy description	MK ; DH	BIRA-IASB	TN 6(2)	LATEX	nov-97	6hc delivered @ ESTEC	Done
2.3	Secondary particle production		BIRA-IASB	TN7			Cancelled	Cancelled
4.1R	Radiation loss injection study	DR	MSSL	TN8	Mac Vers.	nov-97	Preliminary draft	Done
4.2R	METEOSAT-3 analysis: corrections & new DB	DR; SS	MSSL	TN9	LATEX	Jul 97	available; 1hc	Done
3.2R	UNIRAD Improvements and subroutine Library	DH; MK	BIRA-IASB	TN10	LATEX	nov-97	available; 1hc	Done
1.1;1.1R	ISEE DB frame binned flux frame and software description	EK;RF;GL	MPAe	DDD	LATEX	Jun 97	available; 6hc delivered	Done
1.1;1.1R	ISEE DB frame binned flux frame and software	EK;RF;GL	MPAe	SW; DB	LATEX	Jun 97	available; delivered	Done
1;2; 1.3R	Description document for users of MasterScience File : ISEE-2	AJ; GJ	MSSL	DDD	typed	Dec 96	available; 1hc	Done
1;2; 1.3R	ISEE-2 electron RB model	AJ; GJ	MSSL	SW; DB	fortran	nov-97	Not available yet	Done
1.2; 1.2R	MEA3MSSL model software documents	DR; SS	MSSL	SRD; ADD; DDD	LATEX	Aug 96	available; 2hc delivered	Done
	UNIRAD v 3.0 Trapped Radiation Software	DH; MK; JL	BIRA-IASB	User manual	LATEX	nov-96	available; 2hc delivered	Done
	UNILIB subroutines documentation	MK; JMV	BIRA-IASB	User manual	html	Jul 97	available	Done
	UNILIB subroutines PSS-05	MK	BIRA-IASB	URD; SRD	LATEX	Jul 97	available	Done
	UNILIB subroutines	MK	BIRA-IASB	SW	fortran	Jul 97	available; on WWW	Done
	UNIRAD package	DH; MK	BIRA-IASB	SW	fortran; IDL	nov-96	available; to customers	Done
	proton AZUR model / PAB	DH	BIRA-IASB	SW;DB	fortran; IDL	Jul 97	available	Done
	proton SAMPEX model / PSB	DH	BIRA-IASB	SW;DB	fortran; IDL	Jul 97	available	Done
	proton UARS model / PUB	MK; ME		SW;DB	fortran	Jul 97	available	Done
	electron MEA3 / EMM	AD; DR; GL	MSSL	SW;DB	fortran	nov-97	available	Done
	electron ISEE / EIM	AD; DR; GL	MSSL	SW;DB	fortran	nov-97	available	Done
	ESA-SEE1 neural Network model implemetation	DH	BIRA-IASB	SW;DB	fortran	Jul 97	available	Done
	electron METEOSAT-P2 / EMsM	AD; DR; GL	MSSL	SW;DB	fortran	mars-98	not available	Done
	Radiation Environment of Astronomy and LEO Missions	All	BIRA-IASB MSSL MPAe	FR	LATEX	nov-97	not available	Done

Figure 1.1. WP numbers and content, initials of the contributors and their institutes, type, format, and identification number of the deliverables associated with each WP, and their status in October 1997 and in March 1998

- improvement of the functionality of the package, including added graphical capabilities.

1.1.1 New trapped particle models

The new trapped particle models are based on data from the AZUR, SAMPEX, UARS, CRRES, and ISEE missions (Table 2.1 contains a list of the new models). The coordinate systems and final format used for these new models are different from those of the NASA models AP-8 and AE-8 (Vette 1991b). In particular, the equatorial pitch angle α_0 has been used instead of B/B_0 to construct the new flux maps. Consequently, a new interpolation routine (`MODINT`) was written for the new flux maps to replace the `TRARA` routine that is used with AP-8 and AE-8. The AP-8 and AE-8 models are still in `UNIRAD`, and their implementation has not been changed. The new trapped particle models are described in Chapters 4, 5, 6, 7, 8, and 9.

In a parallel study (ESA/ESTEC/WMA/P.O.15135), A.L. Vampola (1996) has developed a new trapped electron model from the CRRES/MEA data, using a neural network. The resulting model, called ESA-SEE1, is meant to be a replacement of AE-8 MIN, and has been implemented in `UNIRAD` in the present study. The new model is in the same format as the AE-8 model.

1.1.2 Directional flux modules

Another improvement of the `UNIRAD` package is the addition of two modules to derive directional proton fluxes from an omnidirectional model (see Sect. 1.2). The direction or field of view for which the unidirectional flux is wanted, can be specified in a frame of reference attached to the orbiting satellite.

1.1.3 `UNILIB` Library

A third enhancement of the `UNIRAD` software suite consists of the building of a structured, modular, user friendly, and well documented library of subroutines which provides the following functionalities:

- coordinate transformations between the most used coordinate systems;
- magnetic field line tracing, including the location of mirror points, foot points, and equatorial crossing;
- magnetic drift shell tracing;
- averaging of atmospheric parameters (densities and temperatures) over drift shells;
- evaluation of the magnetic flux for a drift shell, and the third adiabatic invariant.

The subroutines making up the library were written in Fortran. The library is available on the World Wide Web (WWW) (`http://www.magnet.oma.be/unilib/home.htm`), together with comprehensive documentation in HTML format, a set of examples, and a list of frequently asked questions. The library is described in Chapter 2 of this Final Report and in Technical Note 10.

1.2 Anisotropy of trapped proton fluxes

The widely used NASA AP-8 models provide omnidirectional proton fluxes for a wide range of energies over the whole region of the trapped proton belts. At low altitudes, the gyroradius of protons with energies above 50 MeV is comparable with the scale height of their flux with respect to altitude. For $L \leq 2$, the proton flux scale height is determined by the thermospheric density scale height, which varies between 50 and 100 km depending on the level of solar activity. The resulting steep proton flux gradient causes an asymmetry in the flux registered by spacecraft, both in pitch angle and in azimuth. The azimuthal asymmetry is traditionally called the East-West asymmetry. Physical models of the East-West asymmetry presented in the literature are reviewed in Technical Note 6 and in Chapter 3 of this Final Report.

1.2.1 Conversion of omnidirectional to unidirectional fluxes

The most commonly used model of the proton flux asymmetry has been upgraded and implemented in `UNIRAD`, in the form of two modules: `ANISO` and `ANISOPOS`.

Both modules use an existing model of the azimuthal asymmetry, and offer a choice of two models of the pitch angle distribution. From the omnidirectional flux obtained with the `TREP` module, they derive the unidirectional proton flux for a set of directions specified by the user in a reference frame attached to an orbiting, non-spinning satellite (`ANISO`) or for a user defined point in space (`ANISOPOS`). `ANISO` Also provides the unidirectional fluence over a spacecraft orbit.

The implementation of these new modules are described in Technical Note 6 and in Chapter 3 of this Final Report.

1.2.2 Generalised anisotropy model

In Part 2 of Technical Note 6, a new method is presented to describe the azimuthal asymmetry of the low altitude trapped proton flux. Instead of deriving unidirectional fluxes from given omnidirectional fluxes, this approach starts out from the new unidirectional flux models developed in this study (see Sects. 1.3–1.5). The new method uses a natural coordinate system attached to the magnetic field distribution to provide the full angular dependence of the trapped proton flux. As it is constructed from unidirectional flux maps, the influence of the atmosphere on the flux distribution is implicitly taken into account. The new method has been shown to be more consistent than the methods reviewed in Part 1 of Technical Note 6.

1.3 AZUR/EI-88 Data base and radiation belt model

The AZUR satellite which operated in a low Earth orbit for six months in 1969 and 1970, had on board two energetic particle telescopes, one orientated perpendicular to the magnetic field, and one at an angle of $45°$ with the magnetic field vector. These detectors measured proton fluxes in six energy channels ranging from 1.5 to 104 MeV. About three months of data have been archived at NSSDC

A copy of the data set was obtained from NSSDC and installed at BIRA/IASB. The count rates have been corrected for the telescope opening angle with the method described in Appendix A. The corrected fluxes were binned into an (E, L, α_0) map, which was implemented in `UNIRAD`. The new flux map (called PAB97) was compared to AP-8 MAX, from which it appears that AP-8 MAX overestimates the low energy proton flux for $L \leq 2$. The instrument characteristics, the processing of the data, and the building of the new model are summarised in Chapter 4 of this Final Report and described in detail in Technical Note 5.

1.4 SAMPEX/PET Data base and radiation belt model

The SAMPEX spacecraft was launched in 1992 into a low Earth orbit and is still operational. Its instrument complement includes an energetic particle telescope, which observes (besides electrons and high Z ions) protons in the energy range 18.5–500 MeV. The proton data have been made available to BIRA/IASB by R.H. Mewaldt, CALTECH, and J.B. Blake, Aerospace Corporation, for the purpose of building a new directional trapped proton model.

The countrates for one year of data (1994–1995) have been corrected for the telescope opening angle with the method described in Appendix A. The corrected fluxes were binned into an (E, L, α_0) map, which was implemented in `UNIRAD`. The new flux map (called PSB97) was compared to AP-8 MIN, from which it appears that AP-8 MIN overestimates the proton flux for $L \leq 2$. The instrument characteristics, the processing of the data, and the building of the new model are summarised in Chapter 5 of this Final Report and described in detail in Technical Note 5.

1.5 UARS/PEM Data base and radiation belt model

The low Earth orbiting UARS spacecraft is equipped with a series of instruments designed to study the upper atmosphere. One set of instruments consists of four energetic particle telescopes, with different orientations to the zenith direction. These instruments measure proton count rates in the energy range 0.5–150 MeV. The PEM proton data have been made available to BIRA/IASB by SwRI for the purpose of building a new directional trapped proton model.

The count rates for one year of data (1991–1992) from one of the telescopes have been corrected for the telescope opening angle with the method described in Appendix A (the detailed angular response function of the telescope has not been made available in time by the instrument builders, so that a best guess for this function had to be used). The corrected fluxes were binned into an (E, L, α_0) map, which was implemented in UNIRAD. The new flux map (called PUB97) was compared to AP-8 MAX, from which significant differences are evident, especially in the energy range 70–100 MeV (the data should however, be re-examined when the actual angular response function of the instruments becomes available from the instrument builders). The instrument characteristics, the processing of the data, and the building of the new model are summarised in Chapter 6 of this Final Report and described in detail in Technical Note 5.

1.6 Comparisons of the new trapped proton models

In Chapter=7, we intercompare the flux maps obtained from the AZUR, SAMPEX and UARS data. The AP-8 directional fluxes are added to the comparisons to put the results into perspective. The usage of the models derived from the new flux maps, i.e. their implementation in TREP, is described in Technical Note 10 and in Chapter 2 of this Final Report.

As the new trapped proton models are based on data from low altitude satellites, their use is limited to predictions for low altitude missions. The new models, as well as the AP-8 models, have been applied to a typical MIR or Space Station orbit. The model limitations have been demonstrated on a GTO orbit. All model calculations were made with the UNIRAD programme suite.

1.7 ISEE/WAPS Data base and radiation belt model

The ISEE 1&2 electron measurements were made with the WIM instruments, which are described in detail in Technical Note 1, and briefly in Chapter 8 of this Final Report. The data from these instruments have been retrieved and stored in a new data base. The magnetic field components measured during the ISEE missions (Russell 1987) have been included in the data base, as well as the model magnetic field components obtained with the BLXTRA software. The calculated direction of the magnetic field was used to determine the pitch angles for the individual flux measurements of ISEE 2. A quality flag was added to the data base for each data frame, indicating the relative difference between the observed and calculated magnetic field intensity. The comparison of measured and model magnetic field components is illustrated in a series of plots and histograms in Technical Note 1.

The electron fluxes have been binned in (E, L, α_0) coordinates to produce a new trapped electron model, in the format described in Chapter 2. The ISEE data base and electron belt model cover more than ten years of data, nearly one solar cycle.

1.8 CRRES/MEA Data base and radiation belt model

The CRRES/MEA electron data set has been described and analysed in the TREND-2 study. It appeared, for a number of reasons, that the data had to be re-analysed after applying an additional correction to depressed count rates in the inner radiation belt caused by instrument saturation. At the same time, the time resolution of the data base was doubled to increase the equatorial pitch angle resolution and to expand the data coverage.

The new MEA data base is thus an improvement over the data base produced in TREND-2. The radiation belt model based on the new data base is also significantly improved. With the new data base, different time lag correlation analysis has been performed. These analyses showed that a time delay of about 1.5 days is observed between the increases of the fluxes at 500 keV and those of the 150 keV electrons. The comparison of energies 970 keV and 150 keV gives a longer time lag of 3 days at L=4.0–4.5. For 1470 keV and 150 keV the delay is almost 5 days. These results are confirmed by observations from other missions and are in agreement with the predictions of the recirculation model. Interesting correlations have also been found in the pitch angle distributions of the electrons at $L>5$. It was also noted that there is good agreement between the position and height of the peak between the MEA data and the CRRES/HEEF results presented by Brautigam et al. (1992).

The updated MEA model, called ECM97, is organised in (E, L, α_0) coordinates which have been proven to best organise the data. The standard deviation of the flux in the bins has been calculated and plotted. The new data base has a lower standard deviation than the TREND-2 data base throughout the outer radiation belt, and across almost all of the inner belt. However, standard deviations remain high in the slot region and in the loss cone. This is not unexpected since these regions have low fluxes and are highly variable.

The new electron belt model has been incorporated in the `UNIRAD` software package. It has been compared to the AE-8 model, details on which can be found in Technical Note 2 and in Chapter 9.

1.9 Radiation losses and particle injection studies

The equatorial pitch angle distributions of radiation belt electrons obtained from the data of the CRRES/MEA instrument are solutions of a time dependent Fokker-Planck equation which has been solved first by Roberts (1969), and extended by the MSSL team as part of this study.

For equatorial pitch angles within the loss cone, the solution can be decomposed in a series of normal modes characterised by decay time constants. The normal mode corresponding to the longest time constant can be expressed in terms of the zero order Bessel function of the first kind. The MSSL team has used the CRRES/MEA averaged pitch angle distributions at different energies, at different L values, and for two different geomagnetic activity levels, to fit the free parameters of the lowest order normal mode solution. This resulted in analytical fits of the observed pitch angle distribution for pitch angles between 90° and the L dependent loss cone angle. These fits are found to be more suited than the commonly used $\sin^n\alpha$ functions.

The free fit parameters are the flux intensity $j(\mu_0 = 0)$ at pitch angle 90°, and $\mu_{\rm sc}$, the cosine of the scattering angle characterizing the slope of the pitch angle distribution for $\mu_0 = \cos\alpha_0$ increasing monotonically from 0 to $\cos\alpha_{0\rm c}$, where $\alpha_{0\rm c}$ is the atmospheric loss cone angle. The value of $\mu_{\rm sc}$ is determined experimentally from the ratio of the averaged measured flux $j(\mu_0 = 0)$ at 90° pitch angle to the averaged measured flux $j(\mu_{0\rm c})$ at the edge of the loss cone. The fitted values for $j(\mu_0 = 0)$ and of $\mu_{\rm sc}$ depend on L as well as on the energy of the trapped electrons. This is a first step in the process of searching parametrised (analytical) models for the equatorial pitch angle distribution as a function of L and E.

The same fitting procedure has been used by the MSSL team to fit the pitch angle distribution inside the loss cone. In this case, the lowest normal mode solution of the Fokker-Planck equation is the alternate Bessel function $I_0(x)$ which has the properties that it is equal to 1 at $x = 0$ and increases monotonically as x increases. Using $j(\mu_0 = 1)$, the average flux intensity measured at zero pitch angle, and $j(\mu_{0\rm c})$, the flux at the edge of the loss cone, the two free parameters $j(\mu_0 = 1)$ and $\alpha_{\rm sc}$, the mean scattering angle, can be determined. These parameters depend on L and E.

The electron precipitation flux integrated over the loss cone can be calculated once the two fit parameters are known. In this way, the MSSL team has been able to infer the characteristic decay times of electrons of different energies for different values of L, and for different values of the geomagnetic activity index $K_{\rm p}$. The calculated decay times range from 10 seconds to 3 hours, with the smallest values for the lowest $K_{\rm p}$ range and smaller L values. These decay times are much smaller than those which are determined from direct measurements of the decay times which are normally in the range of 5 to 10 days (McIlwain 1996). The probable reasons for this discrepancy is that in our study the flux in the loss cone is overestimated by the measurements of the MEA detector.

The details of this study are given in Technical Note 8. A summary is presented in Chapter 10 of this Final Report.

1.10 Meteosat/SEM-2 Data base

A comprehensive study of the magnetospheric electron flux (40–300 keV) at geosynchronous orbit was performed during the TREND-2 study, based on observations made by the Space Environment Monitor (SEM-2) onboard Meteosat.

Since the completion of the TREND-2 study, a number of problems have been identified with respect to the Meteosat/SEM onboard data and postprocessing. These problems became apparent in the unnatural clustering of the polar-azimuthal data around certain preferred flux values, and in regular spikes seen in some elements of the polar arrays.

During the present study, the SEM-2 data set was re-examined with the aim of producing a new data base. The comparison of the old and new data bases is presented in Technical Note 9 and in Chapter 11 of this Final Report.

Although the various errors could have significant effects on individual data points, most of the TREND-2 results rely on statistical analyses where the effect of including a few erroneous points in a large sample would have been small. The sample plots of 'before' and 'after' data presented in Technical Note 9 show that the statistical models produced in the TREND-2 study are not significantly modified when the error corrections are applied. Therefore, the conclusions drawn from the old data base concerning local time dependence and overall flux range have not been changed significantly. This conclusion holds for all the local time dependence models, for the Fourier and wavelet analyses, for the correlation analysis showing the time lags between different energy flux variations, and the models of flux probability versus mission duration.

The text of a paper by Rodgers (1991), based on the old Meteosat/SEM data base, has been updated for the new data base. The new text, which covers 18 months of Meteosat-3 anomalies and SEM-2 data, is reproduced in Technical Note 9.