Calibration Report of
the RAPID Measurements
in the Cluster Science Archive (CSA)

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# Table of Contents

Reference Documents

List of Acronyms

1 Introduction

2 Instrument Description
   2.1 The IIMS Instrument
   2.2 The IES Instrument
   2.3 Spin Sectorization
   2.4 Accumulation Time

3 Measurement Calibration Procedures
   3.1 Calibration Releases
   3.2 Calibration and Auxiliary Files
   3.3 The Calibration Procedure for IIMS
   3.4 The Calibration Procedure for IES

4 Measurement Processing Procedures
   4.1 Level 1: The Raw Data Set
   4.2 Level 2: Science Data Processing

5 Results of Calibration Activities
   5.1 IES
     5.1.1 Efficiency decay
     5.1.2 Spectral rebinning
     5.1.3 Pedestal noise correction on SC3 and SC4
     5.1.4 Solar noise on SC3 and its correction
     5.1.5 Failure of IES on SC2
   5.2 IIMS
     5.2.1 1st He and CNO energy channels
     5.2.2 Time-of-Flight efficiency
   5.3 Features of IIMS Series 4

6 Results of Cross-Calibration Activities
   6.1 RAPID/IIMS and CIS/CODIF cross-calibration
   6.2 1st CNO energy channel
   6.3 RAPID/IES and PEACE cross-calibration
     6.3.1 RAPID/IES Histogram mode analysis
     6.3.2 RAPID/IES calibration: statistical study
   6.4 The IES Energy Defect
     6.4.1 Corrections for the energy defect
     6.4.2 Latest determination of the IES energy defect

7 Automatic Spike Removal
   7.1 The Despiking Procedure
   7.2 Heater Spikes (Hatchets)

8 IES Detector Decay
   8.1 Starting time of the decay effect
   8.2 Environmental effects
   8.3 Determination of correction factors
Reference Documents


List of Acronyms

BM  Burst Mode, Cluster high telemetry rate
CDF  Common Data Format (NASA format)
CEF  Cluster Exchange Format (CSA format)
CF   Conversion Factor
CSA  Cluster Science Archive
ENY  Energy Signal Rate (RAPID/IIMS)
GF   Geometry Factor
IES  Imaging Electron Spectrometer (part of RAPID)
IIMS Imaging Ion Mass Spectrometer (part of RAPID)
MCP  Multichannel Plate
MSF  Merged Science File (RAPID raw data)
NM   Nominal Mode, Cluster low telemetry rate
RAPID Research with Adaptive Particle Imaging Detectors (Cluster Experiment)
SAA  Solar Aspect Angle
SCENIC Spectroscopic Camera for Electrons, Neutral, and Ion Composition (part of RAPID)
SCI  SCIence file, RAPID-specific format for processed data
TCR  Triple Coincidence Rate (RAPID/IIMS)
TOF  Time-Of-Flight
1 Introduction

The CSA has the objective of archiving all the relevant scientific data, metadata, documentation, support files, etc., from the Cluster Mission (launched July-August 2000, see Escoubet et al. [1997] for payload description) while the Mission is still operating and the experiment teams still active.

As one of the Cluster experiments, RAPID, an imaging spectrometer for ions and electrons of energies over \( \sim 30 \text{ keV} \), is contributing to this effort.

One of the important activities of the RAPID team is the calibration of data. Since the start of the operations phase of Cluster in early 2001, a number of problems involving RAPID have been recognized, problems which were given only provisional solutions at the time. These problems have now been analyzed to the extent that solutions are now possible.

The purpose of this document is to outline those problems, their causes, and to show how they are to be solved. It is intended as an explanation for the CSA users on how the calibrations were done and which problems one can encounter.

A detailed description of the RAPID products at CSA is given in the RAPID Interface Control Document [RAP-ICD]; a more general overview of the products can be found in Daly and Kronberg [2010], and a description of how to use them in the RAPID CSA Users Guide [RAP-UG].

2 Instrument Description

The RAPID experiment is described by Wilken et al. [1997], and also in the Flight Operation Manual [RAP-FOM]. The RAPID instrument uses two different and independent detector systems for the detection of nuclei and electrons: The Imaging Ion Mass Spectrometer (IIMS) and the Imaging Electron Spectrometer (IES).

2.1 The IIMS Instrument

The IIMS sensor measures ions with energies from \( \sim 28 \text{ keV} \) to \( \sim 4 \text{ MeV} \). The centerpiece of the IIMS sensor system is the so-called SCENIC (Spectroscopic Camera for Electrons, Neutral, and Ion Composition) detector head, shown at the right in Figure 1. In essence, this is a miniature telescope composed of a time-of-flight and an energy detection system. The particle identifying function of the SCENIC spectrometer is obtained from a two-parameter measurement: the particle’s velocity \( V \) and its energy \( E \) are measured as independent quantities; the particle’s mass \( A \) is then uniquely determined either by computation \( (A \sim E/2) \) or by statistical analysis in two-dimensional \((V, E)\) space with the mass \( A \) as the sorting parameter. Actually the velocity detector measures the flight time \( T \) taken by the particle to travel a known distance in the detector geometry.

Each SCENIC head has a field-of-view that is 6\(^\circ\) wide (in the direction of the spacecraft spin) and 60\(^\circ\) in the other direction (in the plane containing the spin axis). By means of the imaging features of this instrument, the particle’s incident direction is assigned to one of 4 subdivisions of this field-of-view, each of 15\(^\circ\) height. With three detector heads in all, the full range of 0–180\(^\circ\) is covered by 12 polar angular segments (left side of Figure 2).

2.2 The IES Instrument

Electrons with energies from \( \sim 30 \text{ keV} \) to \( \sim 400 \text{ keV} \) are measured with the IES (Imaging Electron Spectrometer). Advanced microstrip solid state detectors having a 0.5 cm \( \times \) 1.5 cm planar format with three individual elements form the image plane for three acceptance “pin-hole” systems. Each system divides a 60\(^\circ\) segment into 3 angular intervals (Figure 1, left). Three such detector heads provide electron measurements over a 180\(^\circ\) fan (middle of Figure 2).
Figure 1: Left: One of the three IES heads, containing three solid state detectors to determine the direction of the incoming detected electron to within 20°. Right: One of the three SCENIC heads making up the IIMS part of RAPID. Shown is an incoming ion that triggers a start signal at a foil, which also serves to determine the fine direction, and a stop signal when it enters the solid state detector, where its energy is measured.

Figure 2: The IIMS and IES polar segments relative to the spin axis (left and center) and the RAPID sectorization relative to the sun (right). Note that the spin axis actually points towards the $-Z$ GSE axis (southward).
Figure 3: An idealized histogram plot for IES data. The number of measurements per second is constant, depending on integration time. The majority of measurements are empty, contain just a background charge but no electrons, and they form the pedestal (large peak at left). True electrons deposit an additional charge, so that a monoenergetic beam could create the peak at the right. The center of the pedestal thus corresponds to the zero of energy.

Ions up to 350 keV are eliminated by an absorbing foil in front of the detectors.

The 3rd dimension, energy, is determined by the charge deposited in the detector by the absorbed electron, which is proportional to that energy (minus a constant). IES employs an integration method for this: that is, it accumulates all charges deposited during a selected integration time; the total charge (corresponding to the total energy) is then swept out and measured during a fixed read-out time, which constitutes a dead-time. Thus the total number of counts per second is constant for a given integration time. The analog signal is digitized to a bin number between 0 and 255, at 2.2 keV per bin. The number of counts in each bin can be plotted as a histogram as in Figure 3. The majority of these counts contain no real particles, but contribute to the pedestal, the location of zero energy. The pedestal arises because the detectors are slowly charged during the integration time by background currents. The actual 6–8 science energy channels are defined on-board in terms of the 256 bin numbers, relative to the expected location of the pedestal.

A description of the IES instrument and many of its calibration issues can be found in the thesis by Braginsky [1997].

2.3 Spin Sectorization

For both IIMS and IES, the azimuthal distribution of particle fluxes is obtained by sorting the counts into 16 sectors during one rotation of the spacecraft (right side of Figure 2).

The spin phase relationship between the sun sensor pulse and the start of sector 0 (the start of a new spin) is fixed so that the RAPID detectors are looking into the direction of the sun at sector 13.326, or about one third into sector 13. (This relationship has been set in agreement with the other experiments so that all start a new spin simultaneously.)

Note: For the IES heads 1 and 3, there are really only 8 sectors in the raw data. In order to simplify the dataset for the users, the processed data are put into regular rectangular matrices of 9×16. This is done by splitting each of the 8 sectors into two and by placing half the counts into each sector half. Thus for the polar directions 1–3 and 7–9, although 16 sectors exist mathematically, the fluxes in each pair (0,1), (2,3) … (14,15) are identical.
2.4 Accumulation Time

The RAPID detectors do not accumulate counts all the time; there is a dead time that leads to a duty cycle of less than 100%.

**IIMS:** in the usual serial mode, each ion head accumulates for a fixed 60 ms within each sector, one after the other. This means the duty cycle depends on spin rate. For a nominal 4 s spin, one sector requires 250 ms, so each head accumulates for only 24% of the time. During the remaining dead time, the counts from the previous sector are processed and other housekeeping tasks are performed.

There is also a parallel mode that was used early in the Mission; in this mode, all three heads accumulate simultaneously for 180 ms per sector.

In the first few months of the Mission, before the main patch was uploaded, the accumulation times were 65 and 195 ms, respectively.

**IES:** the total energy deposited by electrons during one integration interval is accumulated and then read out over the next 48 µs. The integration interval is one of 2, 5, 15, and 50 µs, depending on count rate. It is vital that at most one electron per interval is detected, otherwise it is the summed energy of multiple electrons that is registered. Thus the integration time should be as short as possible. On the other hand, it is desirable to have a long integration time to improve the duty cycle. The maximum duty cycle of ~50% is achieved with an integration time of 50 µs. This is the usual case except during times of high count rates.

An autoswitching mechanism is in operation to automatically switch the integration time according to count rates.

3 Measurement Calibration Procedures

3.1 Calibration Releases

There have been four major releases of calibration data for the RAPID experiment since the launch of Cluster. These can be summarized as:

**Commissioning:** preliminary values prepared before the launch, suitable for the commissioning phase.

**Initial Release:** following commissioning, revised values and subsequent updates were applied for the initial operation phase; however it soon became apparent that the provided parameters were not capable of accommodating the observed evolution of the instrument performance.

These are the calibration parameters used for the first release of the RAPID data to CSA, and which are now considered obsolete, hence they will not be further described here.

**Subsequent Releases:** work on improved and more flexible calibration parameters began with systematic analysis of the instrument behaviour in flight, and an initial report on why changes were needed.

A new method of handling and maintaining calibration parameters was introduced. Whereas previously the choice and number of parameters were rigidly fixed, the new method allows additions and modifications without having to redefine and reprocess the entire set.

However, it was not until mid-2007 that reliable values for the new parameters could be safely implemented. Since then regular updates are carried out to extend the validity of the parameters up to the near present.

The second release of the RAPID CSA data have been produced with these calibrations, which bear the calibration version number 2. (This is the most significant digit in the dataset version number, described in Section 5.4 of RAP-UG.)
Beginning in September 2015, a complete redelivery of all datasets was started, the third release, bearing the calibration version number 3. This was not so much the result of a recalibration, but rather a set of systematic fixes for several issues (including bugs) that had arisen over the years. Important additions were the automatic removal of spikes (Section 7) and the correction of the decay of the IES electron detectors (Section 8) and the partial failure of IES on SC2 (Section 9).

In June 2018, after almost a year of reanalysing the IIMS ion calibrations, a new set of calibration files was ready, as the basis of the fourth release. At the same time, the IES electron calibrations were also upgraded for this release to include revised decay correction factors and the removal of an error in the recovery on SC2. For both ions and electrons, the calibration version number is now 4.

### 3.2 Calibration and Auxiliary Files

To get some impression of how calibration files are working one has to be familiar with a couple of definitions described in the following.

**Calibration set:** is a set of parameters needed for calculating flux from counts, valid for one spacecraft and for a given period of time.

**Calibration file:** is the file that the processing software reads, containing a collection of calibration sets.

The software reads this file until it finds the set that is valid for the time being processed, noting the end time as well. When the current process time exceeds this end time, the calibration file is read once more, to find the next valid set. Thus the current calibration set can change at any time, not just at day boundaries.

**Calibration file series and version number:** as the calibration parameters alter with time, new (time-limited) sets are added to the calibration files, which are then given a new number to distinguish them. This sequence of 3-digit numbers forms a series, all beginning with the same digit.

When a major change to the calibrations takes place, a reevaluation of all parameters from the beginning, then a new series is initiated, with a new first digit. Currently the calibration files are numbered 4xx (series 4), replacing the existing series 3 ones at CSA.

The series number is equivalent to the calibration version number that is the first digit of the dataset version (Section 5.4 in RAP-UG, and also in RAP-ICD).

This complicated arrangement has the advantage that per spacecraft and IIMS/IES, there is only one calibration file containing all the time-dependent changes in any of the parameters. This avoids having several files valid for only certain times. The RAPID calibration files as a whole are valid for all times up to a certain expiry date, although the individual sets within them may have limited validity.

For Cluster/RAPID science data users, it is also important to understand the relationship between count rates and fluxes. A description of the procedures to convert raw counts into differential fluxes using geometry factors and detector efficiency, as well as the calculation of omnidirectional flux, can be found in Appendix A.

### 3.3 The Calibration Procedure for IIMS

The IIMS calibration files are produced in three steps:

1. A basic set of calibration files is made containing all the fixed or well-determined parameters. This includes the pure geometrical factor, the ideal TOF efficiencies, the accumulation times, and the MCP voltages. With this, the 3-D count rates, the direct events, and the diagnostic "singles" are generated.

2. The next step is to produce the preliminary calibration files.
• From the direct events, we find the fraction of counts (per species and energy channel) in each of the 12 directions, to give the directional distribution, or DD parameters. This indicates how well the different heads and sub-directions are working, relative to one another.

• From the singles, we get the TOF efficiency as described in Section 5.2.2, the TE factors, one value per spacecraft and day, but only for sufficiently high correlations.

A linear fit with time is carried out for each of these factors. Suitable break-points for the fitting intervals are set when the MCP voltage changes, or when a visual inspection indicates that the linear change with time is no longer reasonable.

The resulting sets of fit parameters then go into the next calibration files. These are used to produce preliminary 3-D fluxes.

3. The final calibration files are now generated to include cross-spacecraft parameters XS. The orbit-averaged fluxes on all the functioning heads are normalized to their mean value and the normalization factors are subjected to a linear fit over time. These fit parameters now conclude the calibration procedure.

It might be objected that the last step is designed to remove not only all anisotropies but also any differences between the spacecraft. This would be true if it were done for each data point. However, the linear fitting guarantees that only the long-term averages (over weeks or months) are made uniform. Any individual time period can exhibit large anisotropies and spatial differences.

Note that only the final calibration files are released for use by the outside community. The basic and preliminary files are used only internally by the RAPID Team.

The calibration files are extended in time as new data become available.

3.4 The Calibration Procedure for IES

The basic set of parameters for IES are as follows:

Geometry factors are $2.22 \times 10^{-3}$ cm$^2$·sr for the “outer” detectors of each head (1, 3, 4, 6, 7, 9) and $2.23 \times 10^{-3}$ cm$^2$·sr for the “inner” detectors (2, 5, 8).

Energy conversion is 2.2 keV per bin (Figure 3).

Detection efficiency is taken to be 100%.

Dead layer loss is 6.5 keV. Originally this was taken to be a constant but it has now become apparent that it increases at lower energies ($<50$ keV), requiring a redefinition of the lowest energy thresholds (Section 6.4).

There are additional parameters to handle special problems that have arisen since the start of the mission, such as pedest al noise (Section 5.1.3) and solar contamination (Section 5.1.4).

Furthermore, starting about 2007, there is an increasing efficiency decay in all detectors, which is strongly dependent on the angle to the spin axis. Additional time-dependent corrections factors need to be determined and applied (Section 8).

What is periodically changed is the definition of the energy channels in terms of the 256 bin numbers. These are set with the integer parameters:

- $P$, the bin number of the center of the pedestal,
- $S$, the width of the pedestal, in bins,
- $B_1, \ldots B_8$, the upper limits to the 8 energy channels, relative to $P$. 

Cluster Science Archive — Calibration Report — RAPID
The lower limit of channel 1 is then $P + 2S$; this is set not only relative to the pedestal position, but also to its width. For channel $n \ (n > 1)$ the lower limit becomes $P + B_{n-1}$. The upper limit of channel $n \ (including \ 1)$ is $P + B_n - 1$, one less than the next lower limit.

Since $P$ represents the bin with zero energy, each bin $N$ corresponds to an electron energy in keV of
\[ 2.2 \times (N - P) + 6.5 + \text{energy defect}. \]

See Section 6.4 for information on the energy defect. For most cases, we have $S = 7$, which leads to a threshold for energy channel 1 of $2.2 \times 14 + 6.5 = 37.3$ keV, without the energy defect. When the energy defect of 1.9 keV is added, we have a value of 39.2 keV, the current ideal value to which all electron spectra are standardized.

The $P$ and $S$ parameters are given for each detector and integration time, as can be seen for example in Figure 5; the $B$ parameters exist once per spacecraft, and, since the initial commissioning set, are the same on all spacecraft. What needs to be changed with time are the $P$ and $S$ values as the pedestals shift and widen. Table 1 lists the different sets used so far.

### Table 1: Dates when different energy channel definitions came into effect

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Description</th>
<th>SC1</th>
<th>SC2</th>
<th>SC3</th>
<th>SC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial values set before launch, used at start</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>4</td>
<td>Major change to make $S$ values as uniform as possible</td>
<td>2006-09-21</td>
<td>2006-09-21</td>
<td>2006-08-28</td>
<td>2006-09-19</td>
</tr>
<tr>
<td>5</td>
<td>Corrections to $P$ values to allow for long-term pedestal shifting</td>
<td>2011-11-01</td>
<td>2011-10-28</td>
<td>2011-11-01</td>
<td>2011-10-28</td>
</tr>
<tr>
<td>6</td>
<td>Corrections to $P$ for further long-term shifting</td>
<td>2013-11-05</td>
<td>2013-11-06</td>
<td>2013-11-06</td>
<td>2013-11-06</td>
</tr>
<tr>
<td>7</td>
<td>Fine-tuning $P$ values for SC1</td>
<td>2014-03-14</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>8</td>
<td>Minor adjustments to SC1, SC3, SC4; major shifts on SC2 following partial failure (Section 9)</td>
<td>2016-05-09</td>
<td>2016-05-09</td>
<td>2016-05-09</td>
<td>2016-05-09</td>
</tr>
<tr>
<td>9</td>
<td>Fine-tuning to $P$ all SC</td>
<td>2017-03-01</td>
<td>2017-03-01</td>
<td>2017-03-01</td>
<td>2017-03-01</td>
</tr>
<tr>
<td>10</td>
<td>Fine-tuning to $P$ all SC</td>
<td>2018-02-07</td>
<td>2018-02-08</td>
<td>2018-02-08</td>
<td>2018-02-06</td>
</tr>
</tbody>
</table>

With set 4, $S$ was set to be 7 for all cases, except where the pedestal was too wide to allow this (see also Section 5.1.3). This value of 7 is used even when the pedestal width is in fact much narrower. The reason is to standardize the channel 1 values. Previously they varied considerably, which made the spectral realignment to the ideal thresholds less reliable.

## 4 Measurement Processing Procedures

### 4.1 Level 1: The Raw Data Set

The RAPID data ground processing begins by merging the raw data from the CD-ROMs (level 0) to **Merged Science Files** (MSF, or level 1). Each such file contains the RAPID raw data for one spacecraft for a single day, regardless of how many CDs originally contributed to it. Records of instrument housekeeping data, spacecraft housekeeping data, and instrument science data (nominal or burst mode, whichever is current) are interspersed on
a common time basis. Whereas the instrument data records are identical to those on the CD-ROMs, the spacecraft housekeeping records are limited to the needed for processing sun reference pulse data plus a temperature byte.

4.2 Level 2: Science Data Processing

A particle instrument like RAPID delivers only a set of counts accumulated over a known time period. Thus, after having processed the raw data set to the so-called MSF, the data have to be calibrated before providing them to the CSA. The standard RAPID software (MSF2SCI) produces counts-per-sec or fluxes from the MSF data and calibration files. These are written to files in an ASCII format specific to RAPID (called SCI files), for further processing, plotting, analysis. For CSA, there is a conversion program to put them into CEF (Cluster Exchange Format) which allows subsequent conversion to CDF with existing software.

Calibration is performed with one file per spacecraft and particle type (electron/ions) for 8 in all. Each one contains all the temporal changes to the various parameters. In addition to the raw data processing, caveat and instrument mode files are provided. Knowledge of the instrument mode is required to understand the products. Caveats give information about instrument behaviour, explanations for problems, warnings when the data are unreliable, and why.

5 Results of Calibration Activities

5.1 IES

Features in electron calibrations

- Decay in the IES detector efficiencies starting about 2007, strongest in those detectors looking perpendicular to the spin axis
- Correction of the spectral data (rebinning) to put all detectors on to a common set of energy thresholds. This compensates for:
  - actual differences in the energy channel definitions
  - spectral shifts that depend on (among others) count rate and aging
- Pedestal noise in some detectors on SC3 and SC4
- Solar noise in some detectors on SC3
- Failure of 6 of the 9 detectors on SC2 in 2015.

5.1.1 Efficiency decay

It has been discovered that starting about 2007 there is a loss of detector efficiency that is symmetric about the plane perpendicular to the spin axis. As described in detail in Section 8, time-dependent correction factors are determined for each IES detector and energy channel. These factors are the reduced efficiency, going from 100% for no decay, to 0% for a completely dead detector.

These corrections are applied to the calibration parameters as an additional multiplier to the geometry factors. Thus when converting from count rates to fluxes by dividing by the GF, (Equation 15 on page 70) a higher flux will be obtained for the same count rate, as compensation for the reduced detector efficiency, and corresponding lower count rate.

As always, only the fluxes are corrected; the count rates are left as raw original data.
5.1.2 Spectral rebinning

Since as mentioned above the thresholds of the IES energy channels do vary among themselves and with pedestal shifting, it is desirable to correct the measured spectra so that they all are based on a uniform set of values.

The rebinning is illustrated in Figure 4. The spectrum on the left is with the original raw data, and the lower threshold of energy channel 1 is 33.3 keV. A power law is fitted to channels 1 and 2, such that the integral over each channel reproduces the measured integral fluxes (the shaded areas). The value of that power law at the target threshold of 39.2 keV is used to obtain the corrected flux in channel 1 in the spectrum on the right. If the power law is now recalculated on the right, the same result is achieved as on the left.

A similar procedure is used to shift the boundary between the other channels: a power law is fitted to two adjacent channels, it is integrated over the shifted energy between them, and that integrated flux is added to the one and subtracted from the other channel. This is shown more clearly in Section 4.3 in RAP-UG.

5.1.3 Pedestal noise correction on SC3 and SC4

For some of the IES detector strips on SC3 and SC4, there are times when the pedestal is so broad that it contaminates the lowest science energy channels (Figure 5). This noise cannot be corrected for, since it is greater than expected signals, so for these times the noisy channels are simply removed by setting them to fill values, as listed in Table 2. This affects both the 3-D data (example in Figure 6) as well as the omnidirectional data.
The result of this pedestal noise correction is shown in summary plots in Figure 7, where the left panel still contains the noise, and the right panel has the noisy detectors removed.

Corrections, as always, are made for the fluxes only, never for the count rates.

Table 2: Detectors/channels removed because of pedestal noise

<table>
<thead>
<tr>
<th>Start Date</th>
<th>Detector</th>
<th>Int. Times</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC3:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2004-10-01</td>
<td>5, 8</td>
<td>50 µs</td>
<td>1</td>
</tr>
<tr>
<td>2005-05-01</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2009-11-01</td>
<td>7</td>
<td>50 µs</td>
<td>1</td>
</tr>
<tr>
<td>2011-04-15</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>SC4:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Launch</td>
<td>7</td>
<td>50 µs</td>
<td>1</td>
</tr>
<tr>
<td>2001-05-18</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>2003-09-03</td>
<td>9</td>
<td>all</td>
<td>1</td>
</tr>
<tr>
<td>2006-09-19</td>
<td>7</td>
<td>50 µs</td>
<td>1</td>
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<tr>
<td></td>
<td>9</td>
<td>50 µs</td>
<td>1</td>
</tr>
<tr>
<td>2007-09-01</td>
<td>7</td>
<td>50 µs</td>
<td>1, 2</td>
</tr>
<tr>
<td>2012-05-01</td>
<td>7</td>
<td>50 µs</td>
<td>1, 2</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>50 µs</td>
<td>1</td>
</tr>
<tr>
<td>2012-10-01</td>
<td>7</td>
<td>50 µs</td>
<td>1, 2</td>
</tr>
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<td>9</td>
<td>50 µs</td>
<td>1, 2</td>
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</tr>
<tr>
<td></td>
<td>8</td>
<td>50 µs</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>50 µs</td>
<td>1, 2</td>
</tr>
</tbody>
</table>

Valid up to at least February 2018
Figure 5: Histogram plots from SC4 on 2012-12-09, for each detector and integration time. The pedestal is especially broad for 50μs (right column) in detectors 7, 8, and 9 (see blow-up at right). The energy channel boundaries are indicated with black dashed lines. One sees how the pedestal extends to the first energy channel for detector 8, and even into the second one for detectors 7 and 9.

Figure 6: Angle-angle plots in spacecraft frame for SC4, energy channel 1, without eliminating pedestal noise, which produces the enhanced rates in detectors 7, 8, and 9, the horizontal stripes near the bottom of each panel. In the actual data at CSA, these noisy data are removed, i.e. set to fill values.
Figure 7: Pedestal noise correction for the omnidirectional electron fluxes. Without correction in the upper panel and with pedestal noise removed in the lower panel.
5.1.4 Solar noise on SC3 and its correction

Sunlight enters the IES head 1 on SC3. This solar noise is very strongly dependent on solar aspect angle (SAA), as shown in Figure 8. It is worst when SAA < 94.6°, which is why the range of SAA has been shifted relative to the other spacecraft since Sep 2005. (But see note below for latest development.)

A method for correcting this noise has been developed. During quiet burst mode times, when no other activity is present, the noise in the SC3 electron head 1 can be measured. As seen from Figure 8, the dependence on SAA is reproducible over many sweeps of SAA (it oscillates with a period of several weeks). Having established this dependence, it is possible to determine the noise for all intervals over this long period, even when quiet burst mode is not occurring. The result is a calibration file with the solar noise values for every day. The solar noise is subtracted from the actual measurements, and if the result is less than 3 standard deviations, the value is set to the fill value. This correction is made to both the 3-D (see the examples of uncorrected and corrected data in Figures 9 and 10, respectively) and omnidirectional flux data (see the examples of uncorrected (left) and corrected data (right) in Figure 11).

Once again, the count rates are not corrected at all, since these are meant to be raw data.

Important note: up until May 2014, the spin axes on all 4 spacecraft have been regularly adjusted every few months to maintain the desired range of SAA values. However, on May 19, 2014, the last such manoeuvre was carried out, setting all the spin axes to a fixed direction in celestial coordinates; this direction will only change slightly in future due to tidal effects from the moon and sun. As a result, the solar aspect angle will in the course of a year oscillate between 87.6°–92.4°.

Already on May 1, 2014, the SAA on SC3 crossed the critical value of 94.6°, and the solar noise increased considerably. The manoeuvre of May 19 set the SAA to 88.2°, resulting in extremely large noise in all energy channels (lower plot in Figure 8). This is expected to stay this way for the rest of the mission. (The fixed spin axes have been set to avoid an unfavourable configuration becoming permanent when the remaining fuel on board finally runs out. This is not a temporary measure.)

5.1.5 Failure of IES on SC2

On March 26, 2015, there was a failure of the IES instrument on board SC2. Three of the 9 detectors did gradually recover and are still usable, albeit with caveats.

This partial failure (or alternatively partial recovery) is described in more detail in Section 9.
Figure 8: The dependence of the solar noise on SC3 with solar aspect angle (SAA). The plots show the noise for 3 detectors and 4 energy channels. The upper plot is from a time when the range of SAA on SC3 was shifted to accommodate RAPID (as well as could be done), while the lower plot shows data from 3 years after the space orientations were fixed and the SAA sweeps over the full range over one year. The different colours indicated different sweeps. It is clear that the dependence is reproducible over many sweeps, except for parts of detector 2, channel 4.
Figure 9: Angle-angle plots, solar noise without correction, SAA=93.8°.

Figure 10: Angle-angle plots, solar noise is removed.
Figure 11: Solar noise correction for the omnidirectional fluxes. Without correction (top) and with correction (bottom).
5.2 IIMS

Features in ion calibrations

Initially a very over-simplistic model of the IIMS instrument was used to get the starting calibration parameters. Once an actual database was available, more realistic aspects could be included, the basis of the 2nd release to CSA:

- Redefine the ion energy channel thresholds
  - In particular, establish that there is a gap between the 1st and 2nd H channels
  - . . . and that the 8th H and He channels are always empty (geom.factor=0)
  - . . . and that the 1st He channel contains mainly H (later it was found that the 1st CNO channel is also mainly H)
- Determine the relationship between omnidirectional and 3-D data (i.e. the efficiency for directional signals)
- Determine the time dependence of the time-of-flight efficiency

5.2.1 1st He and CNO energy channels

The first He energy channel is in the “underrange” region, where no energy signal is received (see the lower part of Figure 12) and as a consequence the ion classification is done only on TOF information. It has long been recognized that this channel is strongly contaminated by low energy protons. Therefore, the data have been removed by setting them to fill values.

It has since been recognized that even the first CNO energy channel is also contaminated (Section 6.2); as a result, the ion calibration version 3 (3rd release) also set this to fill values.

5.2.2 Time-of-Flight efficiency

A means to estimate the TOF (time-of-flight) efficiency factor (and thus the overall ion response) was developed mid-2006.

Figure 13 shows the ideal TOF efficiencies for H, He, and CNO as a function of incoming ion energy. These curves were generated from laboratory measurements on the RAPID flight units.

To correct for degradation with time, and improvement with increasing voltage on the MCPs, we plot the “triple coincidence rate” (start, stop, plus energy signal, available in the SGLs data product, see RAP-ICD) against the rate of energy signals alone (Figure 14). There are times when these are very strongly correlated; but usually they are a scatter plot. Only the times of high correlations are used; these can be hard to find, especially in summer when Cluster is in the tail.

The ideal efficiencies in Figure 13 are used to produce basic geometry factors for each species and energy channel. The true geometry factors are then corrected by the current slope of TCR vs ENY rates relative to its value of 0.5 during commissioning.

The resulting efficiencies behave as expected: they go down after manoeuvres and go up after the high voltages on the MCPs are increased, as shown in Figure 15 for 2004.
Figure 12: The RAPID ion classification system. Every ion “event” occupies a point in the 256×256 energy-TOF space, which is divided into areas for different ion species and up to 8 energy channels. For events of (internal) energy < 30 keV, no energy signal is produced. In this “underrange” region, species determination is done solely with TOF and the fact that the energy is below this threshold.

The upper panel above shows the arrangement of species-channel areas, without any particles, while the lower panel is exactly the same thing but with real direct event data (CP_RAP_DE) added. One sees the clear separation between the three species. In the underrange area, where energy information is missing, only a normalized intensity curve is shown. The large jump in this curve at the boundary between H1 and He1 is a result of the prioritization system (only a limited number of direct events per spin are accepted, and heavier ions are taken preferentially, see Appendix B in RAP-ICD.)
Figure 13: The ideal time-of-flight efficiencies as a function of incoming energy, for each of the three major ion species. These curves are based on laboratory measurements made on the RAPID units prior to launch.
Figure 14: Plots of triple coincidence rate (TCR) versus energy signal rate (ENY) for selected times on SC1. The fitted slope is used to measure the TOF efficiency. The top panel is from the end of the commissioning phase, when the efficiency is considered to be optimal (slope = 0.567). The middle and bottom panels are taken just before and after the increase in MCP voltage on Nov. 15, 2004, indicating the improvement in efficiency (0.167 → 0.274). (See Figure 15 for the fitted slopes over the entire year 2004.)
Figure 15: Fitted slopes of “triple coincidences” (TCR) to “Energy Rate” (ENY) signals for all 4 spacecraft for the year 2004. This slope is a good estimate for the time-of-flight efficiency. Each point is the best fit over 1 hour for each day. Only points with correlation factor >99% are included.
5.3 Features of IIMS Series 4

An overview of the behaviour of the ion detectors over the mission lifetime is given in Figure 16, which shows the raw count rates as monthly averages. (Data from the radiation belts have been excluded.) The red lines at the top of each panel indicate manoeuvres, which are expected to cause deterioration of the detectors, while the vertical dashed lines are times when the voltages on the MCPs were increased, leading to improved efficiency.

**Figure 16: Hydrogen count rates over the mission lifetime of mission.** Each point is a monthly average of the rates in each of the 3 detector heads, above 7 \( R_E \). The dotted lines indicate times when the high voltages on the MCPs were changed (usually increased) and the red lines at the top of each panel show when major manoeuvres occurred, the length and width being proportional to the durations. The horizontal dashed lines mark certain count rates for comparison between the panels.

This figure shows clearly when the ions on SC1 and SC3 failed. (On SC3, data were still collected after the failure, and again during 2017, to see if a recovery were possible, but since the voltages proved to be unstable and the detectors noisy, it was decided not to process these test data.)

Note also the strange mode that SC4 entered on June 21, 2003, when only head 1 was functioning. This lasted until May 09, 2006 when a spontaneous reboot reset the DPU completely. This interval requires special treatment for handling the TOF efficiency, something that was added only at the 4th release.

One also sees in this figure how the remaining two detector heads on SC2 and SC4 start to give quite different results. This is most serious on SC2 where head 1 becomes an order of magnitude less sensitive in 2010, then recovers, then goes bad once more; finally at the start of 2018, it seems to stop functioning completely. On SC4, it is head 3 that loses sensitivity, becoming more serious mid 2015.
Figure 17: Demonstration of how completely different TOF efficiencies can be determined on the same day and spacecraft. The fit on the left for SC2 was taken at an altitude of 6 \( R_E \), at the edge of the radiation belts, whereas the one on the right a few hours earlier at 12 \( R_E \); its correlation is only slightly less than that on the left, but the slope is more than 10 times higher.

During the development of the series 3 calibrations (3rd release), it became clear that in the years when the remaining heads had quite different sensitivities, the TOF efficiencies on SC2 appeared to be very much underestimated, something that then produced considerably higher fluxes on SC2 compared to SC4. This was extremely suspicious since the count rates on the two spacecraft were similar and therefore we would expect the TOF efficiencies also to be similar.

It turned out that at these times the maximum correlations for the TOF efficiency, as described above in Section 5.2.2, was often found at the outer edge of the radiation belts, with very high count rates. As shown in Figure 17, the efficiency found here can be much less than that taken a further out at lower count rates. The reason for this could be that electrons from the radiation belts are triggering the energy detectors but not the time-of-flight signal, thus producing an apparently low efficiency for the ions.

For the series 4 (4th release) it was decided to restrict the TOF efficiency determinations to beyond 10 \( R_E \), to make them more reliable. These values also correspond more to what one would expect from the relative count rates between SC2 and SC4. The disadvantage is that at these distances there are fewer times when good correlations can be found in the later years, a result of the overall lower efficiencies since the first years of the mission.

It should be pointed out that the method really only determines the efficiency averaged over all three heads, including the non-functioning central one. This average is then split up over the individual heads by means of the directional distribution parameters of Section 3.3.

The use of these directional distribution parameters is another change in the 4th release. They determine the differences between the detector heads and their sub-directions in a manner more reliable than what was used in previous releases.

The resulting series 4 conversion factors for hydrogen channel 1 are shown in Figure 18 for the mission lifetime, demonstrating the deteriorations during manoeuvres, the recoveries when the high voltages are increased, and the
Figure 18: The conversion factors (geometry factor times efficiencies) for hydrogen, channel 1, over the mission lifetime, for each detector head and spacecraft, at intervals of 15 days. As for Fig. 16, the dotted lines indicate times when the high voltages on the MCPs were changed (usually increased) and the red lines at the top of each panel show when major manoeuvres occurred, the length and width being proportional to the durations. The horizontal dashed lines mark certain values for comparison between the panels.

large differences in sensitivities between heads 1 and 3 in the later years.

Figures 19–21 show the resulting series 4 fluxes for the 3 ion species H, He, CNO. Note that the differences between the remaining heads in the later years have been compensated for by the difference conversion factors so that the average fluxes in both heads are equal. Of course, the error bars in the less-sensitive head will be much higher since these fluxes are derived from lower count rates.
Figure 19: Hydrogen fluxes from series 4 calibration, in the same format as in Fig. 16, i.e. monthly averages above 7\(R_E\).
Figure 20: Helium fluxes from series 4 calibration, as in Fig. 19.
RAPID I3DD flux
CNO Ions, V405
Monthly averages 2001-01-01 to 2018-06-30

Figure 21: CNO fluxes from series 4 calibration, as in Fig. 19
6 Results of Cross-Calibration Activities

The performance of the particle instruments can be monitored by intercalibration between them. It is important to check if the joint spectra are continuous.

6.1 RAPID/IIMS and CIS/CODIF cross-calibration

This section needs complete revision in the light of new calibrations on both RAPID and CIS

The RAPID/IIMS proton fluxes of the lowest energy channel can not be directly compared with CIS/CODIF proton fluxes of the highest energy channel due to their nonsymmetric energy overlapping. The method described in Kronberg et al. [2010] (where particularly the problem of the IIMS donut was considered) has been applied to the CIS/CODIF data in order to be able to compare proton fluxes at the same energies. Events in the plasma sheet region for 2002–2007 are investigated. The results show that the RAPID proton fluxes and CIS proton fluxes are consistent with each other, and do not have a difference in order of magnitude as it was before using direct comparison of the overlapping energy channels and old calibrations. With new 3rd generation RAPID calibration files and the most recent CIS/CODIF calibration files the average ratio of CIS fluxes (approximated using the kappa-fit to the effective energy of the first RAPID energy channel) to the RAPID fluxes at the first energy channel (27.7–64.4 keV) is about 0.74 ± 0.24. Here we applied the kappa-fit only to the higher CIS channels (5.5–38.3 keV) in order to improve the reliability of the approximated overlapping energy channel. An example of joint spectra for 2002 is shown in Figure 22. More detailed information on the ratios between the intensities of the highest CIS/CODIF energy channel and the lowest RAPID/IIMS energy channel can be seen in Table 3. This result is perfectly acceptable for these two experiments, which are based on two very different measurement principles; (solid state detectors in RAPID versus electrostatic analysers in CODIF). It should be also taken into account that CODIF detects only positive ions whereas RAPID is sensitive to both ions and energetic neutral atoms. We therefore conclude that no spectral shift or recalibrations are required from this study.

### Table 3: Ratios of the CIS fluxes (approximated using the kappa-fit to the effective energy of the first RAPID energy channel) to the RAPID fluxes at the first energy channel (27.7–64.4 keV). Data from SC3 were not used for analysis after 2003 because half of anodes on the CODIF instrument were not working satisfactory.

<table>
<thead>
<tr>
<th>Year</th>
<th>C1</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>0.69 ± 0.09 (15 events)</td>
<td>0.62 ± 0.44 (31 events)</td>
<td>0.8 ± 0.09 (16 events)</td>
</tr>
<tr>
<td>2003</td>
<td>0.8 ± 0.17 (20 events)</td>
<td>1.1 ± 0.09 (34 events)</td>
<td>0.95 ± 0.19 (27 events)</td>
</tr>
<tr>
<td>2004</td>
<td>0.76 ± 0.15 (31 events)</td>
<td>0.61 ± 0.13 (35 events)</td>
<td>0.7 ± 0.24 (365 events)</td>
</tr>
<tr>
<td>2005</td>
<td>0.61 ± 0.13 (35 events)</td>
<td>0.88 ± 0.22 (116 events)</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>0.7 ± 0.24 (365 events)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>0.7 ± 0.24 (365 events)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.75 ± 0.13 (66 events)</td>
<td>0.62 ± 0.44 (31 events)</td>
<td>0.84 ± 0.16 (593 events)</td>
</tr>
</tbody>
</table>

Although the results of the cross-calibration between IIMS and CODIF are assumed to be satisfactory, there are still some caveats present in the joint RAPID/IIMS and CIS/CODIF spectra. For instance we noticed that the level of the IIMS ion fluxes are overestimated relatively to CODIF ion fluxes (ratio is about ~ 0.2) in autumn 2004, see an example in Figure 23. During this time the level of TOF efficiencies was fairly low, see Figure 15. On November 15, 2004 the level of the MCP voltages, and thus the TOF efficiencies, were substantially increased. This leads to the dramatic change of the CODIF/IIMS ion fluxes ratio, which increases to ~ 2.5, see an example in Figure 24. This behaviour suggests that perhaps during the times of low TOF efficiency the IIMS response is being underestimated. However this is still unclear as we do not see direct correlation between the level of TOF efficiencies and the CODIF/IIMS ratio on the long time scale. This caveat still needs to be investigated and users should be aware of it.
Figure 22: Comparison of the CIS and RAPID fluxes on 20 September in 2002, SC4. For CIS data (green colour) 3-D differential particle flux is used and omnidirectional data are created. RAPID (blue color) data were plotted using HSPCT product. In yellow color is the kappa-fit to the 8 highest CIS energy channels extended to the effective energy of the first RAPID energy channel.

The cross-calibration of IIMS CNO with CODIF O\(^+\) intensities cannot be made appropriately as two trustable adjacent energy channels have large separations between each other. The spectra comparisons for these two measurements are presented in Section 6.2, Figure 26.

### 6.2 1st CNO energy channel

While doing investigations on bow shock, strange behaviour of the 1st CNO energy channel was discovered, as CNO bursts, see Figure 25, right column, top panel. Also we were puzzled why the CNO intensity gradients between SC1 and SC3 for the 1st energy channel behave differently from the CNO intensity gradients at the higher energies as well the proton and helium intensity gradients. As they show gradients on the earlier stage, see Figure 25. First some physical explanation was searched.

Then we decided that this could be an instrumental effect. The most obvious was first to check if count statistics are sufficient. The raw counts for the CNO are high, i.e. about 30 and RAPID spectra are more or less reasonable. Nevertheless, if one look to the joint CIS/CODIF and RAPID/IIMS spectra for this event we can immediately see that the 1st RAPID CNO energy channel has too high intensities, while the further channels would continue the CIS spectra, see Figure 26.

Intensity bursts of CNO (1st channel) at about 12:00 to 13:30 helped to solve the problem. As it was noticed there is a correlation with the low energy (~ 2–30 keV) protons and helium in the CIS energy range, see energy spectrograms in Figures 27.

As for the 1st He energy channel the ion classification is done only on TOF information (see Section 5.2). Therefore the species determination is not very precise. We estimated the energies for protons and helium at which particles could trigger the TOF signal erroneously counted as a CNO. For the protons the predicted energy range is 12–14 keV (or CIS energy channel 5) and for the helium 16–25 keV (or CIS energy channels 2–4). We tested the correlation between the proton and helium intensities at corresponding energies and the intensities of the 1st CNO energy channel. The results with the best correlation are presented in Figure 28. The correlation of the intensities of the 1st CNO energy channel with intensities of the predicted energy channels is surprisingly good, i.e. ~0.94 and ~0.96, for protons and helium correspondingly, and it becomes gradually worse for the adjacent channels. The correlation with the CIS 1st CNO channel is not satisfactory, ~0.64.
Figure 23: Comparison of the CIS and RAPID fluxes on 3 October in 2004, SC4 in the format as Figure 22. During this time period TOF efficiencies were low. Here the kappa-fit is applied to the 4 highest CIS energy channels.

Figure 24: Comparison of the CIS and RAPID fluxes on 12 December in 2004, SC4 in the format as Figure 23. During this time period, as a result of the MCP voltages increase, the TOF efficiencies are relatively high.
Figure 25: Proton and CNO fluxes for the upstream event in 18 February, 2003, for SC1 and SC3.

Figure 26: Joint CIS/CODIF O+ and RAPID/IIMS CNO spectra for the upstream event in 18 February, 2003, for SC1.
Figure 27: Energy spectrograms for CIS and RAPID proton (left) and helium (right) fluxes, 18 February, 2003.

Figure 28: Proton (5th CIS energy channel, 11.5–14.5 keV) and CNO (1st RAPID energy channel, 83.8–274.4 keV) fluxes (left); Helium (3rd CIS energy channel, 18.6–23.7 keV) and CNO (1st RAPID energy channel, 83.8–274.4 keV) fluxes (center); CNO fluxes (1st CIS energy channel, 30.1–38.2 keV) fluxes (right) and CNO (1st RAPID energy channel, 83.8–274.4 keV) fluxes for the upstream event in 18 February, 2003, for SC1.
Our conclusion is that the first CNO energy channel is contaminated by low energy helium and protons; for this reason, we have removed it by setting it to fill values.
6.3 RAPID/IES and PEACE cross-calibration

This Section is based on work of C. H. Perry and A. Ásnes.

6.3.1 RAPID/IES Histogram mode analysis

RAPID/IES histogram mode is a special test mode which is run about once per month. It returns a few spins of data from each detector at each integration time. The mode provides full pulse-height determination (256 energy bins) at best energy sampling (2.2 keV). This compares to normal/burst mode data which give 6/8 logarithmically spaced energy channels.

The purpose of this analysis is to examine the lower energy threshold of RAPID and try to reduce the energy gap between highest PEACE and lowest RAPID flux measurement.

For the cross-calibration PEACE CP_PEA_3DXPH dataset was used. This provides full 3-D distribution with 6 polar directions. For the data comparison the nearest PEACE sample to histogram-mode spin was selected. Then the PEACE polar zone closest to each of the 9 RAPID detectors was chosen and PEACE azimuths were integrated to produce spin averaged products.

Figure 29 shows the overlaid PEACE and RAPID spectra for two detectors. Inspecting the RAPID histogram mode data (bottom panels), the falloff in efficiency of the RAPID detectors towards lower energy is apparent. There is also evidence for this in the lowest science energy channel of the IES when compared with the extrapolated PEACE data.

Additionally several intervals of hot magnetotail plasma sheet were investigated for the cross-calibration using kappa-fit, see Figure 30.

The kappa-fits were performed (using PEACE SPINPAD, RAPID IES ESPCT products) using the energy range from 3–400 keV, but excluding the lower RAPID channel and the top PEACE channel.

Visual inspection of several magnetotail plasma sheet intervals show that the kappa fits join PEACE and RAPID IES data nicely most of the time, as long as the distribution assumes a kappa-function shape.

6.3.2 RAPID/IES calibration: statistical study

The studies above, based on limited intervals, indicate that there is reason to believe that there is a problem with the IES calibration at the lowest energies. Calibration studies from before launch suggest that the energy losses in the detector dead layer could be energy dependent and greater than the assumed 6.5 keV at the lower energies.

To investigate this systematically, a spectral analysis program was developed, as shown in Figure 31. Following the method outlined in Section B.1, a power law \( j(E) = A \cdot E^{-\gamma} \) is fitted to energy channels 2 and 3, and then extrapolated back to channel 1. To be more precise, the power law is found such that its integral over channels 2 and 3 yield the measured integral flux in these channels, and it is then integrated over channel 1 as well. The ratio of this extrapolated flux to the measured flux in channel 1 is then the indicator of the mismatch.

A database of 1-minute averages of the E2DD6 data (spin averages for each of 9 detectors) was created for the months of March and September for every year from 2001 to 2012. These two months were selected to ensure that both solar wind and tail regions are included. Further selection criteria for the database are:

- distance from the Earth > 6 \( R_E \), to avoid the radiation belts,
- flux in energy channel 3 > 10 (cm\(^2\) sr s keV\(^{-1}\)), to ensure sufficient statistics

For the analysis itself, we apply the additional conditions:

- the spectral index \( \gamma \) lies between 3.0 and 6.0 (for a flat spectrum the mismatch would disappear even the effect were there)
Figure 29: The electron differential energy spectra from the PEACE and RAPID instruments covering the range from 100 eV to several hundred keV. The plots are from two different polar look directions from the Cluster 2 spacecraft. The upper panels show PEACE 3DX data (+) together with RAPID/IES E3DD (•) and background subtracted, 5 point averaged, RAPID histogram mode data (*). The lower panels show the corresponding uncorrected RAPID histogram mode data including the Gaussian fit to the background noise distribution (pedestal).

Figure 30: Kappa-fit on joint 1-minute averaged PEACE and RAPID IES spectrum. One-count levels of the instruments are shown as dashed lines.
Figure 31: Example of the spectral analysis: a power law is fitted to channels 2 and 3, and then extrapolated back to the energy of channel 1 and compared to the measured flux.

Figure 32: Determination of energy defect from spectral analysis: a new threshold for energy channel 1 is found such that the integral of the fitted power law (black region) equals the measured integral flux in channel 1 (red region).
Figure 33: The ratios between the extrapolated power law and the measured flux in energy channel 1 in each of the detectors on SC1, for two widely separated time periods, plotted against spectral index $\gamma$. Each point represents a 1-min accumulation meeting all the conditions described in the text. The data were produced with calibration V301, without any energy defects. The mean value of the ratios is given at the bottom of each panel.

- the $\gamma$ for channels 2 and 3 differs no more than 0.2 from that for channels 3 and 4, i.e., we have good power law spectrum over all 3 channels and can assume that it can be extended to energy channel 1 as well.

Figure 33 shows the results for spacecraft 1 for 2 months, one early in the Mission, and one more recently. The mismatch is very clear, in all detectors. The other spacecraft exhibit similar mismatches.

It might appear that the effect was greater in the earlier plot, but this is due to the fact that then the actual channel 1 threshold was set much lower than 37.3 keV, in a region where the discrepancy is expected to be greater.

A similar analysis on channel 2, by fitting channels 3 and 4 and extrapolating back produces no significant systematic mismatch. Thus the effect applies only below 50 keV, something that is also confirmed by the analysis in the next section.

### 6.4 The IES Energy Defect

In Section 6.3.2 above we demonstrate that there is a systematic discrepancy between the electron fluxes in the first energy channel and the fluxes expected from a power law extrapolation of the rest of the spectrum. This could be due to energy-dependent efficiency at lower energies, or to increased dead layer losses (energy defect) at low energies. The latter is not only expected, it is also confirmed by the fact that the mismatches seen in Figure 33 increase with $\gamma$. A mismatch due to efficiency fall-off should be independent of the spectral slope.
We conclude that we have an energy defect problem, which we now wish to compensate for or, even better, to correct.

### 6.4.1 Corrections for the energy defect

To date we have had 3 “solutions” to this problem.

1. When the initial spectral analysis was carried out in 2010, it was found that the spectra could be “fixed” by assuming the first channel had a threshold of 40.7 keV, without reprocessing any of the existing data at CSA. The metadata at CSA were correspondingly altered, in anticipation that once a true energy defect was determined, the data would be reprocessed and the metadata once more adjusted.

   This clearly was only a temporary measure and an unsatisfactory one at that.

2. By 2012, values for the energy defect at different energies had been determined. A new calibration version V311 was produced. The energy for channel 1 was now set at 41.2 keV, the original 37.3 keV plus the new energy defect at that energy.

   The CSA electron data for 2011 were produced with this calibration version.

3. The spectral analysis of Section 6.3.2 was repeated with the new calibration. However, it became obvious that this was in fact an overcompensation. The extrapolated fluxes were now lower than the measured ones.

   These energy defects had been determined using histogram data, which are taken for only a few minutes each month. Hence they have either poor statistics, or they are taken inside the radiation belts, a region deliberately avoided in the other studies.

   The search started for a better determination, which is described below. It produces a corrected value for the first channel of 39.2 keV. New calibration version V330 is now employed. All the IES data at CSA, including metadata, have been reproduced using this value.

### 6.4.2 Latest determination of the IES energy defect

To carry out the new determination of the energy defect, we once again make a new database, with the same criteria as before, for March and September, 2001–2012, but this time using data that have not been rebinned to the standard set of energies (Section 5.1.2). Especially in the time before August 2006, we have “raw” energies going down to as low as 20 keV, which allows us to investigate the energy defect at a wide range of energies. And the distortion from the rebinning is not present, making the results much easier to interpret.

The pedestal shift is still taken into account. This shifts the thresholds of all the energy channels. Pedestal shifts are always present, and are even stronger with higher count rates. This shifting does have the advantage for this study of producing additional energies for the defect determination. It is not limited to a set of fixed values.

Figure 32 illustrates the method used. Once again, a power law is fitted to energy channels 2 and 3, but now the energy is found for which the integral from that new energy equals the measured integral flux in channel 1.

The same conditions are applied as for the spectral analysis (3.0 < γ < 6.0, |Δγ| < 0.2)), but with the additional condition that the pedestal shift be within ±5 keV (about 2 bins), since large shifts are subject to error and also indicate extreme situations.

Figure 34 shows the results for the 4 spacecraft (all detectors together) for March and September, 2006. This period is chosen because it spans the change in the channel definitions from August, 2006, and so has a wider range of original energies than other time periods. Each 1-min interval meeting all the conditions is plotted as a dot, which then produces the black cloud of points. There is considerable spread in the energy defects, but the trend is clear and conforms to what was expected.
Figure 34: The energy defect on the 4 spacecraft calculated for March and September 2006, plotted against original energy. The red lines are a linear fit to the data.

Figure 35: Energy defect plotted against original energy, for all spacecraft, all detectors, all modes, over 12 years from 2001 to 2012. The red curve is a quadratic fit to the defect values below 52 keV.
In order to view the results more clearly, they are sorted into 1-keV bins by original energy and the average defect in each bin is found. Figure 35 shows these averages for the period from 2001 to 2012, with all spacecraft and detectors combined. The red curve is a quadratic equation, fitted to the defect values below 52 keV. Even at 50 keV, the defects are \( \sim 0.2 \) keV, which is below the accuracy limit anyway.

The question is now, how well does this global solution in Figure 35 fit to the individual detectors? This is shown in Figure 36 where the average defects are plotted for each of the 9 detectors on all 4 spacecraft. The red curve in each panel is the global solution once more. It can be seen that the global solution is quite acceptable on most detectors, but there are some exceptions, most noticeably on SC4, detectors 6–8. However, these are the ones affected by very wide pedestals (Figure 5) and for which the energy channel 1 thresholds are set higher than for the others. This could possibly play a role here.

Note also that the detectors 1–3 on SC3 are empty. These are the ones subject to solar contamination (Section 5.1.4) and therefore were removed from the study right from the start.

We therefore conclude that the global solution in Figure 35 is perfectly acceptable for all the individual detectors. Some fine tuning might be possible by fitting each detector separately, but the effort is not worth the slight (and probably insignificant) gain.

With the global solution, we get a formula for the corrected electron energy as

\[
E' = 0.0091E^2 + 0.0728E + 23.8153, \quad \text{for } E < 52
\]

where \( E \) is the “original” energy without the defect, and \( E' \) is the original plus defect. In particular, for \( E = 37.3 \), \( E' = 39.2 \) keV, which now becomes the new ideal value for channel 1 and serves as the target for the spectral rebinning.

It remains now only to see how well this solution works. Once again, a 12-year database is produced, this time with the new IES calibration version V330. Figure 37 shows the fit-to-flux ratio, the mismatch parameter, for the 4 spacecraft for the same two periods as in Figure 33. There is still considerable scatter in the individual results, but on average, the mismatch is now greatly improved.

We can be hopeful that we have finally corrected this thorny problem that has plagued us so long.
Figure 36: Energy defect for each detector on all 4 SC for all modes; the red curve is the fit from Fig. 35 superimposed on each panel.
Figure 37: Ratio of extrapolated to measured flux in energy channel 1 after adding the energy defect. Data produced with IES calibration version V330.
7 Automatic Spike Removal

Like any physical instrument, RAPID is subject to random glitches in its data stream subject to various external and internal causes.

For example, very often at turn-on, as the instrument is booting, there can be some leftover garbage in the buffers as the data outputting begins. Or mode changes can also cause displaced data. And there are frequent times when a complete spin is skipped, resulting in random values in the buffer either before or after the skip. This can happen in both electron and ion data.

As an example of an external cause is the turning on of thruster thermistors, as described in Section 7.2 below.

The next sections explain how these two types of noise, or glitches, can be automatically removed during the data processing.

7.1 The Despiking Procedure

The rules for detecting a spurious data spike are basically quite simple:

- Spikes are defined as single records that are significantly higher than their neighbours.

The words in italic are the things that need better defining. A simple ratio is not sufficient (like $10^5$ times the values on either side) since this could be within statistical noise, and if the neighbours are 0, then what do you do?

After much experimenting, we have decided to use the following criteria:

- The data from a single record (spin) are summed over all directions and energies to provide a single value for each record.

- Neighbours are the 5 records on either side of the record to be tested, provided there is no data gap (time difference of >1 min.) within them. At a data gap, the 10 records on the one side are taken as neighbours, and the test point is then not centered.

- For the test parameter, we need
  1. the value $V$ of the test record;
  2. the average $A$ of the neighbours (may be zero);
  3. the expected deviation $\sigma$, found from the standard deviation of $V$ and the actual measured variation of the neighbours; thus if the neighbours are noisy, the expected deviation is increased.

- The condition for declaring the test record to be a spike is that

$$\frac{V - R \times A}{\sigma} > L$$

We use the values of $R = 50$ and $L = 5$, which appear to give acceptable results, conservative enough that only extreme spikes are removed.

An additional condition is also required:

- The test record must be at a time jump of at least one record.

This last ensures that very short-lived but real events are not removed. During the test phase such “spikes” were discovered, but which with closer inspection were clearly physically real.

Figure 38 demonstrates data with and without the spike removal applied.
7.2 Heater Spikes (Hatchets)

Another source of spikes in the electron data is the turning on of thruster thermistors (heaters) near the RAPID instrument, which create a brief voltage surge that causes the IES pedestals to shift drastically, with resultant noise in the electron data. These occur at regular intervals of ~30 min. as the thruster temperature is regulated.

Figure 39, upper panel, shows such spikes in SC1, which started to show up around 2012, and which have become slowly stronger over time. These spikes are really only visible when we are down in the background level; they are not that large. They are also to be seen on SC4, although not so obvious or intense.

These spikes were first observed in 2005 during the months of August and September, on SC2 and SC4. Then they were very much stronger, but like those currently on SC1 and SC4, their times correlated very well with those of the thermistor firing. (Figure 40, upper panel.)

The angle-angle plot in Figure 41 shows the shape of these spikes: they occupy a single sector in head 2, and a double-sector in head 1 (which has only 8 spin sectors in all, unlike head 2 with 16). It is possible to detect these spikes by means of this “hatchet” shape. The rules are:

- take data from heads 1 and 2 only;
- find the 4 pixels with the highest counts;
- check if they are all in the same sector or double-sector (need not be connected);
- check if ratio of these 4 pixels to the rest is over a given threshold;
- if so, remove this record.

Take 4 pixels to ensure that more than one head is being tested; take no more because there are weak hatchets that have only 4 points. And test that the 4 have counts well above the other pixels to avoid being at noise levels.

The lower panels for Figures 39 and 40 show the results of removing these hatchet spikes.
Figure 39: An example of heater spikes (hatchets) on SC1 in the electron data (upper panel), with the result of their removal in the lower panel.

Figure 40: An example of the extreme heater spikes on SC2 in the electron data (upper panel), from August-September 2005; the same plot with their removal is shown in the lower panel.
Figure 41: Angle-angle plots showing the shape of the heater spikes, that they are restricted to a single sector in head 2 and to a single double-sector in head 1. This typical shape reminds us of a hatchet (small axe), hence the name for this spike.
8 IES Detector Decay

IES shows decreased efficiency over a long time interval since 2007. This effect is most dominant in the middle detectors (see right side of Figure 42) and less dominant in the detectors close to the edges looking closer to the parallel and anti-parallel of the spin axis direction (see Figure 2 / middle plot). This “donut effect” is approximately symmetric about the middle detector, but due to differences in the detailed behaviour of detectors we determine correction factors for each detector separately and repeat this in each of the eight energy channels separately. This correction is done relatively to detectors 1 and 9 (these two detectors at the edges are assumed to be unaffected by this “donut effect”). The correction factors as a function of time have been modelled with a piecewise nonlinear function.

8.1 Starting time of the decay effect

The degradation was first observed in electron differential flux 3D data, which contain 16 azimuthal and 9 polar directions in the spacecraft’s reference frame (Figure 2) and two (L3DD) or eight (E3DD) energy channels. The decay effect causes too low fluxes in the plane perpendicular to the spin axis (Figure 46) and in some cases leads to a false conclusion that there is a bidirectional flow of electrons along the spin axis.

In order to check when the long term decay effect started we inspect the relative levels of count rates of the detectors 1-9 looking into different polar directions using histogram mode data (see Section 6.3.1). While the 3D data has two or eight composed energy channels the histogram mode has full energy resolution with 256 channels and is taken for each of the nine detectors over all the sectors (one spin). We normalized count rates (corrected for spectral shape) of each detector and averaged over the histogram mode energy channels, using only those energy channels which contain useful signal after pedestal (Figure 5) has been removed (bottom panels of Figure 29). This way we get a plot of the signal levels of detectors relative to each other (see Figure 42). The histogram mode is taken only once a month with the purpose of checking the pedestals and often there is not enough signal to determine the relative signal levels of the detectors. Therefore, this analysis gives only a coarse time range when the decay effect has started in 2007-2008. In addition, the “donut effect” should be relatively strong in order to be reliably detected using histogram mode data since there is always some scatter among the detectors. As an alternative approach we use the data product E2DD6 and calculate averages over each orbit limiting the data to $>7 R_E$. After filtering, taking the ratio between the middle detectors and the average of detectors 1 and 9 and then filtering again a clear decrease in the efficiency of the middle detectors is observed (see Figure 43). The starting time is defined as the point where the ratio is for the first time below $3\sigma$, where $1\sigma$ is the standard deviation of the ratio in 2002-2005. These starting times are given in Table 4. Depending on the settings of the filtering the starting times may change by ±2 months.

<table>
<thead>
<tr>
<th>SC</th>
<th>Starting time</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1</td>
<td>2007 Apr 29</td>
</tr>
<tr>
<td>SC2</td>
<td>2007 Feb 21</td>
</tr>
<tr>
<td>SC3</td>
<td>2007 Feb 14</td>
</tr>
<tr>
<td>SC4</td>
<td>2007 Apr 15</td>
</tr>
</tbody>
</table>

Table 4: Starting times of the “donut effect” using the ratio of detector 5 to the outermost detectors.

8.2 Environmental effects

During the long Cluster mission the 4 spacecraft have spent less than 5% of each orbit within the radiation belts until 2009 after which this fraction increased significantly and occasionally reached values of more than 12%.
Figure 42: Relative signal levels of all IES detectors (polar directions) based on histogram mode data at 50 µs integration time before (left) and after (right) the long term decay effect has started to decrease the efficiency of the middle detectors. Before the effect started relative signal levels of the detectors scatter around unity.

Figure 43: Determination of the starting time of the “donut effect” using orbit-averaged E3DD6 data where the ratio between the central detectors and the mean of detectors 1 and 9 has been calculated. This ratio has been filtered with a one-year median filter. The vertical lines show the calculated starting times for detectors 4, 5 and 6. Detector 5 is taken as the nominal starting time for a spacecraft.
Figure 44: Absorbed radiation dose in a layer of 0.5 mm Aluminium, based on the actual orbit of SC3. This work has been contributed by Cassian Herbon.

Using the orbit of SC 3 and the SPENVIS (Space Environment Information System) tool of ESA [Heynderickx et al., 2002; Kruglanski et al., 2009, 2010] we have computed the absorbed radiation dose as a function of time (see Figure 44). There are contributions from solar protons, trapped electrons and trapped protons. The component which correlates with the “donut effect” is the trapped protons with an increased dose in 2007 compared to any of the earlier years of the mission. The second stage of degradation, which started in 2011, is simultaneous to the maximum in the absorbed dose caused by trapped protons.

8.3 Determination of correction factors

In order to determine correction factors for count rates, which will be used in the processing of corrected differential fluxes, we use the data product E3DD_R taken in the burst mode. This product has 16x9 directions and 8 energy channels and is available much more frequently than the histogram mode data. Some detectors at low energy channels are contaminated by pedestal noise (Section 5.1.3) and they are replaced by values from neighboring detectors (see Table 5). Since E3DD_R is a science data product it often contains also significant count rate contributions from physical phenomena which may affect individual data points in the analysis of correction factors. Indeed, when plotted as a function of time there is large scatter among the correction factors (top panel of Figure 45), which are determined in the following way.

First, we choose data at 50 µs integration times taken at a distance > 7 R_E from the Earth and select from the 16x9 data matrix those directions which are not far from the direction perpendicular to the magnetic field as determined by the onboard FGM data. This is done to rule out any effects from pitch angle distributions. Then, a mean over the remaining data in the azimuthal direction is taken so that we have one value for each polar direction (i.e. detector). All these averaged data from a single burst mode epoch (typically 3–4 hours) are normalized so that the effect of changing absolute signal level during the few hours of burst mode acquisition is removed. Those cases showing a “donut” effect are then used to calculate a correction factor for each detector 2-8 so that after the correction count rates from those detectors are at the same level as the average of detectors 1 and 9. These two detectors are at the edges looking closest to the parallel and anti-parallel directions of the spin axis and are not corrected. When plotted as a function of time these correction factors show two different stages of decreasing efficiency (Figure 45): first at the beginning of the effect (starting times given in Table 4) and a second drop in efficiency later around 2011-2012. The correction factors as a function of time have been modelled with a two-
stage non-linear curve, where the second part after 2012 is either linear or nonlinear depending on whether a clear drop is detected around 2012. The parameters of this fitted curve are then used in the processing of data products to calculate corrections at arbitrary times. An example of a corrected data product is shown in Figure 46.

Table 5: Detectors which have been replaced (because of pedestal noise) by mean values from neighboring detectors for selected energy channels. When detector 9 is not available it is replaced by the average of detectors 1 and 8.

<table>
<thead>
<tr>
<th>SC</th>
<th>Energy ch.</th>
<th>Year</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC3</td>
<td>1</td>
<td>2010</td>
<td>7</td>
</tr>
<tr>
<td>SC4</td>
<td>1, 2</td>
<td>all</td>
<td>7</td>
</tr>
<tr>
<td>SC4</td>
<td>1, 2</td>
<td>2012-present</td>
<td>9</td>
</tr>
</tbody>
</table>

8.4 Caveats on the corrections

The validity of the correction factors has been checked as a function of time by comparing omnidirectional data sets between 2007–2015 before and after correction factors were applied so that from each orbit we get one averaged data point. These data sets are normalized by the average of detectors 1 and 9. After a visual check of the data sets the following caveats have been found:

- In SC1 energy channel 6 is overcorrected in 2010–2013 by a factor of 1.5-2.0 for detectors 2–7 and by a factor of 2 for detectors 2–8.
- In SC 2 at energy channels 1-3 detectors 2-7 are overcorrected by a factor of 1.5-2 starting November 2007 and until 2010. In 2011 the overcorrection is mainly affecting only energy band 1 and only detector 5.
- In SC3 energy channel 1 middle detector head is overcorrecting by a factor of 2–3 in 2009-2010.
- In SC4 energy channels 1–2 of the middle detector head are overcorrected in 2010 by a factor of 2–3. Detectors 2–6 of energy channel 6 are overcorrected by a factor of 2 in 2011, 2012 and 2014.
Figure 45: Correction factors based on E3DD_R data taken in burst mode. Factors and a 2-stage fitted model for the middle detector on SC 1 at the first energy channel (top) and fitted models for all corrected detectors 2-8 in the same energy channel (bottom).
Figure 46: Example of L3DD data before (upper) and after (lower) correction for the long-term decay effect.
9  Partial Failure of IES on SC2

On March 26, 2015, at 07:00, the IES on SC2 started to go crazy, in that the counts in the pedestal channels either went to zero or were shifted by a large amount, depending on the detector. This would indicate enormous pedestal displacements, making subsequent data analysis impossible.

The unit was then rebooted twice in an attempt to restore it, but without success. We then ordered a special histogram mode test to get a more detailed picture of the output, something that normally is done just once a month. Fortunately the previous histogram test had just been carried out a few days before the failure, on March 22 (Figure 47) so a good comparison of before and after could be made.

The pedestals in the histogram test of April 2 are shown in Figure 48 are clearly very pathological. In detectors 1 and 2, they have disappeared completely, in 3, 4, 5 they are extremely narrow and even distorted, in 6 there is just an almost uniform background, while in 7, 8, 9 there are still recognizable pedestals, although much broader than before.

It was decided to suppress the data processing for IES on SC2 for the time being, but to closely monitor it with the intention of possibly recovering the three detectors that still appeared usable. The monthly histogram tests were continued, and indeed by Oct 20, 2015, (Figure 49) it seems that they have stabilized in that the pedestals are much as they were before the failure, although slightly shifted and somewhat broader, and that the additional background noise is gone. Subsequent analysis of the regular data indicates that the recovery likely took place before mid-June, 2015. Data processing has been reactivated as of June 12, 2015.

The data processing was altered to allow for missing detectors, meaning the omnidirectional IES data is constructed from only the 3 remaining ones. Thus it is a rather lopsided omnidirectional result.

However, several other problems now also became apparent.

**Channel definitions:** because the pedestals have shifted from their previous positions, it was necessary to redefine the energy channel thresholds, something that is done every few years anyway. The new values were uploaded to the RAPID unit on May 9, 2016.

**Autoswitching:** the automatic changes of integration time depending on count rates needed to be corrected, since it was previously using data only from non-functioning detectors. This change was uploaded to the RAPID unit on June 17, 2016.

**New noise spikes:** Figure 50 shows the noise spikes that are now present after recovery; a method has been developed to detect and remove them automatically, shown in the lower panel. However, there might still be some spikes that survive the algorithm. At other times, there are so many spikes removed that the cleaned data show many long data gaps. This method is applied in the data processing on the ground and so can be done retroactively to the entire time period.

**Possible decreased sensitivity:** it was at first suspected that the recovered detectors were considerably (<10%) less sensitive than on the other spacecraft. Initially the geometry factors were corrected accordingly for the deliveries to CSA. However on further inspection, it became obvious that the “corrected” data were an order of magnitude (or more) above the others, and the uncorrected data were only slightly different. Thus this erroneous correction has now been removed from the data deliveries of the 4th release.

In summary, we have a partial recovery of the IES unit on SC2, making use of 3 of the 9 detectors, but one should observe the following caveat:

> Given the many issues listed above, plus the partiality (3 out of 9 detectors) the recovered IES data on SC2 can not be used reliably for pitch angle distributions, spectra determination, or even for absolute fluxes. They can however be used for indicating the existence of electron events and for their timings.
Figure 47: A healthy set of pedestals on SC2 from the histogram data taken a few days before the failure.

Figure 48: The sick pedestals on SC2 from the special histogram data taken a few days later.
Figure 49: Histogram results from Oct 20, 2015, showing that the pedestals in detectors 7, 8, 9 have settled down, while those in the other detectors are still hopelessly lost.

Figure 50: Additional noise spikes appear in the IES data after the partial recovery (upper panel) which can be detected and removed (lower panel).
10 Electron Background Counts

10.1 The background

It has long been observed that the count rates in the IES electron detectors never go exactly to zero, but always remain at a certain relatively constant low level, well below $1 \text{ s}^{-1}$. The background is also spread over all the energy channels, as can be seen in Figure 51.

It was only after sufficient data had been accumulated that a proper analysis could be undertaken. The first question is whether this noise is some kind of internal buzzing at a fixed rate, or of stastical nature. Initial investigations confirm that it does indeed obey Poisson stastistics, so that it is random. The next question is whether it is internal or external. To this end it is desirable to know the long-term time dependence, if any.

10.2 Background product

To carry out such an analysis we first need a database of the noise. We create new data products called $\text{IES}_\text{BG}_R$ (count rates) and $\text{IES}_\text{BG}$ (corresponding fluxes), although both are derived from the actual number of counts per measurement.

We take the E2DD6 counts in NM (which can be emulated from E3DD in BM), and accumulate the counts in each

![Figure 51: Example of electron background, a non-zero floor to the count rates when averaged over longer periods of time. Upper panel shows raw count rates, the lower one differential flux. Note that the background exists in all energy channels.](image-url)
of the 6 energy channels, 9 detectors, and 4 spacecraft, for each spin (~4 s) over a “long” period of time. In this case “long” is meant to be long enough to carry out a reasonable statistical analysis on the low numbers involved. We use 1 hour, which is about 900 measurements. The majority of these measurements contain zero counts, and a number of them a single count, and a few 2 or more. The average is less than 1 per spin, which makes the statistical analysis tricky.

For example, here is a sequence of 40 measurements from the data in Figure 51:

0 0 1 0 1 0 2 1 0 0 1 0 0 0 0 0 0 0 0 1 1 0 0 1 0 0 0 2 0 0 1 0 0 0 0 2 0 0

It contains 29 0’s, 8 1’s, and 3 2’s. A Poisson distribution with mean \( \lambda \) has as the probability for \( n \) counts:

\[
Pr(n) = \frac{e^{-\lambda} \lambda^n}{n!}
\]  

(2)

Setting \( \lambda = 0.275 \) as in this sample, we would get the average number of 0’s, 1’s, 2’s for 40 samples as 30, 8, 1, respectively. Hence this sequence appears to be consistent with a Poisson distribution.

However we want to have a more rigid mathematical test. The 900 samples in one hour also form a more reliable basis for any testing.

We wish to select intervals for which we can be certain that we are at the background level and not within some true event. Our selection criteria are:

- the integration time must be 50 \( \mu s \), since any other value occurs only when count rates are high;
- the distance from the Earth exceeds 7 \( R_E \), to avoid radiation belts;
- the distribution of counts within the interval be consistent with a Poisson distribution of fixed mean; this applies to each energy channel and detector individually;
- if all channels and detectors fail the tests, the output record is skipped; if only some fail, a record is output with those failed entries set to fill values.

It is the third point that is the most complicated and needs further explanation.

10.3 Poisson testing

To test whether a set of integers is consistent with a single Poisson distribution we need some measure (a statistic) and we need to know its likely deviation from the ideal value. For example, in the sample above the mean value is 0.275 and the variance is \( (n^2) - \langle n \rangle = 0.424 \), which is considerably higher than the expected value of 0.275. (Recall, the variance should also be \( \lambda \).) Is this unreasonably high? For this small sample size, probably not, but we would like to quantify that statement.

We emphasize that we work here only with the raw counts, not count rates nor fluxes, since the Poisson statistics apply only to such counts. The counts background is then converted to rates or fluxes afterwards.

First let us explain the data model and define some terms. We have a set \( \{x_i\} \) of \( N \) samples, such that each sample \( x_i \) is subject to a Poisson distribution, all with the same mean value \( \lambda \).

\[
\forall i, \quad \langle x_i \rangle = \sum_{n=0}^{\infty} n \cdot Pr(n) = \sum_{n=0}^{\infty} \frac{n \lambda^n}{n!} e^{-\lambda} = \lambda
\]  

(3)

The mean value \( \langle \rangle \) is a sum over all values of the distribution, valid for an infinite number of samples, while the average of the sample values is summed over the \( N \) values of the set \( \{x\} \) and depends on the values in that
particular set.

Sample average:  $\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$  \hspace{1cm} (4)

and its mean value:  $\langle \bar{x} \rangle = \frac{1}{N} \sum_{i=1}^{N} \langle x_i \rangle$

$= \lambda$  \hspace{1cm} (5)

The statistic $\bar{x}$ is thus an unbiased estimator for the population mean value $\lambda$.

Here are some other mean values that will be needed:

$\langle x^2 \rangle = \frac{1}{N} \sum_{n=0}^{\infty} \frac{n^2}{n!} \lambda^n e^{-\lambda}$

$= \frac{1}{N} \sum_{n=0}^{\infty} \frac{n(n-1) + n}{n!} \lambda^n e^{-\lambda}$

$= \frac{\lambda^2}{N} \sum_{n=0}^{\infty} \frac{\lambda^n}{n!} e^{-\lambda} + \frac{\lambda}{N} \sum_{n=0}^{\infty} \frac{\lambda^n}{n!} e^{-\lambda}$

$= \lambda^2 + \lambda$  \hspace{1cm} (6)

from which we can derive the population variance $\langle x^2 \rangle - \langle x \rangle^2 = \lambda$. The sample variance on the other hand is

$\text{Var}(x) = \frac{1}{N} \sum_{i=1}^{N} x_i^2 - \bar{x}^2$  \hspace{1cm} (7)

with mean value $\langle \text{Var}(x) \rangle = \frac{1}{N} \sum_{i=1}^{N} \langle x_i^2 \rangle - \frac{1}{N^2} \sum_{ij} \langle x_i x_j \rangle$

$= \frac{1}{N} \sum_{i=1}^{N} \langle x_i^2 \rangle - \frac{1}{N^2} \sum_{i \neq j} \langle x_i \rangle \langle x_j \rangle - \frac{1}{N^2} \sum_i \langle x_i^2 \rangle$

$= \lambda (\lambda + 1) - \frac{N-1}{N} \lambda^2 - \frac{1}{N} \lambda (\lambda + 1)$

$= \frac{N-1}{N} \lambda$  \hspace{1cm} (8)

The sample variance is a biased estimator of the true variance since its mean value is not exactly the same, but differs by the factor $(N-1)/N$.

Similarly mean values of other powers can be found as:

$\langle x^3 \rangle = \langle x \rangle^3 + 3 \langle x \rangle^2 + \langle x \rangle$  \hspace{1cm} (9)

$\langle x^4 \rangle = \langle x \rangle^4 + 6 \langle x \rangle^3 + 7 \langle x \rangle^2 + \langle x \rangle$  \hspace{1cm} (10)

What we now use for the Poisson testing is the sample average as an estimator for $\lambda$ and the sample variance $\times N/(N-1)$ and see how far it deviates from its expected value $\lambda$. To test the significance, we once more need
the variance of the sample variance, which can be derived with considerable algebra as

\[ N(N - 1) \text{Var}(\text{Var}(x)) = (N - 1) \langle x^4 \rangle - (N - 3) \langle x^2 \rangle^2 + 4(2N - 3) \langle x^2 \rangle \langle x \rangle^2 - 4(N - 1) \langle x^3 \rangle \langle x \rangle - 2(2N - 3) \langle x \rangle^4 \] (11)

A value for \( \text{Var}(\text{Var}(x)) \) can then be found from equation 11, using equations 6, 9, 10 with the sample average \( \bar{x} \) as an estimate for \( \langle x \rangle \) (equation 5). The statistic that is then applied as a measure of the goodness of the Poisson assumption is then

\[
\frac{\text{Var}(x) - \bar{x}}{\sqrt{\text{Var}(\text{Var}(x))}}
\]

the deviation of the sample variance from its (estimated) expected value in units of standard deviations.

The next task is to set significance levels for this deviation. For example, for a normal distribution, the 95% significance level is at 1.64, meaning 95% of the random values will have a deviation < 1.64 standard deviations from the mean value. How well can this be applied to a Poisson distribution?

We apply a Monte Carlo method to our Poisson model and statistic (5000 tests per value of \( \lambda \)) to determine the limit below which 95% of the deviations lie, with the following results:

- the limiting deviation is only weakly dependent on the sample size \( N \);
- as \( \lambda \) increases, the limit \( \rightarrow 1.64 \), the value for a normal distribution; \( \lambda > 5 \) is already into this region (1.60);
- for \( \lambda > 0.09 \), we can fit the limiting deviation for 95% to a cubic equation in powers of 1/\( \lambda \);

95% limit = 1.64 - 0.299 \cdot \lambda^{-1} + 0.0403 \cdot \lambda^{-2} - 0.001922 \cdot \lambda^{-3}

e.g. this gives for \( \lambda = 0.1 \) a value of 0.75 standard deviations;
- for \( \lambda < 0.09 \), use the above formula with \( \lambda = 0.09 \).

### 10.4 Application and validity

As described earlier, the background product IES BG is made up by taking one-hour intervals of single-spin (\( \sim 4 \) s) count measurements meeting the criteria for integration time and distance from the Earth, and which also pass the Poisson test. That test consists of estimating the mean value and variance of the \( \sim 900 \) measurements and checking that the deviation of the variance from its expected value is within the 95% confidence limit.

There are two ways in which this test can go wrong:

- **false negatives**: the 95% confidence limit means that even for a true Poisson distribution, 5% of these results will be wrongly rejected simply because of statistical variations; since we are looking for a long-term minimum in the background based on the hourly determinations, this is not so critical;
- **false positives**: there is also a chance that non-Poisson distributions might be erroneously accepted; estimating how high this rate might be is not so easy since it requires a model for such distributions.

We do indeed see that at times of obvious activity in the electron fluxes, the Poisson test does fail, as expected. However to check the behaviour at more borderline situations, we set up Monte Carlo tests in which the 900 measurements are generated (randomly) with the mean value varying from \( \lambda \) to 2\( \lambda \), and seeing how many are rejected by the test. The results are:

- for \( \lambda = 5 \rightarrow 10 \) and higher, the rejection rate is 100%;
Figure 52: Minimum electron background rate per orbit over 17.5 years, for all 4 spacecraft and 5 energy channels. Channel 1 has been suppressed as described in the text. (The jump in the data on SC2 in 2015 is due to the partial failure in IES, Section 9).

- for $\lambda = 1 \rightarrow 2$, it is $\sim 32\%$;
- for $\lambda = 0.1 \rightarrow 0.2$, it is only about 6% (which is close to the 5% of false negatives inherent in the system).

This means that the rate of false positives is very low for a mixture of high $\lambda$, but at the realistic low values of $\sim 0.1$, it is very high. This might be considered to be unsatisfying until one realizes

1. at such low values of $\lambda$, the relative error (standard deviation to mean value) is very large ($\gg 1$), and therefore deviations of a factor of 2 are quite likely to be accepted;
2. Such a low average over such a long time is most likely background anyway;
3. what could still lead to false positives would be a very steady flux at high rates, over a long time, from something like solar events, which can continue for days.

We conclude that this Poisson test is a reasonable method to detect times of steady background, and to eliminate most other true events.

10.5 Long-term analysis

To investigate the long-term variation, if any, in the electron background, we take all the hourly measurements for all 4 spacecraft over the entire Mission, from 2001 to (currently) the middle of 2018. We then proceed as follows:
1. For each single orbit (∼2.5 days) we take the minimum background for each detector and energy channel, which we then plot as a matrix, one for each spacecraft.

2. We establish from this that, apart from other known interferences such as the solar noise (Section 5.1.4) and pedestal noise (Section 5.1.3), the 9 detectors all show the same behaviour.

3. For this reason, we combine all the 9 detectors (without those suspect ones) to make up an omnidirectional background.

4. We also remove energy channel 1, since this suffers from many redefinitions of the lower threshold, and so is not consistent over all detectors, spacecraft, and time.

5. The final results are now plotted in Figure 52.

Note that in Figure 52 we are plotting rates, not raw counts. The rates range from ∼0.1 s⁻¹ to ∼0.25 s⁻¹, or counts per spin of 0.4–1. Note also the differences between channels does not reflect a possible energy dependence, since these are total rates over the whole channel width; channel 6 is by far the widest and so it is not surprising that its rates are the highest.

The time variation over the 17.5 years is reminiscent of the 11-year solar cycle, and in fact, this profile is very similar to ones observed on other missions [e.g., on Cassini by Roussos et al., 2011], which were attributed to intergalactic cosmic rays, modulated by the solar activity.

We thus conclude, that our electron background is similarly solar-cycle modulated cosmic rays.
11 IES contamination in the radiation belts

The RAPID/IES data can be contaminated by energetic protons and electrons. This is especially worrying in the radiation belts. An assessment of a possible contamination has been done by Kronberg et al. [2016]. They assess the level of distortion of energetic electron spectra from the RAPID/IES detector, determining the efficiency of its shielding. The assessment is based on the analysis of experimental data (from the National Institute of Standards and Technology and the Stopping and Range of Ions in Matter program) and a radiation transport code (Geant4). In simulations, the incident particle energy distribution of the AE9/AP9 radiation belt models was used. The results of the simulations which present the contamination percentage of the RAPID/IES energy channels at different L* are shown in Figure 53 and their values can be found in Table 6.

Applying the simulation results, the RAPID/IES data can be corrected using the following methods:

(1) The experimental data show that the RAPID/IES at all energy channels (40–400 keV) are strongly contaminated by protons of (∼230 to 630 keV and >600 MeV) at 3≤L*≤4. Therefore, in case of simultaneous availability of electron intensities and proton intensities in the range from ∼230 to 630 keV, we recommend to subtract the proton intensities from the electron intensities as described in section 5, equation (3) in Kronberg et al. [2016]. In case of the IES energy channel 6 one can simply subtract the proton intensities at ∼230 to 630 keV from the electron data for liberating data from proton contamination.

(2) In case that proton intensities in the aforementioned range are not available, we recommend to use equation 12 to remove the proton and electron contaminations:

\[ I_{e, \text{clean}} = I_e - I_e C, \]  

where C is the contamination percentage taken from Table 6).

In summary, the Roederer L-values (for quiet magnetic field), L*, and energy channels that should be used with caution are identified: at 3≤L*≤4 all energy channels (40–400 keV) are contaminated by protons (∼230 to 630 keV

Figure 53: IES data contamination in the electron and proton radiation belts at different L*-shells, for different energy channels and for the solar maximum. The percentage of the contamination by protons, high-energy electrons and the sum of those is denoted by magenta, green and blue colors respectively.
and >600 MeV); at $L^* \approx 1$, 4–6 the energy channels at 95–400 keV are contaminated by high energy electrons (>400 keV). However, choosing carefully the energy channels and the L shells according to the results of Geant4 simulations (Table 2), one can still use the IES radiation belt and ring current observations. Or the data can be corrected using the methods (1) and (2) proposed above.

Table 6: Contamination (%) of the IES detector in the Earth’s radiation belts for the solar maximum.

<table>
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<th>Nr. Channel</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>43.51</td>
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<td>0.52</td>
<td>1.06</td>
<td>4.9</td>
<td>13.31</td>
<td>21.3</td>
</tr>
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</table>
12 Summary

The result of the cross-calibration activities of RAPID with PEACE and CIS show that those instruments are well cross-calibrated and do not need special corrections apart from a possible adjustment to the 1st energy channel. Still at least for CIS/CODIF and RAPID/IIMS the data starting from 2006 have to be cross-checked, as at both instruments the TOF efficiencies become worse with time.

For Cluster/RAPID science data users another important fact will be of interest. To understand the relationship between count rates and fluxes a few notes have to be taken on factors and calculation procedures, being involved in the data processing chain performed by the RAPID software.

To this end, it is important to pay attention to the standard deviations of all the RAPID measurements in order to check their statistical significance. These standard deviations are delivered as part of every RAPID data product.
Appendices

A Calculation of Fluxes from Count Rates

Here an overview is presented for the derivation of the particle fluxes from the measured count rates.

A.1 Geometry Factor

Consider a particle of energy $E$ and incoming direction $\Omega$, striking the detector surface at some point $S$. The probability that it successfully navigates through the entrance aperture and collimators to reach the detector at that point is $\text{Pr}(E, \Omega, S)$, which is either 1 or 0. The integral of this probability over the field-of-view $\Delta \Omega$ and detector surface $\Delta S$ is the geometry factor (GF):

$$G(E) = \int_{\Delta \Omega} d\Omega \int_{\Delta S} dS \text{ Pr}(E, \Omega, S)$$  \hspace{1cm} (13)

The geometry factor $G(E)$ has units of cm$^2$ · sr; it essentially describes how much of the detector surface can be ‘seen’ externally, summed over all input directions.

In the case of RAPID, the particle paths do not contain electric and magnetic fields, hence the GF is independent of energy and species.\(^1\) Calculations for one SCENIC sensor yield

$$G = 8.85 \times 10^{-3} \text{ cm}^2 \cdot \text{sr}$$  \hspace{1cm} (14)

or $2.21 \times 10^{-3} \text{ cm}^2 \cdot \text{sr}$ for one polar segment of $15^\circ$.

The rate of particles of energy $E$ striking the detector surface can now be written as

$$\mathcal{R}(E) = \int_{\Delta \Omega} d\Omega \int_{\Delta S} dS j(E, \Omega, S) \cdot \text{ Pr}(E, \Omega, S) = G(E) \cdot \bar{j}(E)$$  \hspace{1cm} (15)

where

$$\bar{j}(E) = \frac{1}{G(E)} \int_{\Delta \Omega} d\Omega \int_{\Delta S} dS j(E, \Omega, S) \cdot \text{ Pr}(E, \Omega, S)$$  \hspace{1cm} (16)

Note that $\bar{j}$ is the average of $j$ over the field-of-view and detector area, weighted by the geometry factor.

A.2 Detector Efficiency

The probability that a particle is detected and measured once it strikes the detecting surface is described by the detector efficiency $\epsilon(E)$, which is a function of particle energy and species, but not of direction and position on the surface.

The efficiency has been measured by ion beam experiments on the channel plate detectors, and can be fitted to an exponential:

$$\epsilon \approx a \exp(bE) + c \quad \text{for} \quad E < E_{\text{max}}$$

$$\approx \epsilon_{\text{max}} \quad \quad \quad \quad \quad \text{for} \quad E > E_{\text{max}}$$  \hspace{1cm} (17)

The coefficients $a, b, c$, as well as $E_{\text{max}}$ and $\epsilon_{\text{max}}$ depend on particle type. The maximum $\epsilon_{\text{max}} \sim 0.1–0.2$.

\(^1\)This statement does not apply when the deflection voltage is on to sweep ions out of the detection region.
A.3 Conversion Factor for Particle Flux

We now derive the conversion factor (CF) between particle flux and measured count rates. The number of counts recorded per unit time is the integral over the selected energy range of the rate \( R \) (equation 15) that particles strike the detector times the probability \( \epsilon \) that they are measured:

\[
\int_{\Delta\Omega} d\Omega \int_{\Delta S} dS \  Pr(E, \Omega, S) \ \epsilon(E) \cdot j(E, \Omega, S) \\
= \int_{E_1}^{E_2} dE \ G(E) \ \epsilon(E) \cdot \bar{j}(E)
\] (18)

We now want to find an approximation for the particle flux knowing the count rate \( \mathcal{N} \). The problem is to invert equation (18). In fact, what we really obtain is only the integral flux \( J \):

\[ J(E_1, E_2) = \int_{E_1}^{E_2} dE \ \bar{j}(E) \] (19)

Let us define the weighted mean conversion factor for this energy range as

\[
\bar{CF} = \frac{\int dE \ w(E) G(E) \ \epsilon(E)}{\int dE \ w(E)}
\] (20)

\[
\approx \frac{1}{\Delta E} \int_{E_1}^{E_2} dE \ G(E) \ \epsilon(E)
\] (21)

If the weighting function \( w(E) \) were to be proportional to \( \bar{j}(E) \), then (20) yields

\[
\bar{CF} \int_{E_1}^{E_2} dE \ \bar{j}(E) = \int_{E_1}^{E_2} dE \ \bar{j}(E) \cdot G(E) \ \epsilon(E)
\]

\[
\bar{CF} \ J(E_1, E_2) = \mathcal{N}(E_1, E_2)
\] (22)

or

\[ J(E_1, E_2) = \mathcal{N}(E_1, E_2) / \bar{CF}(E_1, E_2) \] (23)

\( \bar{CF} \) is thus the conversion factor between the integral flux in one energy channel and the count rate in that channel.

From equation (20) we see that the conversion factor at a given energy is \( G(E) \ \epsilon(E) \) and that \( \bar{CF} \) is the mean of this factor over the energy channel. Since \( G(E) \ \epsilon(E) \) varies only slightly with energy (except at low energies), the mean value should not differ too much from any value within the range.

Ideally the weighting function \( w(E) \) in equation (20) should be of the same shape as \( \bar{j}(E) \); in reality we take it to be constant. This assumption is legitimate to the extent that \( G(E) \ \epsilon(E) \) is only weakly dependent on energy.

The averaged CF does not depend directly on the \( \Delta E \) of the energy channel. One often quotes a differential conversion factor, in units of cm\(^2\) · sr · keV which is really \( \bar{CF} \times \Delta E \). In this paper, we deal entirely with the 'integral' CF.

A.4 Conversion to Differential Flux

One really would like to have an estimate for the differential flux \( j \). This is usually achieved with

\[ j = J(E_1, E_2) / \Delta E \] (24)
but this produces only the average differential flux within the energy channel, and it is not at all clear to which energy it should be assigned. A better method is to try to fit the observed counts, or integral fluxes, to a spectrum model.

Incidently, by taking \(w(E)\) in equation (20) as constant, the flux in equation (24) is really an average of the differential flux \(\bar{j}(E)\) over the energy channel, weighted by the conversion factor \(G(E)\epsilon(E)\).

### A.5 Calculation of Omnidirectional Flux

For each of the three ion species, we will be given the omnidirectional counts for 8 energy channels. For each energy channel, and species, we will have the effective omnidirectional CF, \(\Sigma CF\), the sum of the CF’s over the polar segments.

We also allow for a possible background count rate for each energy channel and direction. The background rates must also be summed over all polar segments to produce the rate in the pseudo omnidirectional detector, \(\Sigma BG\).

The omnidirectional flux in energy channel \(n\) is thus:

\[
J_n = \frac{C_n/T - \Sigma BG}{\Sigma CF}
\]  

(25)

where \(C_n\) is the number of counts in energy channel \(n\) accumulated over time \(T\) (one spin for protons, 4 spins for the others); \(C_n/T\) corresponds to \(N\) of equations (18) and (23).

**Note:** it was originally thought that the background would be isotropic penetrating particles or electronic noise. It now turns out that for the ions, there is solar contamination, predominantly in the sun sector. It is also a different rate in serial and parallel mode, since in serial only one third of the sector is “active”, and this third misses the sun. In the latest version of the calibration data, no background removal is applied, since this can lead to strange irreversible results; it is better to let the user work on this himself. The only exception is for some large solar contamination in the IES head 1 on SC3, which is very strongly dependent on the solar aspect angle.

### B Phase Space Density Conversion

All the products delivered to CSA by the RAPID Team are in differential particle flux units. Because of RAPID’s wide energy bins, a conversion to phase space density (as commonly used by lower energy spectrometers) is not feasible, since the effective energy of each bin depends on the spectrum. Nevertheless, we give here an outline of how such a conversion is to be done.

The differential flux of particles with velocity \(\bar{v}\) is given by

\[
\bar{j}(E, \Omega) dE d\Omega = f(\vec{v}) v^3 dv d\Omega
\]  

(26)

where \(f(\vec{v}) v^2 dv d\Omega\) is the number of particles per unit volume with velocity between \((v_x, v_y, v_z)\) and \((v_x + dv_x, v_y + dv_y, v_z + dv_z)\). From the equation (26) using relationship \(dE = m v dv\) we get the standard relation between differential flux and phase space density (non-relativistical case)

\[
\bar{j} = \frac{2E}{m^2} f(\vec{v})
\]  

(27)

The phase space density can be written in units of \(\text{km}^{-6}\text{s}^{-3}\) as

\[
f = \frac{m^2}{E_{\text{eff}}} \cdot 0.53707
\]  

(28)
where \( m \) is the particle mass in atomic mass units, \( \bar{\jmath} \) is recorded in cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\)keV\(^{-1}\) and \( E_{\text{eff}} \) is the effective energy of the energy channel in keV.

For the relativistic case, we must use the total energy \( E_T = E_0 + E \), where \( E_0 \) is the rest energy and \( E \) the measured kinetic energy. Applying the relativistic formula

\[
E_T = \frac{E_0}{\sqrt{1 - v^2/c^2}}
\]  

(29)

to equation 26, we get the equivalent of equation 27 to be

\[
\bar{\jmath} = f(\bar{\nu}) \frac{E_0^2 c^4}{E_T^3} \left[ 1 - \left( \frac{E_0}{E_T} \right)^2 \right]
\]  

(30)

The equivalent of equation 28 in the same units, becomes:

\[
J = E_T \left( \frac{E_T}{E_0} \right)^2 \frac{\bar{\jmath}}{1 - (E_0/E_T)^2} \cdot 1.2379 \times 10^{-12}
\]  

(31)

### B.1 Calculation of the Effective Energy for the Energy Channels

The differential flux is delivered as the integrated flux divided by \( \Delta E \). The problem is to what energy does it correspond? Here is a simple analysis for a power law distribution

\[
J = \int_{E_1}^{E_2} A \cdot E^{-\gamma} \, dE = \frac{A}{\gamma - 1} \left( E_1^{-\gamma+1} - E_2^{-\gamma+1} \right)
\]  

(32)

where \( E_1 \) and \( E_2 \) are the energy channel thresholds, \( \gamma \) is a spectral index and \( A \) is a normalization.

Let \( E_m = (E_2 + E_1)/2, \Delta = (E_2 - E_1)/2 \) and we denote as

\[
\delta = \frac{\Delta}{E_m}
\]  

(33)

then equation (32) can be transformed to

\[
\frac{J}{E_2 - E_1} = \frac{A}{\gamma - 1} \frac{(1 - \delta)^{-\gamma+1} - (1 + \delta)^{-\gamma+1}}{2\delta} E_m^{-\gamma} \equiv A \cdot E_{\text{eff}}^{-\gamma}
\]  

(34)

where \( E_{\text{eff}} \) is the energy at which the spectrum with given \( A \) and \( \gamma \) has the differential flux equal \( J/\Delta E \). Equation (34) leads to

\[
\left( \frac{E_{\text{eff}}}{E_m} \right)^{-\gamma} = \frac{(1 - \delta)^{-\gamma+1} - (1 + \delta)^{-\gamma+1}}{2\delta(\gamma - 1)} \approx 1 + \frac{\gamma(\gamma + 1)\delta^2}{6} + ...
\]

\[
E_{\text{eff}} \approx E_m \left( 1 - \frac{\gamma(\gamma + 1)\delta^2}{6} + \ldots \right)
\]  

(35)

The spectral index \( \gamma \) can be estimated by using fluxes for two adjacent energy channels and their effective energies

\[
\gamma = \frac{\ln(j_1/j_2)}{\ln(E_{\text{eff}2}/E_{\text{eff}1})}
\]  

(36)
This expression is derived from the definition of the differential flux \( j = A \cdot E^\gamma \).

Some upper energy channel thresholds are double or more the lower one. In this case where \( E_2 = 2E_1, \Delta = E_1/2, E_m = 1.5E_1 \) we get \( \delta = 1/3 \). Requiring \((\gamma + 1)\delta^2/6 < 0.1\) (i.e. 10% accuracy in \( E_{\text{eff}} \)) we obtain \( \gamma < 5.6 \) for \( \delta = 1/3 \). Thus the mean energy, \( E_m \) is a good first approximation of the effective energy, \( E_{\text{eff}} \), i.e. \( E_{\text{eff}} = E_m \).

Therefore a first guess of \( \gamma \) can be obtained from equation (36) using \( E_{\text{eff}} = E_m \), and then we can get a better estimate of \( E_{\text{eff}} \) from equation (35) and iterate again.

**Example:** We take the realistic energy thresholds \( E_1 = 27.7 \text{ keV}, E_2 = 64.4 \text{ keV}, E_3 = 75.3 \text{ keV} \) and \( E_4 = 92.2 \text{ keV} \) and the differential fluxes \( j_1 = 7.58 \times 10^4 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{keV}^{-1} \) and \( j_2 = 1.93 \times 10^4 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{keV}^{-1} \). The \( \delta \) values can be estimated using formula (33), thus \( \delta_1 = 0.3985 \) and \( \delta_2 = 0.1001 \). Assuming that \( E_{\text{eff}1} = 46.05 \text{ keV} \) and \( E_{\text{eff}2} = 83.75 \text{ keV} \), i.e. the mean energies of the energy channels, we can calculate new \( \gamma \) using expression (36). Then the new calculated spectral index is \( \gamma = 2.28 \). With this using the last expression in formula (35) we can find new effective energies \( E_{\text{eff}1} = 42.05 \text{ keV}; E_{\text{eff}2} = 83.29 \text{ keV} \) and the new spectral index \( \gamma = 2 \); then again \( E_{\text{eff}1} = 42.39 \text{ keV}; E_{\text{eff}2} = 83.33 \text{ keV} \) and \( \gamma = 2.02 \). Iterate until \( E_{\text{eff}1} \) and \( E_{\text{eff}2} \) will be approximately constant, usually 2 to 3 iterations are sufficient.

It is also possible to estimate the effective energy in a simpler way assuming for example that the \( \gamma = 4 \) and then calculate the \( E_{\text{eff}} \) using the last expression in formula (35). The estimations of the effective energy at different \( \gamma \) shows that the values of the effective energy are differ from each other in the less than 10% range. And this is not higher than the standard deviation error for the energy channel thresholds calculations which is about 10%.

**B.2 Conversion Factors for Mean Energies**

Rather than employing the complicated method described above, one can simply use the geometric mean energy \( E_g = \sqrt{E_1 \cdot E_2} \) with equations 28 and 31 to generate a set of fixed conversion factors between differential flux and phase space density, as listed in Table 7.

<table>
<thead>
<tr>
<th>Chan</th>
<th>( E_g )</th>
<th>( f/j )</th>
<th>( E_g )</th>
<th>( f/j )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Protons</td>
<td>Helium</td>
<td>Oxygen</td>
<td>Electrons</td>
</tr>
<tr>
<td>1</td>
<td>42.23</td>
<td>1.271 \times 10^{-2}</td>
<td>64.18</td>
<td>1.338 \times 10^{-1}</td>
</tr>
<tr>
<td>2</td>
<td>83.32</td>
<td>6.445 \times 10^{-3}</td>
<td>154.0</td>
<td>5.576 \times 10^{-2}</td>
</tr>
<tr>
<td>3</td>
<td>121.3</td>
<td>4.426 \times 10^{-3}</td>
<td>201.2</td>
<td>4.269 \times 10^{-2}</td>
</tr>
<tr>
<td>4</td>
<td>244.3</td>
<td>2.197 \times 10^{-3}</td>
<td>287.2</td>
<td>2.991 \times 10^{-2}</td>
</tr>
<tr>
<td>5</td>
<td>599.8</td>
<td>8.953 \times 10^{-4}</td>
<td>508.6</td>
<td>1.689 \times 10^{-2}</td>
</tr>
<tr>
<td>6</td>
<td>1340.</td>
<td>4.005 \times 10^{-4}</td>
<td>1100.</td>
<td>7.806 \times 10^{-3}</td>
</tr>
<tr>
<td>7</td>
<td>2748.</td>
<td>1.954 \times 10^{-4}</td>
<td>2533.</td>
<td>3.392 \times 10^{-3}</td>
</tr>
<tr>
<td>8</td>
<td>4007.</td>
<td>1.340 \times 10^{-4}</td>
<td>3799.</td>
<td>2.261 \times 10^{-3}</td>
</tr>
</tbody>
</table>

Table 7: Conversion factors from differential flux (cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\)keV\(^{-1}\)) to phase space density (km\(^{-6}\)s\(^{-3}\)).
B.3 Effective Energy and Geometric Mean Energy

The geometric mean energy $E_g$ defined above is in fact a good approximation to the effective energy $E_{\text{eff}}$. Let us recast equations 32 and 34 in terms of $E_g$:

$$
\frac{J}{E_2-E_1} = A \cdot E^{-\nu} \\
= \frac{A}{E_2-E_1} \frac{E_g^{-\nu+1}}{\nu-1} \left[ \left(\frac{E_1}{E_g}\right)^{-\nu+1} - \left(\frac{E_2}{E_g}\right)^{-\nu+1} \right]
$$

(37)

Let us simply this by setting $r^2 = E_2/E_1 > 1$, from which $E_1 = E_g/r$ and $E_2 = rE_g$. Equation 37 then leads to:

$$
\left(\frac{E_{\text{eff}}}{E_g}\right)^{-\nu} = \frac{1}{\nu-1} \frac{r^{\nu-1} - r^{-\nu+1}}{r-r^{-1}} \\
\rightarrow 1 \text{ as } r \rightarrow 1
$$

(38)

Demonstration: for $E_2 = 2E_1$, and $\nu = 4$, we have $r = \sqrt{2}$ and equation 38 yields $E_{\text{eff}}/E_g = 0.962$; this shows that $E_g$ is a good estimate of $E_{\text{eff}}$ even for this “extreme” case.

B.4 Energy Density with Geometric Mean Energy

Energy density, $\varepsilon$, for a finite energy channel should be

$$
\varepsilon = \int_{E_1}^{E_2} f E \, d^3 v,
$$

(39)

where $f$ is the phase space density of particles with velocity $v$, $E_1$ and $E_2$ are the energy channel thresholds. The energy density expressed through the omnidirectional flux will be the following:

$$
\varepsilon = \int_{E_1}^{E_2} \frac{m}{2} \sqrt{E} j(E) \, dE \, d\Omega = 2\pi \frac{m}{2} \int_{E_1}^{E_2} \sqrt{E} j(E) \, dE,
$$

(40)

where $\Omega$ is the field of view. Here, phase space density, $f$, was converted into differential flux using equation 27. Therefore, the simple formula to calculate the energy density for the narrow energy channel will be:

$$
\varepsilon = \pi \sqrt{2m} \sqrt{E} j(E) \, \Delta E,
$$

(41)

The problem, which can appear in case of wide energy channel, is the definition of the energy $E$, which is suppose to be an effective energy of the corresponding channel. As it was mention in Section B.2 for the defining the effective energy, $E$, the geometric mean energy, $E_g = \sqrt{E_1 \cdot E_2}$ is often used, rather than more precise definition from Section B.1. The question is how reliable this simplification and at which spectral slopes and energy channel width it is appropriate to use.

It is reasonable to assume that at RAPID energies the differential flux $j = A \cdot E^{-\nu}$ has a power law dependence on energy. Therefore,

$$
\varepsilon = \pi \sqrt{2m} \int_{E_1}^{E_2} \sqrt{E} A \cdot E^{-\nu} \, dE \\
= \pi \sqrt{2m} \frac{A}{\nu-3/2} \left[ E_1^{-\nu+3/2} - E_2^{-\nu+3/2} \right]
$$

(42)
Let us test how well this exact power-law formula compares with the “geometric mean energy density” found by setting $E \rightarrow E_g$ and $j(E) \rightarrow J/(E_2 - E_1)$ in equation 41. Recall that the measured mean differential flux $J/(E_2 - E_1) = A \cdot E^{-\gamma}$ (equation 34), expressed in terms of the effective energy.

Again we use $r^2 = E_2/E_1 > 1$, and then $E_1 = E_g/r$ and $E_2 = rE_g$; and for further simplification, we set $\alpha = \gamma - 3/2$.

$$
\varepsilon = \pi \sqrt{2m} \frac{A E_g^{-\gamma+3/2}}{E_1/E_g - 3/2} \left[ \left( E_1/E_g \right)^{-\gamma+3/2} - \left( E_2/E_g \right)^{-\gamma+3/2} \right] \\
= \left\{ \pi \sqrt{2m} \sqrt{E_g (A \cdot E_{\text{eff}}^{-\gamma}) \Delta E} \right\} \frac{1}{E_g (E_{\text{eff}})} \frac{E_g}{E_{\text{eff}}} \left( \frac{r^{\gamma-3/2} - r^{-\gamma+3/2}}{r - r^{-1}} \right) \\
= \left\{ \pi \sqrt{2m} \sqrt{E_g (J/\Delta E)} \Delta E \right\} \frac{1}{E_g (E_{\text{eff}})} \left( \frac{E_g}{E_{\text{eff}}} \right)^{-\gamma} \left( \frac{r^{\gamma-3/2} - r^{-\gamma+3/2}}{r - r^{-1}} \right) \\
= \varepsilon_g \frac{1}{E_g / E_{\text{eff}}} \left( \frac{E_g}{E_{\text{eff}}} \right)^{-\gamma} \left( \frac{r^{\gamma-3/2} - r^{-\gamma+3/2}}{r - r^{-1}} \right)
$$

(43)

Here $\varepsilon_g$ is the geometric mean energy density, equation 41 with $E_g$ in place of $E$ and $J/\Delta E$ for $j(E)$.

We now apply equation 38 and get for the deviation $\text{dev}$ between the power-law energy density and the geometric mean energy density:

$$
\text{dev} = \varepsilon / \varepsilon_g \\
= \frac{\gamma - 1}{\gamma - 3/2} \frac{r^{\gamma-3/2} - r^{-\gamma+3/2}}{r^{\gamma-1} - r^{-\gamma+1}}
$$

(44)

Using our previous example of $E_2 = 2E_1$ and $\gamma = 4$, equation 44 yields $\text{dev} = 0.949$.

Note that $r > 1$ and ideally $r \rightarrow 1$ for a narrow bin. In this case $\text{dev} \rightarrow 1$. However, in case of wide energy channels one has to use the formula 44 for calculation of the energy density deviation.