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WP304. Particle-induced background analysis

Report on demonstration of particle-induced background in detectors analysis

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Authors: Mike Hapgood, CLRC Rutherford Appleton Laboratory

ESA technical Officer: A Hilgers D/TOS, TOS-EMA

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1 Preface

1.1 Document change record

Issue	Date	Notes/remarks
0.5	01 Dec 2002	Intermediate draft released for review by ESA
1.0	11 Aug 2004	Updated to add Annex A and B
1.1	08 Jan 2005	Complete description of tools in Annex A

1.2 Purpose of the document

This document is the technical note reporting the results of the SEDAT demonstration work package 304, entitled “Particle-induced background in detectors analysis”.

1.3 Definitions, acronyms and abbreviations

AMPTE	Active Magnetospheric Particle Tracer Explorers
ASCII	American Standard Code for Information Interchange
CDF	Common Data Format (NASA data format)
CSV	Comma separated values
ESA	European Space Agency
ESTEC	European Space Technology Centre
GEI	Geocentric equatorial inertialco-ordinates
GSE	Geocentric solar ecliptic co-ordinates
GSM	Geocentric solar magnetospheric co-ordinates
IDL	Interactive Data Language. Commercial product with good mathematical and graphics functionality used as the scripting language in SEDAT.
ISEE	International Sun-Earth Explorer
ISTP	International Solar-Terrestrial Physics programme
KED	Keppler’s daughter
keV	kilo electron-volt
L	McIlwain L parameter
NASA	National Aeronautics and Space Administration
PIB	Particle-induced background
RAL	Rutherford Appleton Laboratory
Re	Earth radius
RSI	Research System Inc
SEDAT	Space Environment Database
SI	Système International, the international system of units.
TBC	To be confirmed
TBD	To be done
UKS	United Kingdom Satellite
USOC	?
XMM	X-ray Multi-Mirror mission, now XMM-Newton

1.4 Important Documents

We list here the various documents used as source material for this report. These include both hardcopy and web sources. Documents may be referenced in the test and this is indicated by a sequential code of the form Xn, where n is an integer and X = A or R (for applicable and reference documents respectively). The series of integers are separate for applicable and reference documents.

1.4.1 Applicable documents

A1 SEDAT Statement of Work. Appendix 1 to AO/1-3306/97/NL/NB

A2 Space Environment Database and Analysis Tools. Proposal in response to ESA ITT AO/1-3306/97/NL/NB. RAL/RRS/201/97. January 1998.

1.4.2 Reference documents

R1 Note on "SEDAT prototyping - particle-induced background", Draft 2, prepared by Mike Hapgood, 9 Dec 1998.

R2 A. Hilgers et al. EWP 1942. X-ray background induced by electron bremsstrahlung emission in XMM telescopes: Environmental input data and mathematical model. October 1998.

R3 An introduction to space physics coordinate systems, http://sspg1.bnsc.rl.ac.uk/Share/Coordinates/ct_home.htm

R4 Modified Julian Date http://sspg1.bnsc.rl.ac.uk/Share/Coordinates/mjd.html

R5 Reference Document for CSDS CDF Implementation, DS-QMW-TN-0003 http://www.space-plasma.qmw.ac.uk/DOC/DS-QMW-TN-0003.ps

R6 ISTP/IACG Guidelines for CDF files http://spdf.gsfc.nasa.gov/istp_guide/istp_guide.html

R7 ISTP/IACG Global Attributes, http://spdf.gsfc.nasa.gov/istp_guide/gattributes.htm

R8 ISTP/IACG Variable Attributes, http://spdf.gsfc.nasa.gov/istp_guide/vattributes.htm

R9 http://spdf.gsfc.nasa.gov/istp_guide/variables.htm#Epoch

R10 N.A. Tsyganenko, (1989) “A magnetospheric magnetic field model with a warped tail current sheet”, *Planet. Space Sci.*, **37**, 5-20.

R11 M.A. Hapgood, T.G. Dimbylow, D.C. Sutcliffe, P.A. Chaizy, P.S. Ferron, P.M. Hill and X.Y. Tiratay, (1997) "The Joint Science Operations Centre", *Space Sci. Rev.*, **79**, 487-525.

R12 Demonstration of particle-induced background in detectors analysis, RAL-SED-TN-0304

2 Introduction and structure

This document presents the results of SEDAT work package 304 which is a demonstration of the application of SEDAT to perform an analysis of particle-induced background in X-ray detectors. There are several aspects of this application and these are reflected in the subsequent sections of the document.

Section 3 describes the implementation of the PIB analysis model as a SEDAT tool. This tool takes in electron fluxes from the SEDAT database and estimates the consequent PIB fluxes. It is described in detail here as it is a key element of WP304.

Similarly section 4 describes the orbit generator that has been implemented for SEDAT. This uses sets of closely-spaced Keplerian elements as its input; these are available for example from the USOC tool used within ESA.

Section 5 describes the datasets used in this workpackage. These include the extensive ISEE-2 dataset that was used in previous ESA work [R2] and is also the mainstay of this work (because of its comprehensive coverage of near-Earth space). The other electron dataset used here is the AMPTE-UKS dataset produced by RAL. This does not give such good coverage of near-Earth space as ISEE-2 but it has better coverage of the key electron energies (around 1 keV) for PIB generation. Thus it can provide a useful check on the extrapolation needed when using ISEE-2 data. Section 5 also includes a discussion on the orbit data and its ingestion into SEDAT.

Section 6 describes the comparison between results from previous ESA work [R2] and equivalent results produced from analysis of the same data (ISEE-2) as part of this workpackage. We show that there is good agreement between the two analyses.

Section 7 describes the results of applying the tools developed in section 6 to a different dataset – namely the AMPTE-UKS electron data. We find that there is broad agreement when comparing the total electron fluxes estimated from the two datasets but that there are some interesting differences when comparing the corresponding PIB fluxes. The AMPTE-UKS dataset suggests the presence of higher PIB fluxes in the vicinity of the magnetopause. This requires further study.

Section 8 describes a tool that can estimate the likely range of PIB fluxes along an arbitrary trajectory. It does this by finding energetic electron fluxes previously measured at positions close to points on that trajectory and then deriving PIB spectra from those fluxes. This yields a large set of PIB values at each of many points on the trajectory. Thus we can derive useful statistics such as the minimum, median and maximum PIB flux at each point. Examination of results suggests that it is more profitable to specify closeness in terms of magnetic coordinates such as L value (rather than geometrically).

Section 9 presents a summary of the work and makes some suggestions for further work.

At the end of the report two annexes provide a summary of the tools developed and a compliance matrix showing how the results presented in this report match the test plan.

3 Calculation of the PIB spectrum

3.1 Introduction

The key element in this workpackage is the estimation of the particle-induced X-ray background in the mirror shells that form the telescope system of the XMM-Newton spacecraft. This is done by a SEDAT tool that calculates the PIB spectrum using the approach given in [R2]. This paper shows that the PIB differential flux at photon energy u is given by

$$\partial N/\partial u(u) = \int X(w,u)\, g(w)\, dw$$

where w is electron energy, g(w) is the electron flux energy spectrum, u is the energy of the photons generated electron impacts, N is the number of PIB photons reaching the detector and X(w,u) is the a transfer function describing the generation of photons by electron impacts. The transfer function is calculated beforehand using a separate tool described in section 3.2. The equation above has been implemented via a set of routines as shown in Figure 1 below. The top level of these routines is calc_pib, which provides the user interface and handles the scan over all energies in the photon spectrum. The main data inputs to calc_pib are the electron flux energy spectrum and the PIB transfer function – together with their associated supporting data (electron and photon energies, units, null values). The top-level routine calls two main sub-routines:

1. present_electron_data. This is an important routine as it prepares the electron flux data for the calculation of PIB spectrum. This includes:
   - removing null values,
   - inter-/extrapolating the electron data on to the grid of electron energy values used in the transfer function. This is important for speed of execution. The use of a fixed grid of electron energies allows us to calculate the transfer function just once. However, it then requires that the electron fluxes are interpolated on to that grid at each step. This approach also has the great advantage that it automatically includes interpolation over missing data points (null values).
   - adjusting the units of electron energy and flux to a fixed values (keV for energy and /m**2/s/sterad/keV for flux) so we know the units of the resulting PIB spectrum.
2. apply_fef. It calculates the product of the transfer function and the electron spectrum and then integrates these to obtain one value in the PIB spectrum.

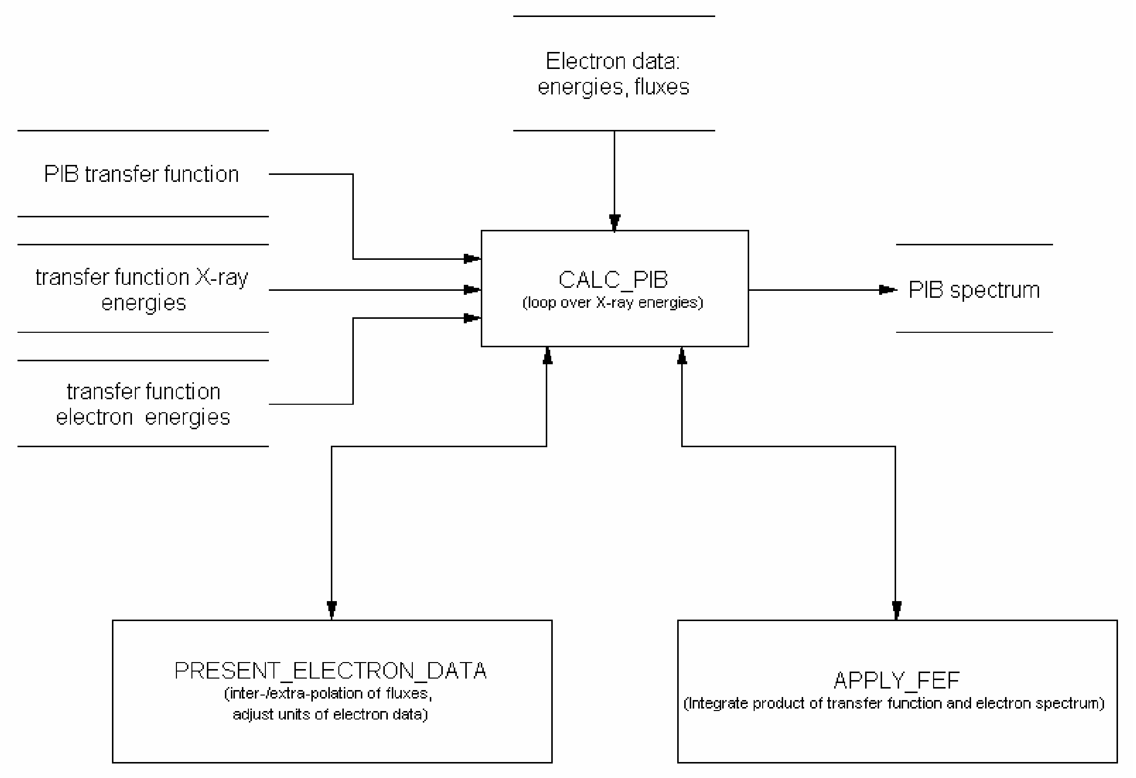

Figure 1. Calculation of the PIB spectrum.

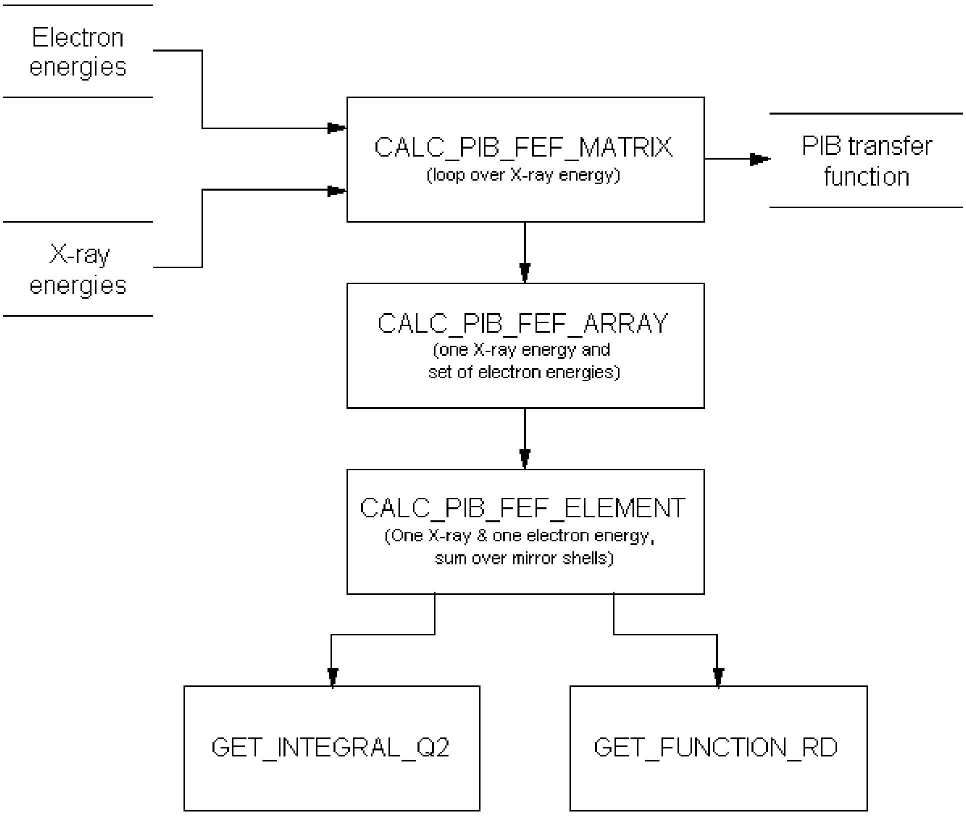

Figure 2. Calculation of the PIB transfer function

3.2 Transfer function

This transfer function is discussed in detail in [R2] and was the subject of a prototyping activity within the SEDAT work [R1]. That prototyping showed that the equations given in [R2] can be manipulated to obtain the following form:

$$X(w,u) = C_0 H(w-u) \sum_i 2\pi r_i D(0,i,u) \int Q_2(w,i,z)\,dz$$

where $C_0 = 5 \times 10^{-5}$ $keV^{-1}s^{-1}$, H(w-u) is the Heaviside step function, r_i is the radius of mirror shell i and D(z,i,u) is the function for photon propagation to the detectors from distance z inside the aperture for mirror shell i and photon energy u. The function Q_2 describes the ability of electrons to enter the mirror shells and can be calculated as $Q_2 = \iint \sin\alpha \ \cos\phi \ A(\alpha,\phi,i) \ B(\alpha,w,z,i) \ d\phi d\alpha$ where A is the solid angle from which ambient electrons can enter the mirror shell and B is the probability that a particle entering the mirror shell can propagate to distance z. The parameters α and ϕ are angles describing the initial direction of motion of an electron with respect to the mirror shell [R2].

The equation above has been implemented via a set of routines as shown in Figure 2 above where

- calc_pib_fef_matrix is the top level routine. It provides the user interface and handles the scan over photon energies.
- calc_pib_fef_array is called by calc_pib_fef_matrix. It handles the scan over electron energies.
- calc_pib_fef_element is called by calc_pib_fef_array. It calculates the transfer function for a particular pair of electron and photon energies. It handles the scan over the XMM mirror shells.
- get_integral_q2 provides an estimate of the term $\int Q_2 dz$. [R2] provides a table of values for this term so we use a numerical approximation to interpolate to the required values.
- get_function rd calculates the function r_i D(0,i,u). This function is purely geometric and has been implemented as an IDL code that explicitly calculates the function using the equations given in [R2].

The output of the transfer function is naturally a two-dimensional matrix in which the two dimensions represent (a) the energies of the input electron fluxes and (b) the energies of the output photon fluxes. These two sets of energies are part of the metadata that must always be associated with the transfer function.

4 Orbit generator

4.1 Introduction

The orbit generator tool (make_orbit_pos) has been designed to exploit orbit data provided as closely spaced Kelperian elements, e.g. as provided by ESA’s USOC tool. tool. It can calculate the spacecraft position in inertial co-ordinates at any date and time within the time range for which elements are available. It has been implemented via a set of routines as follows:

- make_orbit_pos is the top level routine. It provides the user interface.
- kepler is called by make_orbit_pos. Given the elements and the time of interest, it solves Kepler's equation to obtain the eccentric anomaly. It then calculates the true anomaly and radial distance at the time of interest.
- calc_xyz is called by make_orbit_pos. Given the elements, true anomaly and radial distance, it calculates the cartesian position in inertial co-ordinates..

Table 1. SEDAT position structure

```
position= {dat: fltarr(3),      $
           label: '',           $
           null: 1.0,           $
           units: '',           $
           si_conversion: ' ',  $
           sys: '',             $
           form: ''             }
```

The resulting spacecraft position is retunred in an IDL data structure as shown in Table 1. This holds variety of useful metadata as well as the numerical values of the position. These fields within the structure are described in Table 2. These metadata include a code indicating the coordinate system in which the position is represented and another code indicating if the position is expressed in cartesian (X, Y, Z) or polar (latitude, longitude, radial distance) form. This structure is identical with that used by other SEDAT tools that manipulate positions – in particular the coordinate conversion tool (convcoord). The orbit generator sets the value of the sys field according to the frame of the orbit data – see Table 6. This facilitates conversion to other systems such as GSE [R3] using tools such as convcoord.

Table 2. Fields in the SEDAT position structure

Sys	Four character string specifying the co-ordinate system applicable to the position data held in dat- using the codes listed below. make_orbit_pos always returns inertial co-ordinates, i.e. sys = ' GEI'.
form	Three character string specifying the format of the co-ordinate system applicable to the position data held in dat - using the codes listed below. Make_orbit_pos always returns cartesian format, i.e. form = ' CA'.
null	Null value for the position data held in dat.
si_conversion	SI conversion string for length units applicable to the position data held in dat. make_orbit_pos always returns positions in km, so si_conversion = '1.0e3>m'.
units	String giving the name of the units applicable to the energy values held in dat. make_orbit_pos always returns positions in km, so units = 'km'
label	String giving a label applicable to the position data held in dat.
dat	32-bit real array of length 3 holding the position data. Since make_orbit_pos always returns cartesian format the contents of the array are the values of the X, Y and Z components of the position.

4.2 Orbit data

The input to the orbit generator is a series of Kelperian elements. They are supplied in a SEDAT data file with each set of elements held in one record with fields as shown in Table 3. For ease of ingestion the orbit data file should be made available to SEDAT as a CDF file with appropriate global and variable attributes [R7, R8] as shown in Table 4 below.

Table 3. Keplerian elements used by the orbit generator

Field name	Description
mjd	Epoch of the elements (as Modified Julian Date)
a	Semi-major axis in km
e	Eccentricity
i	Inclination in degrees
ra_node	Right ascension of the ascending node in degrees
arg_peri	Argument of perigee in degrees
tr_anom	True anomaly at the epoch – in degrees

Table 4. CDF attributes for the orbit data

Global attributes	Variable attributes
Acknowledgement	Fieldnam
Generated_by	User_fnam
Generation_date	Fillval
Title	Lablaxis
Central_body	SI_conversion
BigG_x_Mass	Units
Frame	

The first four global attributes and all the variable attributes are standard attributes as specified in [R6]. However, the last three global attributes have been specially created for the orbit data files and are specified in Table 5 below. These attributes are important as they determine the orbital period and the coordinate system of the output (see Table 6).

Table 5. Special global attributes for orbit data

Central_body	A string containing the name of the central body around which the Keplerian orbit is specified. The two main values that used in SEDAT are Earth and Sun.
BigG_x_Mass	A floating point value containing the product of the gravitational constant and the mass of the central body. Together with the semi-major axis this determines the orbital period.
Frame	The coordinate frame in which the elements are expressed. The values used in SEDAT are: MEE_1950 for earth-centred coordinates based on the old epoch of 1950.0 MEE_2000 for earth-centred coordinates based on the modern epoch of 2000.0 MCE_ECLIP for ecliptic coordinates based on the epoch of date The ecliptic coordinates may apply to orbits centred on a variety of bodies.

Table 6. Coordinate systems for orbit generator outputs

Central body Frame	Earth	Sun	Other
MEE_1950	GEI5	not valid	not valid
MEE_2000	GEI	not valid	not valid
MCE_ECLIP	GEI	HEE	UKNW

5 Datasets used in the demonstration

5.1 AMPTE data

These are electron fluxes at energies of 10 eV to 16 keV at one-minute time resolution. They were taken on the electron instrument on the AMPTE-UKS spacecraft between 25 August 1984 and 15 January 1985. They were provided by RAL as ISTP-compliant CDF files and ingested into SEDAT.

5.2 ISEE-2 data

These are electron fluxes at energies of 18 keV to 1 MeV at one-minute time resolution. They were taken by the KED instrument on the ISEE-2 spacecraft between 6 November 1977 and 02 March 1987. They were provided by ESTEC as ASCII files and ingested into SEDAT.

5.3 Orbit data

For the present application the XMM orbit data were made available by ESA in an ASCII file generated using ESOC USOC system. To convert these files to CDF format, we first converted them to a fixed ASCII format that comprises:

- a set of header records containing the metadata listed in Table 5: (a) the name of the central body around which the Keplerian orbit is specified, the product of the gravitational constant and the mass of the central body and (c) the coordinate frame in which the elements are expressed.
- this is followed by data records in a comma-separated value (CSV) format with a fixed order of meaning for the values. The CSV format is used as it is easily generated as an output from Excel. Note that direct ingestion from USOC files is not recommended because there is no standard order to those files. It is better to manually manipulate USOC files into a fixed form that can be reliably read by a computer.

Data in this fixed format can then be converted to CDF format using standalone IDL tool make_orbit_cdf. This program first creates an empty CDF file with the global and variable attributes shown in Table 4 below. It then reads each set of elements from the ASCII file, converts the epoch to a Modified Julian Date [R4] and writes the elements to a record of the CDF file. The resulting CDF file was ingested into SEDAT as a system dataset (XMM_ORBIT).

6 Comparison with previous ESA study

An important aspect of WP304 is to compare “the output with a previous study that made use of ISEE-2 data only”. The previous study is ESTEC Working Paper 1942 [R2]. To make that comparison we have selected three figures from the previous study as reference plots and then replicate them using tools developed within SEDAT. These figures are

- Figure 3. Orbit track
- Figure 4. Plot of maximum electron fluxes
- Figure 17. Plot of maximum particle induced background (PIB) X-ray flux

Copies of these figures are showm in Figure 3, Figure 4 and Figure 5 of this paper.

The reference plots of flux maxima are chosen, in preference to medians, to facilitate the demonstration of SEDAT. One can select a set of values and compute their maximum (and minimum and mean) during a single pass through a dataset – while computation of medians requires two separate passes (a selection process first and then a separate computation of the median). Thus we can demonstrate the ability of SEDAT to replicate previous results using a simple tools that will execute quickly.

6.1 Reference plots

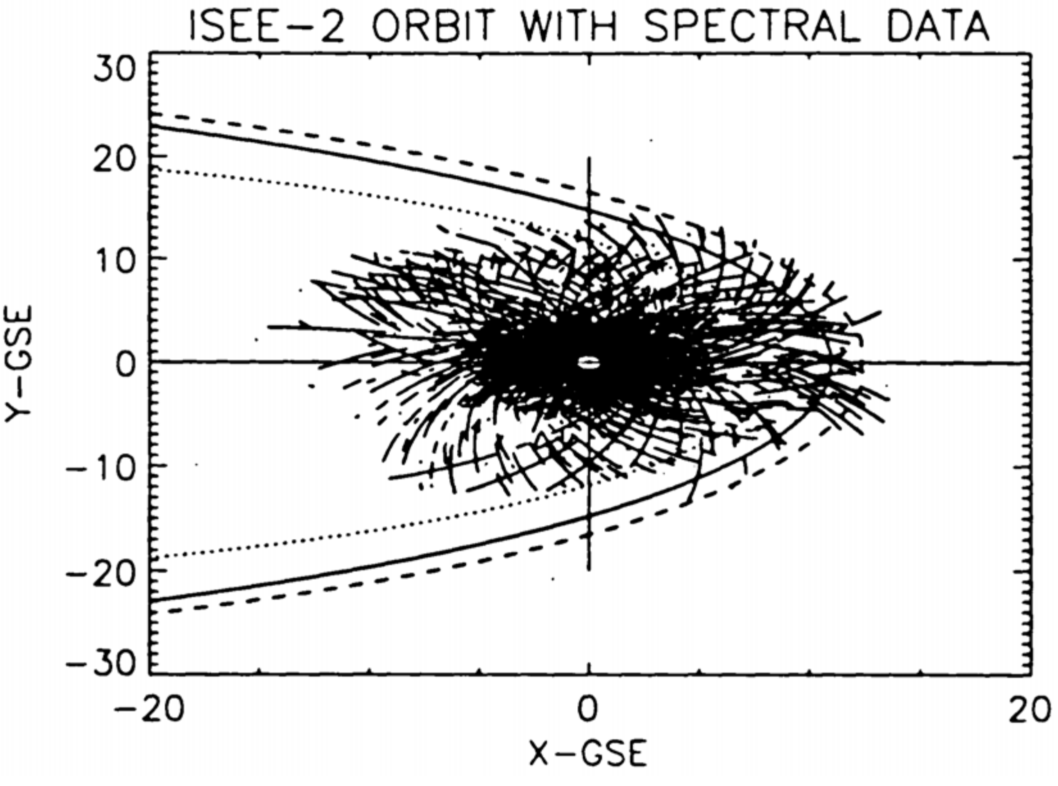

Figure 3. ISEE-2 orbit data locations where spectral data was recorded

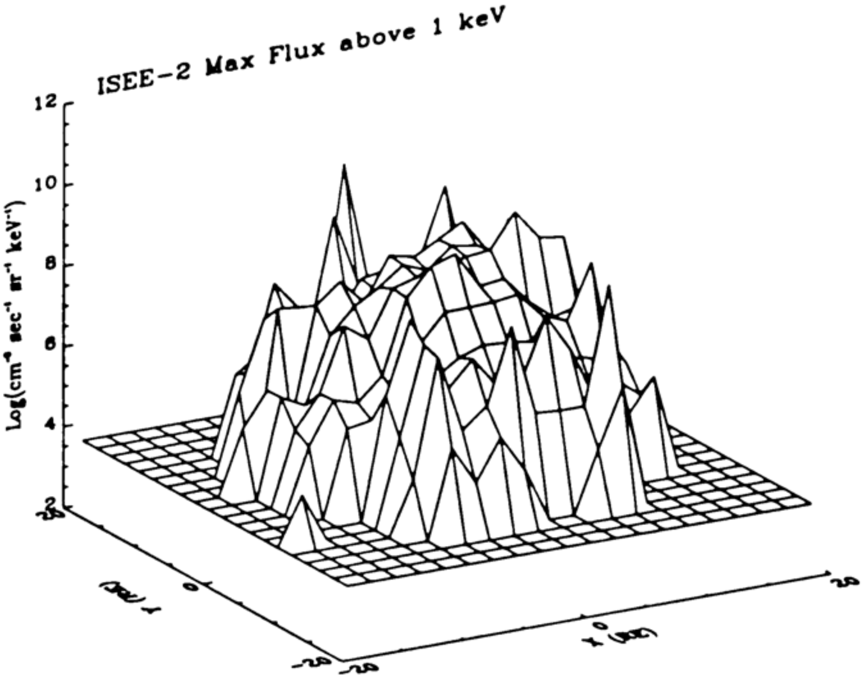

Figure 4. ISEE-2 maximum electron fluxes

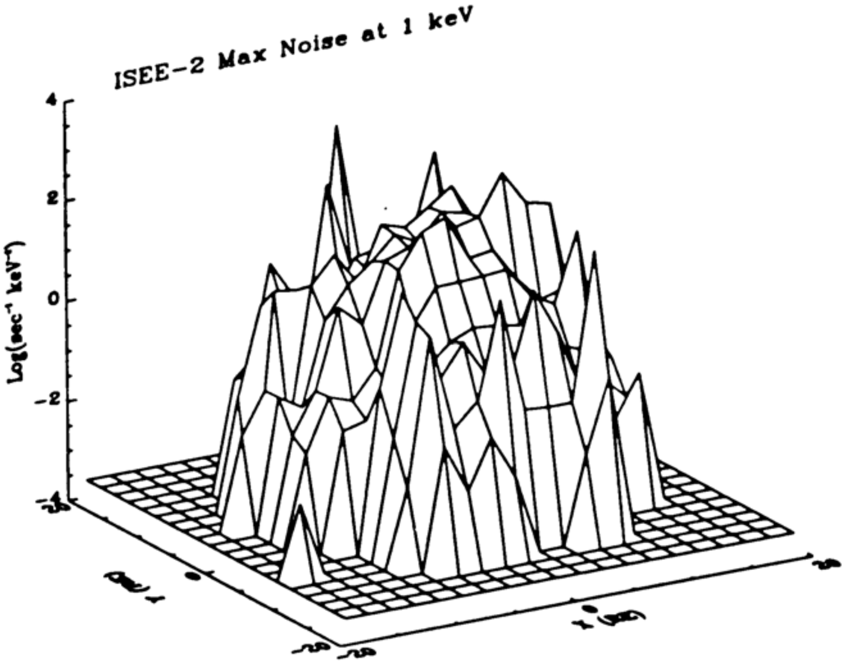

Figure 5. Maximum PIB values derived from ISEE-2 electron fluxes

6.2 Replication of the orbit track

The orbit track was determined by a tool that scanned through a time range of ISEE-2 data records and retrieved the quality flag. If bit 6 in this field is set (i.e. if the quality flag ≥ 64), it indicates that spectral data are present. If so, the time and spacecraft position are extracted from the record. The spacecraft position given in the ISEE-2 data records is in geocentric coordinates, so this is converted to GSE co-cordinates using the convcoord system tool. The X and Y components of that position are then plotted as shown in Figure 6 and Figure 7 below. Figure 6 shows the tracks for spectral data taken in 1978 while Figure 7 shows them for the whole dataset.

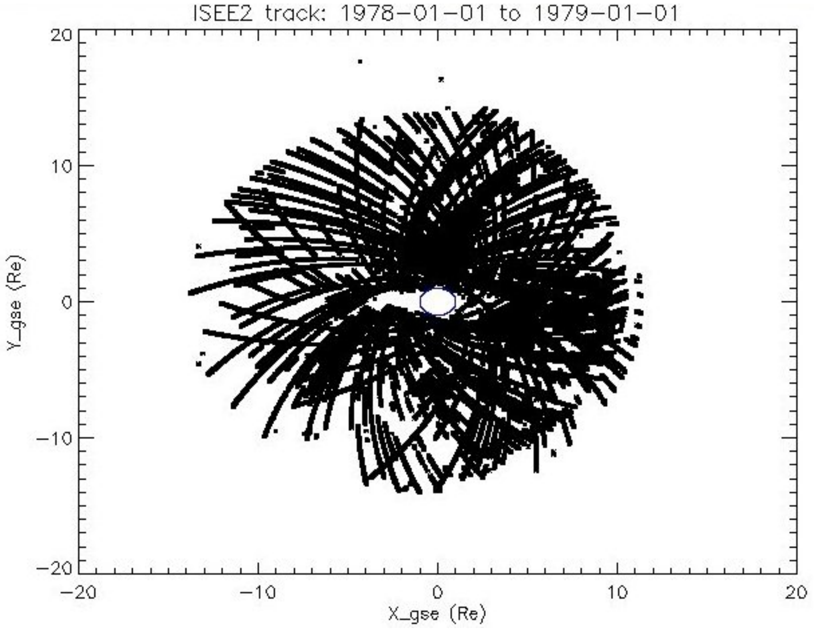

Figure 6. Locations where ISEE-2 recorded electron spectra during 1978

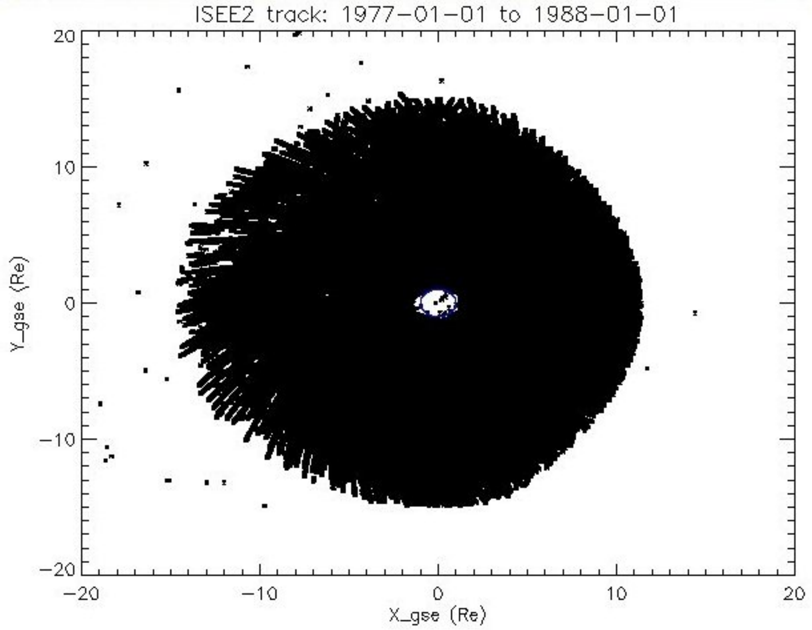

Figure 7. Locations where ISEE-2 recorded electron spectra during the whole mission

The lower density of points in Figure 6 allow us to see the elliptical shape of the ISEE-2 orbit and its annual precession around the Earth when plotted in GSE co-ordinates. The higher density of points in Figure 7 hides these features but demonstrates clearly that the ISEE-2 data provide good coverage of near-Earth space in terms of GSE co-ordinates.

6.3 Replication of electron flux plot

The electron fluxes were examined using a similar procedure to that described in [R2]. The tool scans through the ISEE2 data and extracts the electron spectrum, the quality flag and the spacecraft position from each record in turn. We then check to see if the spectral data are adequate for analysis, i.e. the quality factor indicates the prescence of good spectral data (qf < 64) and there are at least 2 valid flux values. If so, we process it as follows:

1. We extract the valid flux values and interpolate/extrapolate them to a grid of 21 logarithmically spaced energies between 1 and 100 keV. The interpolated/extrapolated fluxes are then integrated to derive an estimate of the total flux above 1 keV.
2. We convert the spacecraft position to GSE co-ordinates and assign it to one of 400 bins in the GSE XY plane. The binning grid is centred at the Earth and contains 20 by 20 bins, each of which is 2 Re by 2 Re in extent. So the whole grid extends ±20 Re in each of the GSE X and Y dimensions.
3. We determine whether or not the estimated total flux in the current record is greater than the existing maximum value for the assigned bin. If so, we increment that maximum to the new value. Note that the maximum value is initialised to zero at the start of the analysis.

This procedure is repeated for each record in the dataset and yields a 20 by 20 array containing the maximum flux above 1 keV for each bin. Empty bins are indicated by a maximum value of zero and are reset a floor value at the first power of ten below the minimum non-zero value in the array. The binned data can then be displayed as a surface plot as shown in Figure 8 below. The floor values indicating empty bins can be easily seen at the edges of the plot with a level of 10^6 cm^{-2} s^{-1} sr^{-1}. Inside these floor values there is a sharp rise which matches the sharp edge of the region sampled by ISEE-2 (as shown in Figure 7). Inside the sharp rise there is a region of undulating values between around 10^{10} cm^{-2} s^{-1} sr^{-1}, which is similar to the values shown in Figure 4.

These results are quite sensitive to the interpolation/extrapolation procedure because most of the ISEE2 electron data are taken at energies above 30 keV where the electron spectrum follows a power law [R2]. However, we have to extrapolate down to 1 keV, so the dominant contribution to the total flux comes from energies below 30 keV, where the electron spectrum follows an exponential [R2]. We initially tried to use IDL’s generic interpolation and extraolation procedure (INTERPOLATE) but this yielded fluxes several orders of magnitude higher than those shown in Figure 4. We assume that this is an overestimate and that it arises because the generic procedure picks up the power law form of the electron spectrum and extrapolates this to lower energies. To ensure exponential extrapolation to lower energies we fit the observed spectra to a mix of exponential and power law forms as described in [R2]. However, to derive a reasonable fit for the exponential form at lower energies, we need to include several energy channels in that fit. To achieve this it is necessary to include some channels above 30 keV in the fit. After some experimentation we made this fit at energies up to 100 keV.

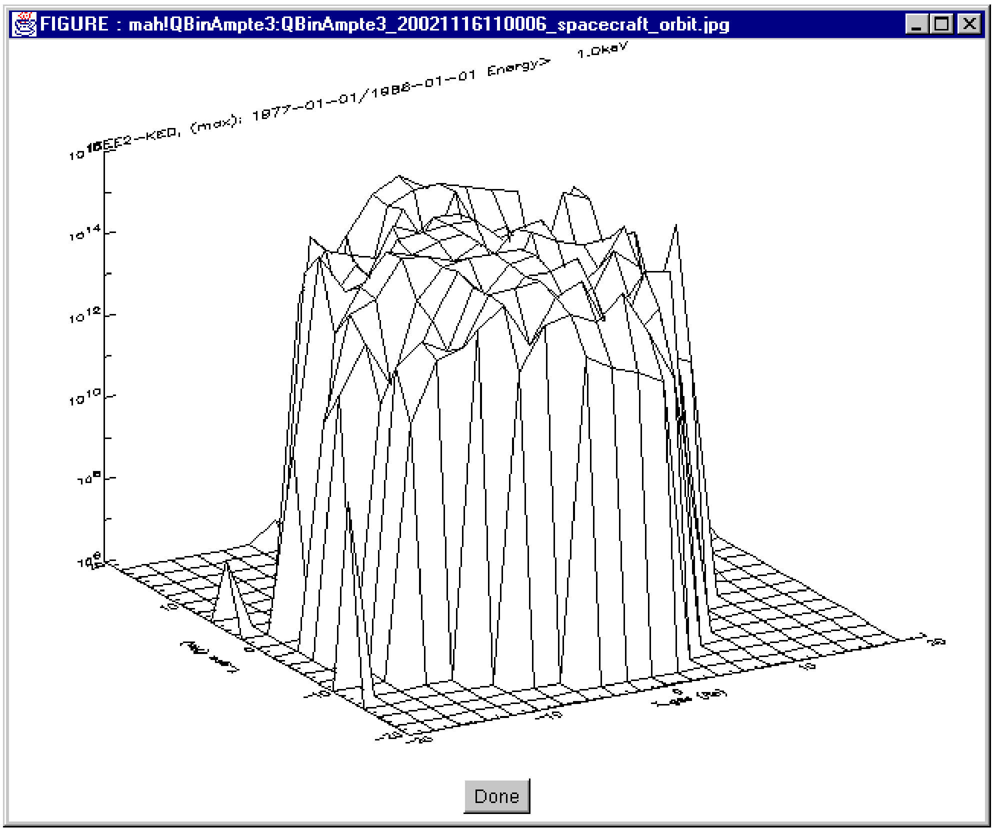

Figure 8. ISEE2 maximum fluxes.

6.4 Replication of the PIB flux plot

The PIB fluxes were derived and analysed using an extension of the approach used above for the electron fluxes. As in that work the tool scans through the ISEE2 data, extracts the electron spectrum, the quality flag and the spacecraft position from each record and checks to see if the spectral data are adequate for analysis. If so, we process it as follows:

1. We extract the valid flux values and process them through the PIB tool described in section 3 and extract the X-ray flux at 1 keV from the PIB spectrum.
2. We convert the spacecraft position to GSE co-ordinates and assign it to one of 400 bins in the GSE XY plane using the same grid as used for electron fluxes in section 6.3.
3. We determine whether or not the 1 keV X-ray flux derived from the current record is greater than the existing maximum value for the assigned bin. If so, we increment that maximum to the new value. As before the maximum value is initialised to zero at the start of the analysis.

This procedure is repeated for each record in the dataset and yields a 20 by 20 array containing the maximum 1 keV X-ray flux for each bin. Empty bins are indicated by a maximum value of zero and are reset a floor value at the first power of ten below the minimum non-zero value in the array. The binned data can then be displayed as a surface plot as shown in Figure 9 below. The floor values indicating empty bins can be easily seen at the edges of the plot with a level of 0.1 s^{-1} keV^{-1}. In the centre of the plot there is a region of undulating values rising to almost 10000 s^{-1} keV^{-1}.

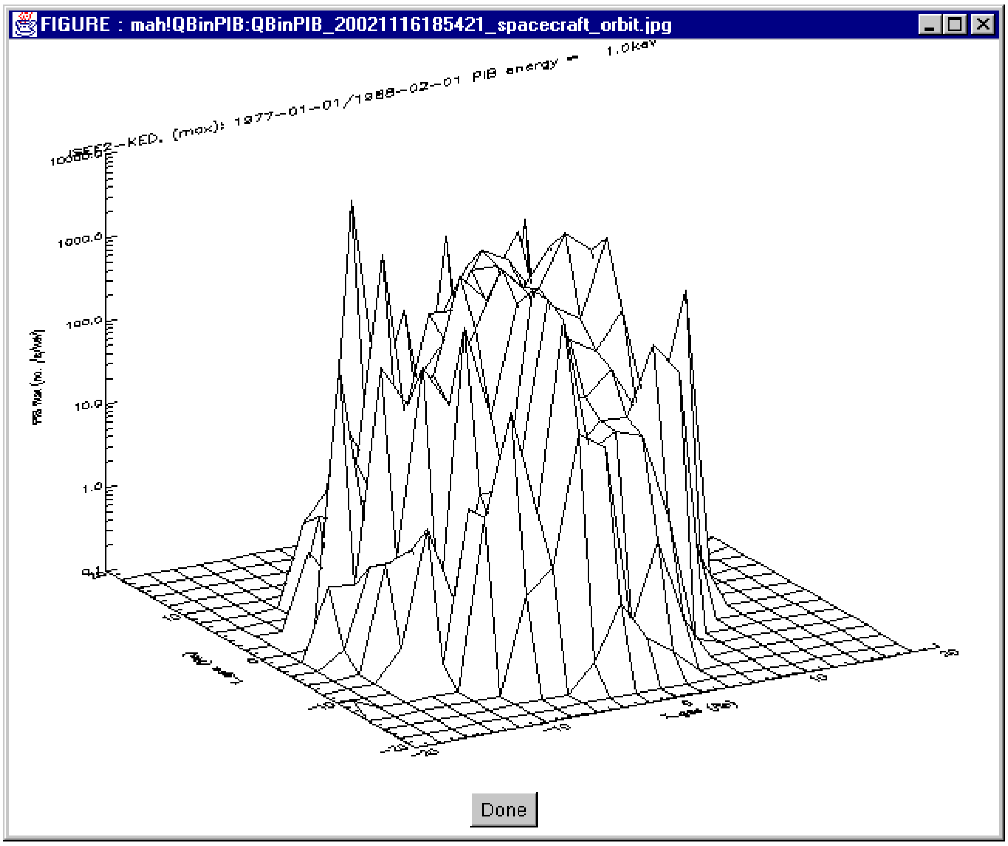

Figure 9. Maximum PIB X-ray fluxes estimated from ISEE2 data.

7 Results for AMPTE data

The tools described in the previous section were also applied to the AMPTE-UKS dataset with results as follows:

Figure 10 below shows the locations where AMPTE-UKS recorded electron spectra. This was generated using the same tool as for Figure 6 and Figure 7. The limited orbit coverage for AMPTE-UKS reflects the short duration of this mission. The orbit tracks at the upper right are where the first data were taken after launch in August 1984. At this time apogee lay in the early afternoon sector. During the following five months the orbit precessed across the dayside and apogee was around dawn when the spacecraft failed abruptly on 16 January 1985.

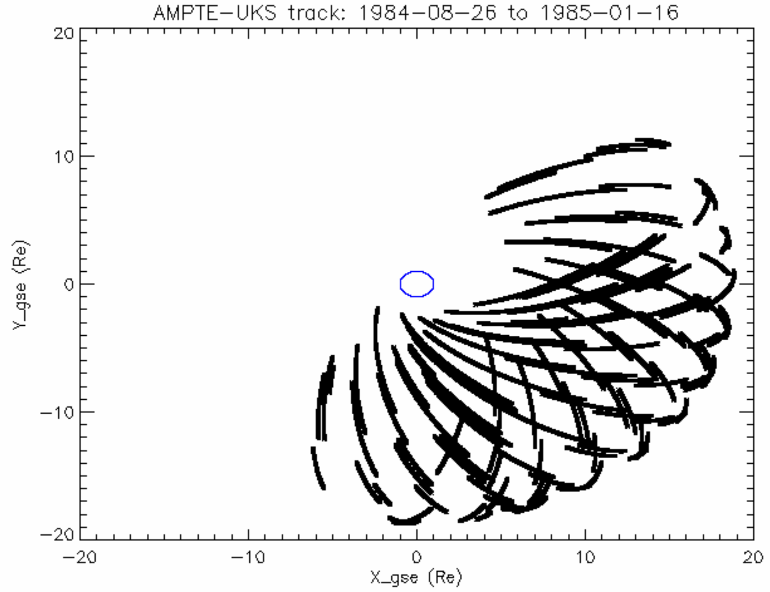

Figure 10. Locations where AMPTE-UKS recorded electron spectra.

Figure 11 shows the maximum electron fluxes above 1 keV as estimated from AMPTE-UKS data using the same tool as for Figure 8. The data are again binned on to a 20 by 20 grid in the GSE XY plane but the limited duration of the mission means that a smaller part of the grid is populated as can be seen in Figure 11. However, the AMPTE-UKS data have much better coverage of energies below 30 keV – with spectra typically having 12 channels between 1 keV and 16 keV. Thus they provide a much better estimate of the exponential part of the electron spectrum that dominates the total flux. It It is therefore interesting to compare the AMPTE results with those from ISEE-2 in order to validate the extrapolation technique. Comparison of Figure 8 and Figure 11 suggests that there is good agreement with maximum values around 10^{10} cm^{-2} s^{-1} sr^{-1} in the region of XY plane sampled by AMPTE_UKS. These are similar to the maxima derived from ISEE-2 data.

Figure 12 shows the maximum PIB X-ray fluxes as estimated from AMPTE-UKS data using the same tool as for Figure 9. The better low energy coverage of AMPTE-UKS is also relevant here since PIB production is probably dominated by <30 keV electrons. Thus we can again compare the AMPTE results with those from ISEE-2 in order to validate the technique. Comparison of Figure 9 and Figure 12 suggests that there is a measure of agreement with maximum values around 10000 s^{-1} keV^{-1} in the inner magnetosphere – which is broadly similar to values observed by ISEE-2. But the

AMPTE-UKS shows a number of markedly higher bins with maxima around10^6 s^{-1} keV^{-1} that appear to lie around the magnetopause location. These require further investigation.

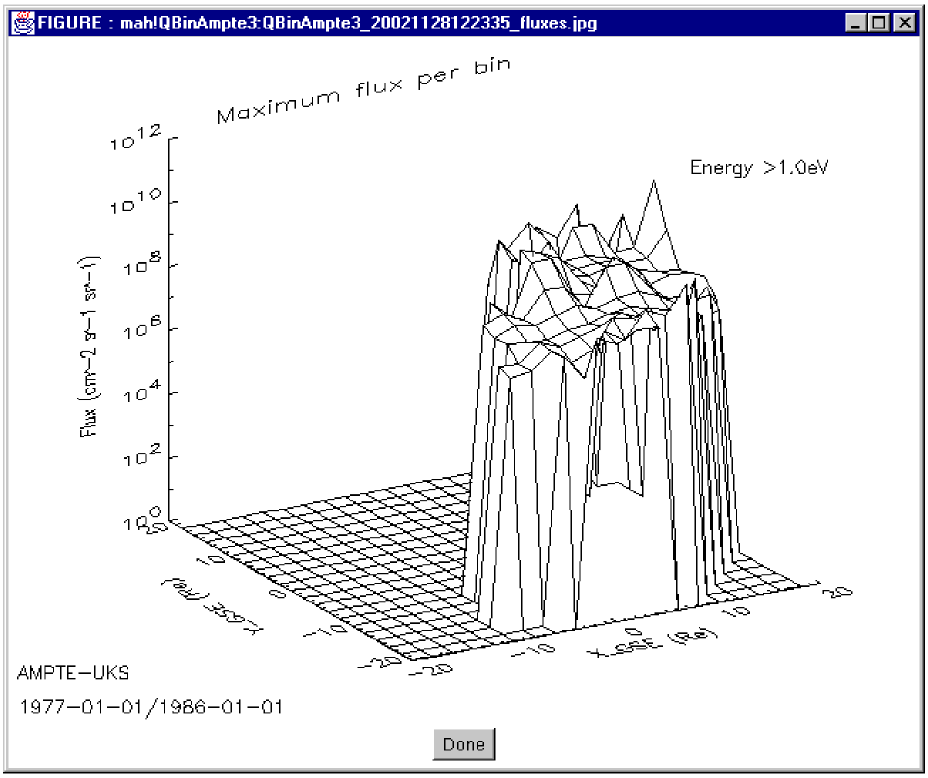

Figure 11. Maximum electron fluxes from AMPTE-UKS

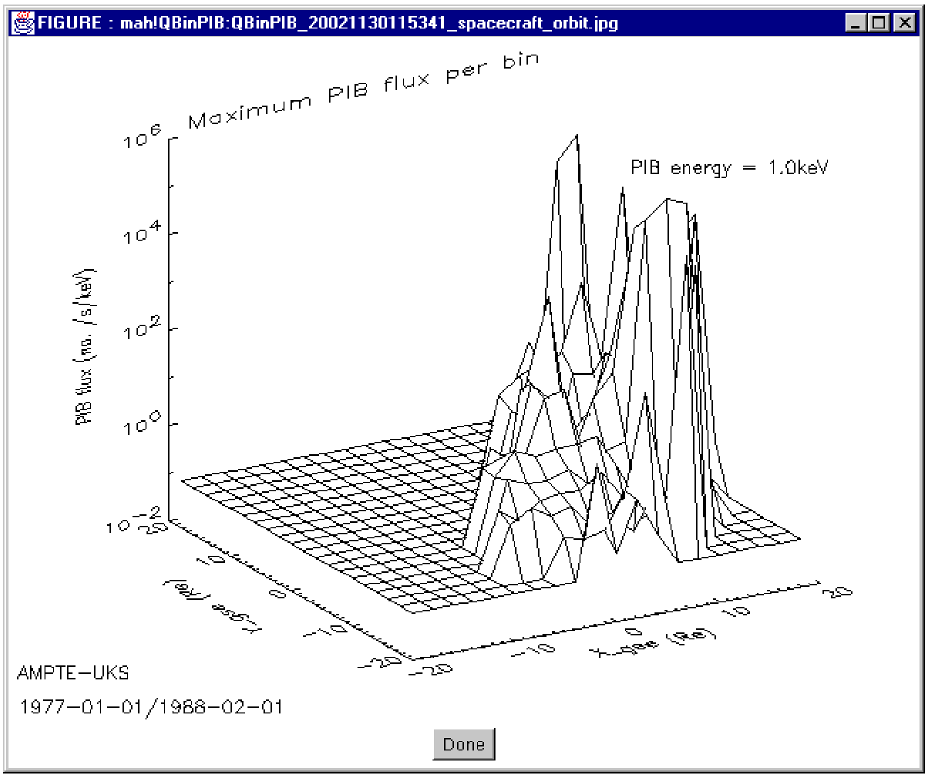

Figure 12. Maximum PIB fluxes from AMPTE-UKS.

8 PIB flux along a trajectory

8.1 Introduction

The final objective in WP304 is to estimate PIB fluxes along an arbitrary trajectory by reference to energetic electron data previously taken at positions along that trajectory and the PIB spectra derived from those fluxes. To do this we:

- build a dataset of PIB fluxes labelled with positional data
- generate the trajectory for which PIB fluxes are required
- retrieve the PIB fluxes close to each position on the trajectory and calculate their minimum, median and maximum values
- display these values as a function of position along the trajectory

The positional data used in this analysis may be a geometric position (X, Y and Z in a suitable coordinate system) or a magnetic position (McIlwain L parameter). We present examples of both approaches.

8.2 Building the PIB spectra

This tool scans through the electron data and processes each record as follows:

- It extracts the electron spectrum and checks any quality flags, e.g. the ISEE-2 quality flag described at the beginning of section 6.2.
- If the electron spectrum is of good quality, it derives the corresponding PIB spectrum using the tool described in section 3.
- The PIB spectrum (energies and fluxes) is then written to a new record in the output dataset. Each record is also tagged with the time-tag of electron spectrum, a code indicating the electron dataset from which the spectrum was extracted, the GSE position at which the electron flux was measured together with the McIlwain L parameter and total magnetic field strength at that position.

8.3 Scanning along a trajectory

This tool first reads the required trajectory from a file produced by the orbit generator described in section 4 and stores the trajectory data in a suitable data structure. The trajectory data are set of records giving the geometric and and magnetic position at each point. The geometric position may be transformed from GSE to the desired system using the convcoord system tool.

The next step is to scan through the PIB spectra dataset described in section 8.2 above to identify the spectra that can be associated with each point on the trajectory. To do this the tool creates a “bin” for each point that can hold up to 5000 PIB spectra. It then processes each record of the PIB spectra dataset as follows:

- It retrieves the position data from each record and, if necessary, converts the geometric position from GSE to the desired system using the convcoord system tool.
- It then checks whether the position is close to one or more points on the trajectory. For geometric positions closeness is defined as a separation of less than 2 Re and for magnetic position a difference of 1 unit in L value.

- For each point on the trajectory that is close to the current position, the PIB spectrum is stored in the bin for that point on the trajectory.

Once the scan is complete, the tool calculates the minimum, maximum and median PIB flux at each point on the trajectory, which are then plotted as a function of position along the trajectory. The present tool does these last steps for just a single PIB energy, which can be selected by the user.

8.4 Results

Figure 13 shows the tool output for an orbit of the XMM-Newton spacecraft with the data binned according to closeness in GSM X, Y and Z coordinates, i.e. separation = $\sqrt{(\Delta x^2+\Delta y^2+\Delta z^2)}$. The PIB values are derived from the extensive ISEE2 dataset. The top panel shows the distance of the spacecraft from the centre of the Earth and is used an indicator of position around the orbit from perigee (start) to apogee (middle) and back to perigee (end). The middle panel shows the number of 1 keV PIB fluxes associated with each point on the trajectory. This is high near perigee but rapidly falls off away from perigee – and is zero for the majority of the orbit. This distribution reflects the the fact that the ISEE-2 data had a near-equatorial orbit (inclination 13.5°) whilst the XMM orbit has significant inclination (40°). Thus, if we specify the closeness criterion in all three dimensions, XMM is in the region sampled by ISEE-2 only when close to perigee. The bottom panel shows the resulting PIB flux statistics at 1 keV. The three curve show the minimum, median and maximum values of the flux. These are coloured cyan, black and magenta respectively though they can be identified by their position on the plot. This panel shows that there is considerable variability in the likely PIB fluxes with three or four orders of magntitude spread between minimum and median and another two orders of magntitude between median and maximum. The convergence of three curves away from perigee is an artifact of the rapidly reducing numbers of samples contributing to the statistics.

Figure 14 shows the tool output for an orbit of the XMM-Newton spacecraft with the data binned according to closeness in L value and with the PIB values again derived from ISEE2 data. The panel layout is as before. The middle panel shows that the numbers of 1 keV PIB fluxes associated with points on the trajectory are now high over a much larger part of the orbit, i.e. binning by L value gives a much better coverage of the orbit. The only region in which these numbers are low is at high L value (>20). The bottom panel of Figure 14 shows again that there is very considerable variability in the likely PIB fluxes.

- The median PIB flux is about 10 s^{-1} keV^{-1} around perigee and gradually falls away as L increases reaching a value of 0.1 s^{-1} keV^{-1} at around L=15, after which it remains constant with increasing L value. Given that L value distinctions are not very meaningful above L = 15, it would be reasonable to assume that this constant level of 0.1 s^{-1} keV^{-1} also applies across the apogee data gap. The high perigee fluxes probably represent the effects of trapped electrons in the inner magnetosphere while the constant level represents some average flux in the outer magnetosphere.
- The minimum PIB flux is about 10^{-4} s^{-1} keV^{-1} around perigee but falls quickly away as L increases reaching a value of 10^{-6} s^{-1} keV^{-1} at around L=10 but rises again beyond L=15 and reaching 10^{-2} s^{-1} keV^{-1} around L=20. The low values between L=10 and L=15 may represent the very low fluxes that are possible on open field lines when the heliospheric population is low. In this case the magnetospheric electron population can escape and is not replaced by incoming heliospheric electrons. The high values beyond L=20 may represent the tail neutral sheet population.

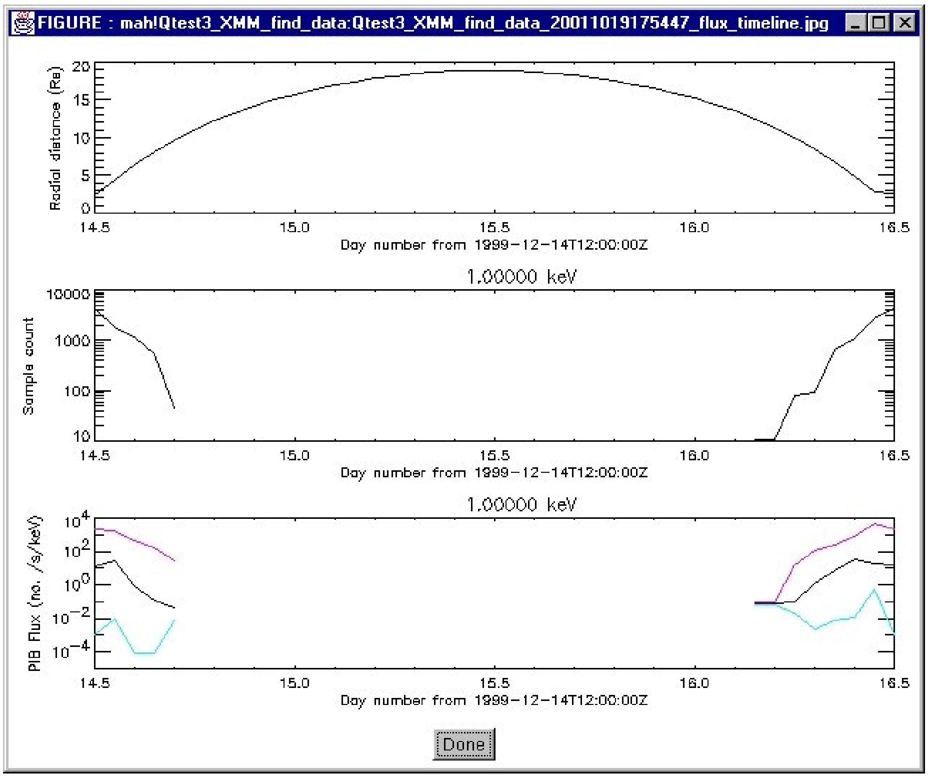

Figure 13. PIB fluxes along an XMM orbit - binned by GSM X, Y and Z.

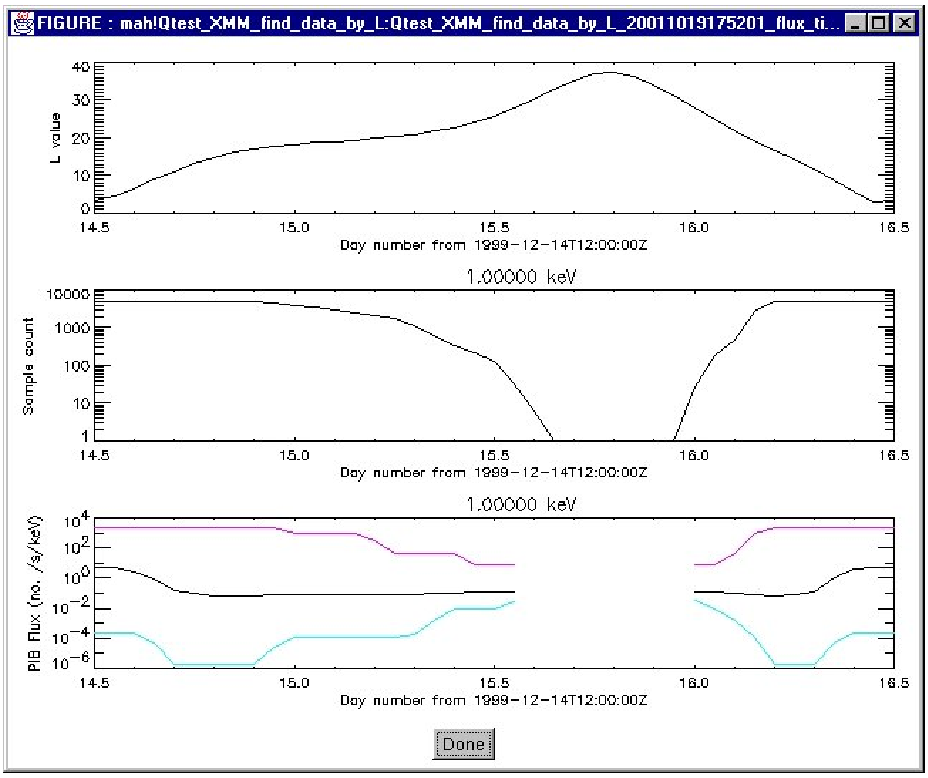

Figure 14. PIB fluxes along an XMM orbit - binned by L value.

- The maximum PIB flux is above 1000 s^{-1} keV^{-1} around perigee and in a region extending to L=15. Beyond this maximum falls reaching 10 s^{-1} keV^{-1} at L=20 after which it remains constant with increasing L value. As with the median values it would be reasonable to assume that this constant level also applies across the apogee data gap. This distribution suggests that the highest PIB fluxes are due to strong electron fluxes generated within the Earth's magnetosphere.

In summary, Figure 14 shows that there is a large spread between minimum, median and maximum PIB fluxes. But binning of data by L value suggests that it may be possible to classify the PIB flux statistics if L value is used to distinguish different magnetospheric regions together with the magnetic topology and electron populations expected in those regions.

9 Conclusions

9.1 Comparison with EWP 1942

The plots and discussion in section 6 indicate that the SEDAT tools, applied to the same ISEE2 dataset as used in the EWP 1942 study [R2], give results (both for flux and PIB) in broad agreement with that earlier study. In gaining that agreement it was vital to pay close attention to the schemes used to interpolate and extrapolate electron flux data to other energies. The use of purely mathematical procedures, such as the generic interpolation tools available in IDL, proved unsatisfactory. It was necessary to use a more complex scheme informed by our physical understanding of the typical behaviour of electron spectra (e.g. exponential scaling with energy below 30 keV, power law scaling above).

The results of EWP 1942 were also compared with SEDAT results using an independent dataset, namely the AMPTE-UKS electron data, and are presented in section 7. This is a small dataset with limited coverage in magnetic local – it is mainly focused on the dayside magnetosphere and magnetopause. But its energy range (10 eV to 16 keV) includes the most effective energies for PIB production (1-10 keV). Thus its use in PIB analysis is less sensitive to the extrapolation procedure than is the ISEE-2 data, with its higher energy range of 18 keV to 1 MeV. Despite this important difference, the flux and PIB values derived from AMPTE data were generally in good agreement with those shown in EWP 1942. This agreement of independent indicates that the SEDAT tools are in good agreement with EWP 1942 and that they both provide a robust estimate of the PIB fluxes.

The one caveat on the AMPTE analysis is the presence of occasionally peaks in PIB in the vicinity of the magnetopause. This requires further study.

9.2 PIB flux along a trajectory

The calculation of PIB fluxes along a trajectory is presented in section 8. This shows that it is possible to use measured electron fluxes to estimate the statistical distribution of PIB along a trajectory. But the quality and coverage of the results depends critically on the method used to match the trajectory with the spatial distribution of PIB. If this matching is done by matching positions in all three dimensions of geometric space (e.g. GSE X, Y and Z), the result is poor because it is hard to find a match if the electron measurements are made on a different orbit to the PIB target spacecraft. Instead we need a matching criterion that can link positions on orbits with different geometric positions. We used the McIlwain L parameter for this purpose because this gives a crude way of matching points on the same geomagnetic field line, and the spatial distribution of electrons is constrained by that field. Our results show that L value matching yields PIB distributions with much better coverage of the XMM orbit.

This coverage is not complete because XMM sometimes crosses the magnetopause and thus enters regimes (magnetosheath and solar wind) where L values are not applicable. This leads to a lack of coverage around apogee. This requires further attention, e.g. using a different matching technique outside the magnetopause.

This analysis might also be extended by:

1. Binning by separation in GSM X, Y only. This would ensure good coverage of the XMM orbit because the different inclinations of ISEE2 and XMM-Newton lead to a large separation in the

Z component. However, binning in these coordinates is probably less physically meaningful than binning by L value, which effectively samples the magnetic topology that orders the energetic electron fluxes.

2. Distance from the tail neutral sheet. One key region in which energetic electron fluxes are enhanced is the tail plasmasheet. This region is centred on the tail neutral sheet and extends several Earth radii either side of the neutral sheet. To identify the plasmasheet in a datset, it is best to order the data with respect distance from the tail neutral sheet, where that distance is the difference in the GSM Z component of positions where the data was recorded and of the neutral sheet (at the same GSM X and Y). This may be done using a suitable model of the neutral sheet location, e.g. [R10] as used in Cluster planning [R11]. However, this would require substantial enhancement of existing SEDAT tools and thus beyond the scope of this study.

10 Annex A – summary of tools used in this demonstration

The tools used in WP304 comprise a mixture of standalone and interlinked tools. The standalone tools are those used to replicate the previous ESTEC results presented in EWP 1942 [R2] – namely (a) to plot data-taking trajectories (mah!ReadAmpte), (b) to calculate and display statistics of electron fluxes in bins in the GSE X and Y plane (mah!BinAmpte), and (c) to calculate and display statistics of PIB values in the same binning scheme (mah!BinPIB). The interlinked tool set is used to calculate PIB along trajectories of interest as required by the Statement of Work [A1]. This set is shown in Figure 15 below with the top-level tools as blue boxes and the SEDAT datasets flowing between those tools as green boxes. The full set of top-level tools and queries is listed in Table 7 together with a summary of the functionality that they provide. The parameters for these queries are listed in Table 8.

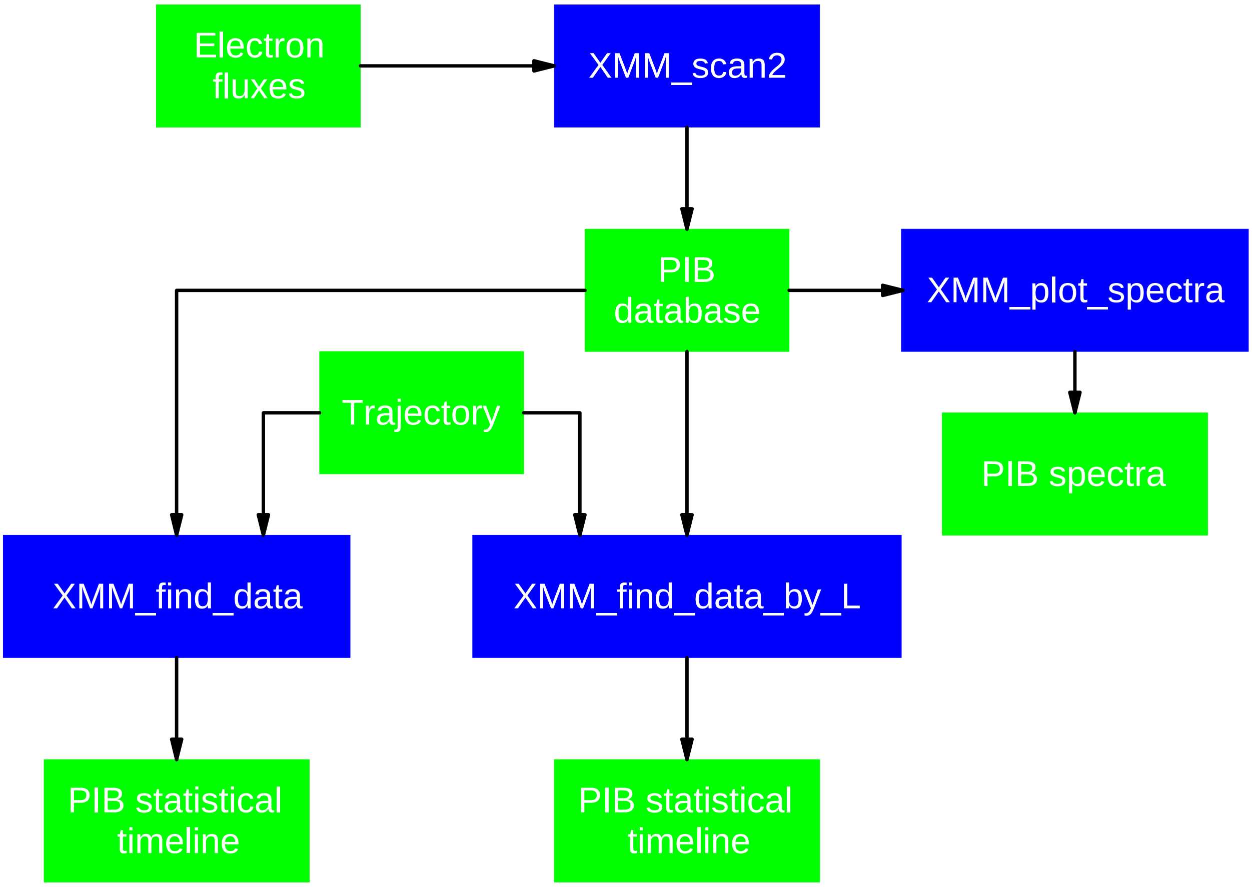

Figure 15. Data flow for WP304.

The first step in the interlinked tool set is to convert electron fluxes into particle induced background values. This is done by the mah!XMMscan2 tool, which generates a database of PIB spectra, each tagged with a geometric and a magnetic position. The database can be inspected using the mah!XMM_plot_spectra tool. The timeline of PIB values along a given trajectory is calculated by tools that search the PIB database to find a set of spectra that match each point on the trajectory. This matching can be done in terms of geometric position (using the mah!XMM_find_data tool) or in terms of L-value (using the mah!XMM_find_data_by_L tool). Both tools take the PIB database and the trajectory as input. They both generate statistical values (minimum, median and maximum PIB flux) at each point along the trajectory and output these in graphical form.

Table 7. Top-level tools for WP304 plus their queries

Tool	*Query*	*Function*
mah!readampte	mah!QreadAMPTE	Plot data-taking trajectories
Mah!binampte	mah!Q2BinAMPTE	Calculate and display binned electron fluxes
Mah!binPIB	mah!Q2BinPIB	Calculate and display binned PIB fluxes
Mah!XMM_scan2	mah!QXMM_scan2	Convert electron fluxes into a PIB database
Mah!XMM_plot_spectra	mah!QXMM_plot_spectra	Inspect PIB database
Mah!XMM_find_data	mah!Qtest3_XMM_find_data	Calculate PIB fluxes along a geometric trajectory
Mah!XMM_find_data_by_L	mah!Qtest_XMM_find_data_by_L	Calculate PIB fluxes along a trajectory in L values
Mah!make_usoc_orbit	mah!Qmake_usoc_orbit	Calculate spacecraft trajectory given orbit elements in USOC format

Table 8. Parameters used by WP304 queries

Parameter	*Description*	*Recommended values*
mah!QreadAMPTE		
Start_time	Start time of data search	Start time as CCSDS ASCII code A, i.e. yyyy-mm-ddThh:mm:ssZ
End_time	Stop time of data search	Stop time as CCSDS ASCII code A
Dataset_code	Integer code identifying the spacecraft on which data were taken	1 = AMPTE-UKS, 2 = ISEE2
Electron_data	Dataset that contains the position data to plot	Select “Dataset” from dropdown menu, then use second dropdown menu to select the name of the electron dataset to process
mah!Q2BinAMPTE		
Start_time	Start time of data search	Start time as CCSDS ASCII code A, i.e. yyyy-mm-ddThh:mm:ssZ
End_time	Stop time of data search	Stop time as CCSDS ASCII code A
Dataset_code	Integer code identifying the spacecraft on which data were taken	1 = AMPTE-UKS, 2 = ISEE2
Electron_data	Dataset that contains the electron data to be binned	Select “Dataset” from dropdown menu, then use second dropdown menu to select the name of the electron dataset to process

Parameter	*Description*	*Recommended values*
mah!Q2binPIB		
Start_time	Start time of data search	Start time as CCSDS ASCII code A, i.e. yyyy-mm-ddThh:mm:ssZ
End_time	Stop time of data search	Stop time as CCSDS ASCII code A
Dataset_code	Integer code identifying the spacecraft on which data were taken	1 = AMPTE-UKS, 2 = ISEE2
Electron_data	Dataset that contains the electron data to be convert to PIB and bin	Select “Dataset” from dropdown menu, then use second dropdown menu to select the name of the electron dataset to process
Mah!QXMM_scan2		
Electron_data	Dataset that contains the electron data to be analysed	Select “Dataset” from dropdown menu, then use second dropdown menu to select the name of the electron dataset to process
Start_time	Start time of data search	Start time as CCSDS ASCII code A, i.e. yyyy-mm-ddThh:mm:ssZ
End_time	Stop time of data search	Stop time as CCSDS ASCII code A
Dataset_code	Integer code identifying the spacecraft on which data were taken	1 = AMPTE-UKS, 2 = ISEE2
mah!QXMM_plot_spectra		
Dataset	Dataset that contains the PIB database, e.g. as produced by mah!QXMM_scan2	Select “Dataset” from dropdown menu, then use second dropdown menu to select the name of the dataset containing the PIB database.
mah!Qtest3_XMM_find_data		
Trajectory_data	Name of dataset holding the spacecraft trajectory in terms of time-tagged Cartesian position, L and B values.	Select “Dataset” from dropdown menu, then use second dropdown menu to select the name of the orbit data to analyse
PIB_data	Dataset that contains the PIB database, e.g. as produced by mah!QXMM_scan2	Select “Dataset” from dropdown menu, then use second dropdown menu to select the name of the dataset containing the PIB database
Energy_channel	Integer that identifies energy level for which PIB is to be plotted.	Value between 1 and 21, representing energies logarithmically spaced between 0.1 and 10.0 keV, e.g. N keV 1 0.100 6 0.316 11 1.000 16 3.162 21 10.000

Parameter	*Description*	*Recommended values*
mah!Qtest_XMM_find_data_by_L		
Name of dataset holding the spacecraft trajectory in terms of time-tagged Cartesian position, L and B values.	Name of dataset holding the spacecraft trajectory in terms of time-tagged Cartesian position, L and B values.	Select “Dataset” from dropdown menu, then use second dropdown menu to select the name of the orbit data to analyse
Dataset that contains the PIB database, e.g. as produced by mah!QXMM_scan2	Dataset that contains the PIB database, e.g. as produced by mah!QXMM_scan2	Select “Dataset” from dropdown menu, then use second dropdown menu to select the name of the dataset containing the PIB database
Integer that identifies energy level for which PIB is to be plotted.	Integer	Value between 1 and 21, representing energies logarithmically spaced between 0.1 and 10.0 keV, e.g. N keV 1 0.100 6 0.316 11 1.000 16 3.162 21 10.000
mah!Qmake_usoc_orbit		
Orbit_data	Name of dataset holding elements in USOC style	Select “Dataset” from dropdown menu, then use second dropdown menu to select the name of the orbit data to analyse
Time_string	String that specifies start and end times, and step size, of calculation. Times are MJD and step size is in days. Values have Fortran format (18X,F7,7X,F7,7X, F5).	xxxxxxxxxxxxxxxxxx51566.5xxxxxxx51568.5xxxxxxx00.05

Table 9. Other important tools used in WP304

Name	Type	Description
mah!calc_xyz	Function	Calculate GEI Cartesian position of spacecraft given radial distance, true anomaly and orbit elements
mah!cluster_wrapper	Function	Maps the clustran_one call interface on to the system level convcoord interface
mah!extract_si_con	Function	process an SI conversion string supplied in the format
mah!extrapolate_eflux2	Functions	Set of procedures for interpolating and extrapolating electron fluxes

Name	Type	Description
mah!kepler	Function	Calculate radial distance and true anomaly given Keplerian elements and time
mah!make_orbit_pos	Function	Calculate GEI Cartesian position of spacecraft given orbit elements and time
mah!make_this_orbit	Function	Select the set of Keplerian elements applicable to given time
mah!make_tn304_photons	Function	Specifies data structure for X-ray photon spectrum
mah!time_lib	Functions	Library of tools for manipulating time values: • CDFepoch_CCSDS - function to convert CDF epoch to CCSDS A format • CCSDS_CDFepoch - function to convert CCSDS A format to CDF epoch • CDFepoch_MJD - function to convert CDF epoch to MJD • MJD_CDFepoch - function to convert MJD to CDF epoch
mah!valid_num	Function	Check if string is a valid IDL number – routine from SOHO library
mah!XMM_calc_pib_v2	Function	calculates a PIB X-ray spectrum for the XMM mirror shells
mah!XMM_matrix_tool	Function	calculates transfer function between electron spectra and the PIB X-ray spectra for the XMM mirror shells

11 Annex B - Compliance matrix

The table below shows the compliance between this report and the demonstration plan [R12]. The item numbers relate to items in the procedure section (4.2) of that plan and compliance section numbers relate to the sections of this document.

Item from Plan	Description	Compliance in section
1,3	Electron data selection	**Error! Reference source not found.** and **Error! Reference source not found.**
2	FEF inspection	**Error! Reference source not found.**
4		**Error! Reference source not found.**
5	Merging of event lists	**Error! Reference source not found.**
11-14	Analysis of event lists against a log-normal model	**Error! Reference source not found.** and **Error! Reference source not found.**
15-18	Fluence prediction by a JPL-like model	**Error! Reference source not found.**
Section 4.2.1 Generation of PIB spectra		
1-2	Fluence prediction by sampling	**Error! Reference source not found.** and **Error! Reference source not found.**