Cluster Active Archive:

Interface Control Document for CIS

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DOCUMENT STATUS SHEET

Issue	Date	Details
Version 1.0	04.05.2005	1st version, prepared for the CAA Implementation Review. Document referenced as CIS-CES-ID-040505.
Version 2.0	05.12.2006	Revised version, now referenced as CAA-CIS-ICD-0001, and adopting the standard ESA style. Changes include: • the “grouping together” of some of the CIS Level 3 data products; • the addition of new data products in particle phase space density units; • the addition of a software package allowing the CAA user to read the CIS Level 3 CEF files and calculate partial or total moments of the ion distributions, for selected energy and solid angle ranges; • the addition of an appendix providing a CIS data selection guide for the CAA user; • the addition of an appendix describing how raw instrument data are transformed in various physical units, and how moments of the ion distribution functions are calculated; • updated CIS Level 2 data products description; • updated “Points of Contact”; • various minor updates.
Version 2.1	06.03.2007	Updated description of CIS Solar Wind Modes
Version 3.0	05.12.2008	Changes include: • the addition of ion pitch-angle distribution data sets; the addition of HIA Level 2 data products; • the addition of quality factor data sets; • updated description of the CODIF uncalibrated data sets.
Version 3.1	15.05.2010	Various updates, in preparation of the 5th CAA Operations Review.
Version 3.2	29.04.2011	Various updates, in preparation of the 6th CAA Operations review : • addition of CIS modes and CIS caveats datasets description • general reorganisation of datasets description
Version 3.2.1	02.05.2011	Taking in account modifications done during 2011 CAA CIS PM.
Version 3.3.1	10.05.2012	• Inclusion of suggestions made during the 2012 CIS-CAA Progress Meeting. • Addition of CIS data quality indices description.
Version 3.4.1	07.05.2013	• Inclusion of suggestions made during the 2013 CIS-CAA Progress Meeting.
Version 3.4.2	09.05.2014	• Update of CIS quality indexes datasets description • Update of CIS metadata header files
Version 3.4.3	27.10.2015	Inclusion of suggestions made during the 2015 CIS-CAA Progress Meeting and various other updates.

DOCUMENT CHANGE RECORD

Issue	RID/Ref	Details

REFERENCE DOCUMENTS

1. *Cluster Active Archive : Instrument Archive Plan for CIS,* H. Rème and I. Dandouras, CAA-CIS-AP-0001, October 2003.
2. *Archival of the Cluster Ion Spectrometry (CIS) data in the Cluster Active Archive (CAA),* I. Dandouras et al., Proceedings of the Cluster and Double Star Symposium: 5th Anniversary of Cluster in Space, ESTEC, Noordwijk, 2005.
3. *First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster Ion Spectrometry (CIS) experiment,* H. Rème et al., Annales Geophysicae, 19, 1303, 2001.
4. *Data Delivery Interface Document (Cluster Data Disposition System)*, ESOC, CL-ESC-ID-0001. http://caa.estec.esa.int/documents/.
5. *Expérience CIS, Cluster Ion Spectrometry - Structure des fichiers de Niveau 1*, A. Barthe, CESR, Apr. 2001.
6. *Description syntaxique des jeux de données CIS*, I. Dandouras, CESR, Apr. 2000.
7. *CIS Data Processing: Calibration File Structure, Version 2,* A. Barthe and I. Dandouras, CESR, Apr. 2002.
8. *Users Guide to the Cluster Science Data System*, P. W. Daly et al., DS–MPA–TN–0015. http://caa.estec.esa.int/documents/.
9. *Cluster Exchange Format – Data File Syntax*, CSDS Archive Task Group (A. Allen et al.), DS-QMW-TN-0010. http://caa.estec.esa.int/documents/.
10. *Cluster Metadata Dictionary,* CAA Metadata Working Group (C.C. Harvey et al.), CAA-CDPP-TN-0002. http://caa.estec.esa.int/documents/.
11. *Dandouras et al. in Tenerife book 2010*

12. *Cluster CODIF Calibration Report. Part III: TOF Peak Analysis. Mass Threshold and "Spillover" Determination* (Lynn Kistler, 2000)

TABLE OF CONTENTS

ACRONYMS

CIS	Cluster Ion Spectrometry
CODIF	COmposition DIstribution Function analyser
HIA	Hot Ion Analyser
HS	High sensitivity Side
LS	Low sensitivity Side

1 . PURPOSE

The Cluster Active Archive (CAA) / Cluster Science Archive (CSA) aims at preserving the complete set of 4 Cluster spacecraft data, so that they are usable in the long-term by the world-wide scientific community as well as by the instrument team PIs and Co-Is. The CAA instrument Interface Control Documents (ICDs) describe the formal interface between instrument teams and the CAA. The CIS - CAA ICD provides the detailed specification of the CIS (Cluster Ion Spectrometry) products at the CAA/CSA.

The broad outline of the archiving in the ESA CAA/CSA of the data from the CIS instrument onboard Cluster has been provided in Ref. 1. A more detailed outline is given in Ref. 2 and 11.

Note: The term CAA is used throughout this document, but it applies equally to the CSA.

2 . Points of Contact

For the operation of archiving the high-resolution data from CIS the following contacts have been agreed:

- As scientific correspondents:
  - CAA: H. Laakso and P. Escoubet
  - CIS: I. Dandouras
- As technical correspondents:
  - CAA: H. Laakso and C. Perry
  - CIS: A. Barthe and E. Penou
- As managerial correspondents:
  - CAA: H. Laakso and
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3 . CIS Instrument Description

3.1 Science Objectives

The prime scientific objective of the CIS experiment is the study of the dynamics of magnetised plasma structures in and in the vicinity of the Earth's magnetosphere, with the determination, as accurately as possible, of the local orientation and the state of motion of the plasma structures required for macrophysics and microphysics studies [*Ref. 3*]. The four Cluster spacecraft with relative separation distances that can be adjusted to spatial scales of the structures (a few hundred kilometres to several thousand kilometres) give for the first time the unambiguous possibility to distinguish spatial from temporal variations.

The four Cluster spacecraft encounter ionic plasma of vastly diverse characteristics in the course of one year (Figure 3.1.1). In order to study all the plasma regions with the fluxes shown in Figure 3.1.1, the CIS experiment needs, therefore, to be a highly versatile and reliable ionic plasma experiment, with the following requirements:

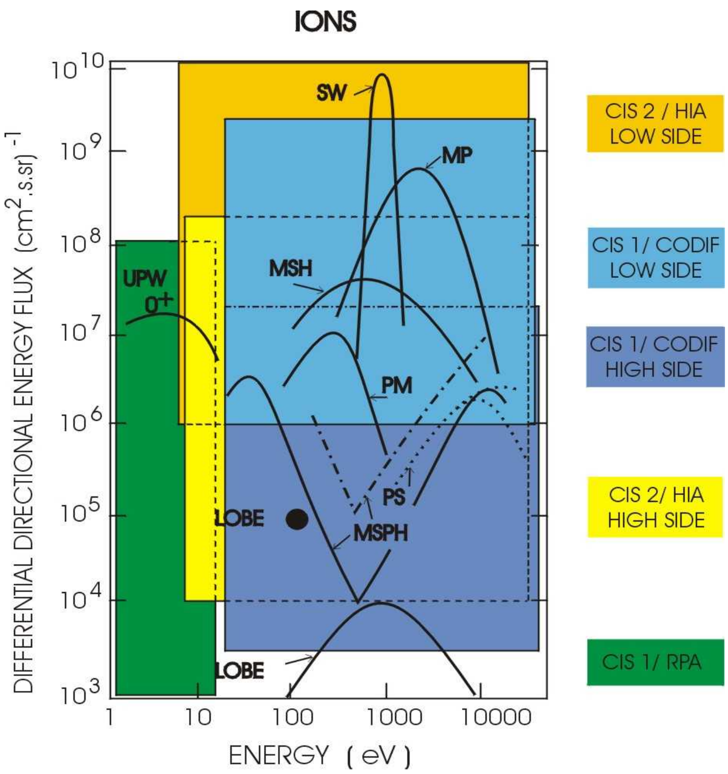

Figure 3.1.1 Representative ion fluxes encountered along the Cluster orbit in the solar wind (SW), the magnetopause (MP), the magnetosheath (MSH), the plasma mantle (PM), the plasma sheet (PS), the lobe and upwelling ions (UPW). The range of the different sensitivities of CIS1/CODIF (Low Side, High Side and RPA) and CIS2/HIA (Low Side and High Side) are shown with different colours.

The key scientific requirements for ion measurements are:

- A very great dynamic range is necessary in order to detect fluxes as low as those of the lobes, but also those as high as solar-wind fluxes, throughout the solar cycle. This cannot be done with a single instrument and with a single geometrical factor.

- A broad energy range and a full 4π angular coverage are necessary to provide a satisfactory and uniform coverage of the phase space with sufficient resolution. The angular resolution must be sufficient to be able to separate multiple populations, such as gyrating or transmitted ions from the main population downstream of the bow shock, and be able to detect fine structures in the distributions.
- Require a high angular and energy resolution in a limited energy and angular range for detection of cold beams, such as the solar wind. Because of the limited energy range required, a beam tracking algorithm has been implemented in order to follow the beam in velocity space. Moreover, in the foreshock regions, for example, any study of backstreaming ions requires the simultaneous observation of the solar-wind cold beam and of the backstreaming particles. Therefore, together with the solar-wind coverage described above, a coverage of the entire phase space excepting the sunward sector, with broad energy range, is also used.
- Moments of the three-dimensional (3D) distribution (and of the sunward sector, in solar-wind mode) are computed on-board, with high time resolution, to continuously generate key parameters, necessary for event identification.
- To study detailed phenomena of complex magnetospheric plasma physics multiple particle populations must be identified and characterised; therefore, a 3D distribution is needed. In order to transmit the full 3D distribution, while overcoming the telemetry rate limitations, a compression algorithm has been introduced, which allows an increased amount of information to be transmitted.

To achieve the scientific requirements, the CIS instrumentation has been designed to satisfy the following criteria, simultaneously on the 4 spacecraft:

- Provide a uniform coverage of ions over the entire 4π steradian solid angle.
- Have high (5.6° x 5.6°) and flexible angular sampling resolution to support measurements of ion beams and solar wind.
- Separate the major mass ion species from the solar wind and ionosphere, i.e. those that contribute significantly to the total mass density of the plasma (generally H^+, He^{++}, He^+, and 0^+).
- Have high sensitivity and large dynamic range ($\geq 10^7$) to support high-time-resolution measurements over the wide range of plasma conditions to be encountered in the Cluster mission (Figure 3.1.1).
- Cover a wide range of energies, from spacecraft potential to about 40 keV/q.
- All measurements above shall be done at spin-resolution (~4 sec)
- Have versatile and easily programmable operating modes and data-processing routines to optimise the data collection for specific scientific studies and widely varying plasma regimes.

The CIS plasma package is versatile and is capable of measuring both the cold and hot ions of Maxwellian and non-Maxwellian populations (for example, beams) from the solar wind, the magnetosheath, and the magnetosphere (including the upper ionosphere) with sufficient angular, energy and mass resolutions to accomplish the scientific objectives. The time resolution (~4 sec) of the instrument is sufficiently high to follow density or flux oscillations at the gyrofrequency of H^+ ions in a magnetic field of 10 nT or less. Such field strengths can be frequently encountered by the Cluster mission. Oscillations of O^+ at the gyrofrequency can be resolved outside 6-7 R_E.

3.2 Instrument Overview

To satisfy all these criteria, which cannot be met with a single instrument, the CIS package consists of two different instruments [*Ref. 3*]:

- a COmposition and DIstribution Function (**CODIF**) sensor, also called **CIS-1**,
- a Hot Ion Analyser (**HIA**) sensor, also called **CIS-2**.

In addition, each instrument, in order to be able to cover a dynamic range of about 6 orders of magnitude in particle fluxes, has two different geometric factors: a **high-sensitivity side** and a **low-sensitivity side**.

The CIS experiment comprises also a sophisticated dual-processor based instrument control and data processing system (**DPS**), which permits extensive onboard data processing.

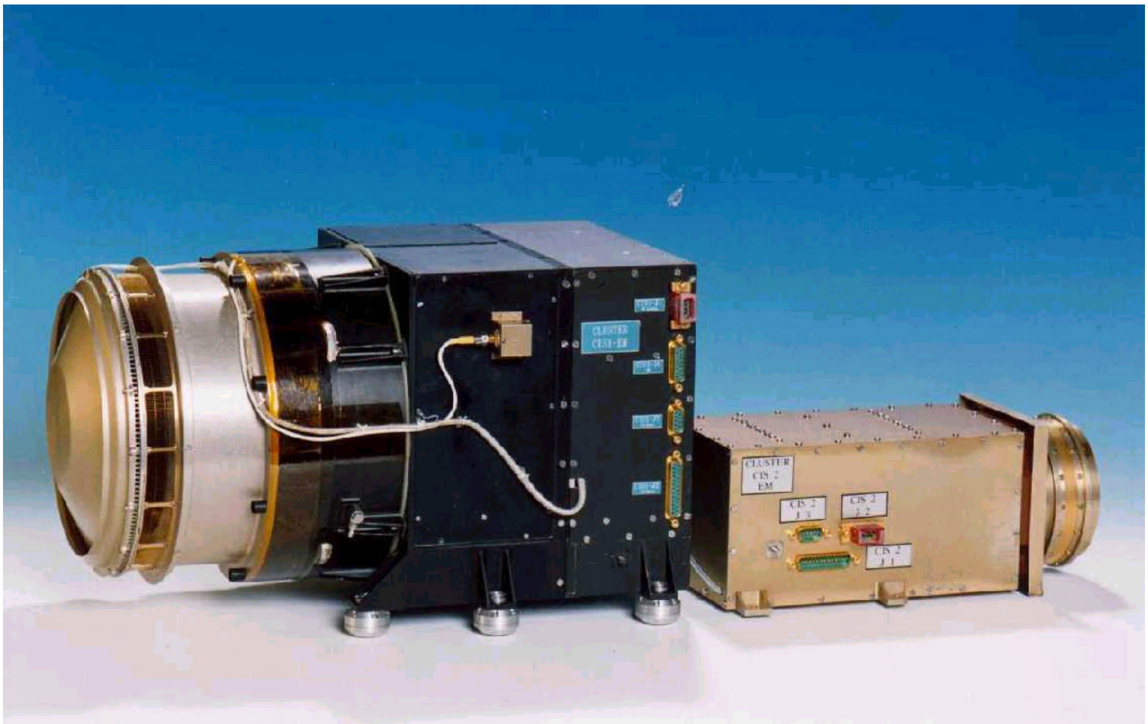

Figure 3.2.1 The CODIF (on the left) and the HIA (on the right) ion detectors of the CIS experiment

3.2.1 Hardware Overview

3.2.1.1 CODIF (CIS-1) Overview

The CODIF instrument is a high-sensitivity mass-resolving spectrometer with an instantaneous 360° x 8° field of view to measure full 3D distribution functions of the major ion species (in as much as they contribute significantly to the total mass density of the plasma), within one spin period of the spacecraft. Typically these include H^+, He^+, He^{++} and O^+, with energies from ~ 0 to 40 keV/q and with medium (22.5°) angular resolution. The CODIF instrument combines ion energy per charge selection, by deflection in a rotationally symmetric toroidal electrostatic analyser, with a subsequent time-of-flight analysis after post-acceleration to ~15 keV/q. The lowest measured energy is 25 eV/q except in the RPA mode where the energy range starts from 0.7 eV (so the incoming ion energy is 0.7 eV plus the spacecraft potential).

A cross section of the sensor showing the basic principles of operation is presented in Figure 3.2.2. The energy-per-charge analyser is of a rotationally symmetric toroidal type, which is basically similar to the quadrispheric top-hat analyser used for HIA. It has a uniform response over 180° of polar angle. Ions are selected as a function of their *E/q* (energy per charge) ratio, by sweeping the high voltage applied between the two toroidal hemispheres. The analyser has a characteristic energy response of about 7.3, and an intrinsic energy resolution of $\Delta E/E \approx 0.14$. The deflection voltage is varied in an exponential sweep. The full energy sweep with 31 contiguous energy channels is performed 32 times per spin. Thus a partial two-dimensional cut through the distribution function in polar angle is obtained every 1/32 of the spacecraft spin (125 ms). The full 4π ion distributions are obtained in one spacecraft spin period, although in some modes the data are accumulated onboard over a few spins before being transmitted.

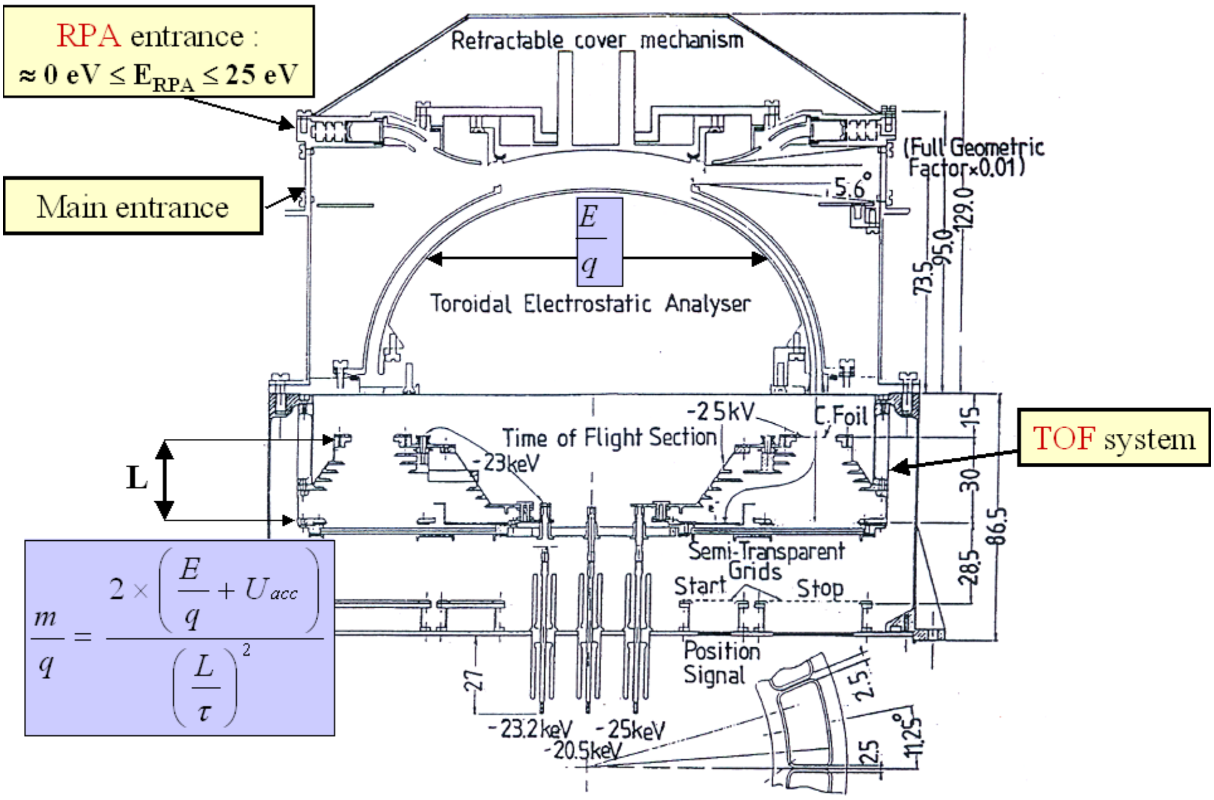

Figure 3.2.2. Schematic of the CODIF instrument

At the exit of the electrostatic analyser the ions go through a post-acceleration section where they gain an energy of $q.U_{ACC}$ ($U_{ACC} \approx 15$ kV, commandable value) , and then enter the time-of-flight (TOF) unit. In the time-of-flight section the velocity of the incoming ions is measured (Figures 3.2.2 and 3.2.3).

The energy per charge selected by the electrostatic analyser E/q, the energy gained by post-acceleration $q.U_{ACC}$, and the measured time-of-flight through the length L of the time-of-flight unit, τ, yield the mass per charge of the ion m/q according to : $m/q = 2\ (E/q + U_{ACC})\ \alpha / (L / \tau)^2$. The quantity α represents the effect of energy loss in the thin carbon foil (~ 3 μg cm^{-2}) at the entry of the TOF section and depends on particle species and incident energy.

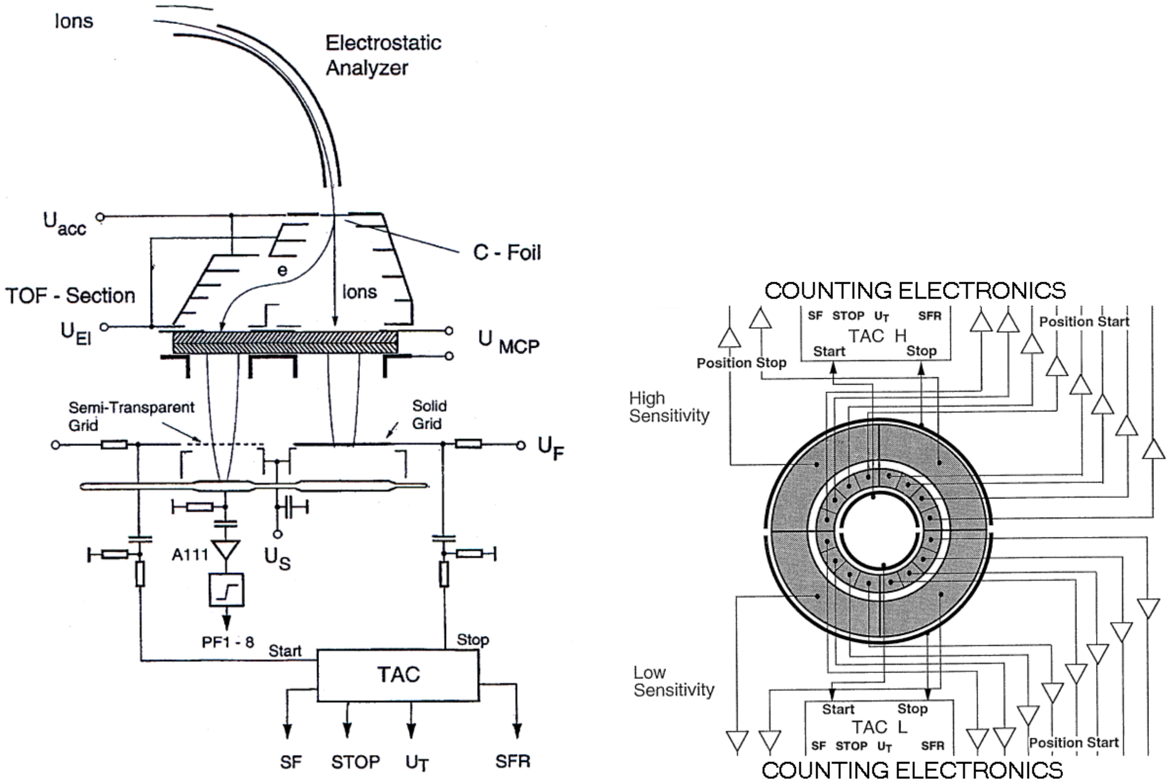

Figure 3.2.3 Schematic of the CODIF time-of-flight section (left) and MCP sectoring (right).

Microchannel plate (MCP) electron multipliers are used to detect both the ions and the secondary electrons, which are emitted from the carbon foil during the passage of the ions and give the “start” signal, for the time-of-flight measurement, and the position information (22.5° resolution). The MCP ring consists of 4 sectors, covering 90° each. The division in 22.5° sectors of the “start” anode, which collects the electrons under the MCP, gives the ion position information. The “stop” anode is divided in 90° sectors, just for consistency check between the “start” and the “stop” signal (Figure 3.2.3).

In order to cover populations ranging from magnetosheath protons to tail lobe ions (consisting of protons and heavier ions), a dynamic range of more than 10^5 is required; the measurement of solar wind stream is not a science requirement for the CODIF instrument. CODIF consists of two sections, each with 180° field of view, with geometry factors differing by a factor of ~ 100. This way, one section will always have counting rates which are statistically meaningful and which at the same time can be handled by the time-of-flight electronics. However, intense ion fluxes can in some cases saturate the CODIF instrument (particularly if data are acquired from the high sensitivity side), but these fluxes are measured with HIA. The operation of the high-sensitivity side (“high-G”, or “HS”) and of the low-sensitivity (“low-g”, or “LS”) side on CODIF is mutually exclusive, and only one of the two sides can be selected at a time to supply data. This selection is performed by time-tagged commands, independently of the instrument operational mode, allowing thus any combination of instrument operational mode and selected CODIF sensitivity side.

Including the effects of grid transparencies and support posts in the collimator, each 22.5° MCP sector has a typical geometry factor of 2.4×10^{-3} $cm^2 \cdot sr \cdot keV \cdot keV^{-1}$ in the HS side, and 2.6×10^{-5} $cm^2 \cdot sr \cdot keV \cdot keV^{-1}$ in the LS side (exact values vary between the spacecraft). There are eight 22.5° sectors (or anodes) in the high-sensitivity side, and six 22.5° sectors in the low-sensitivity side, i.e. there are two “blind” anodes or anodes that do not return data. The field of view of the CODIF anodes is shown in Figure 3.2.4, where the two “blind” anodes are in grey. The field of view of these anodes is masked, and thus they do not acquire any data.

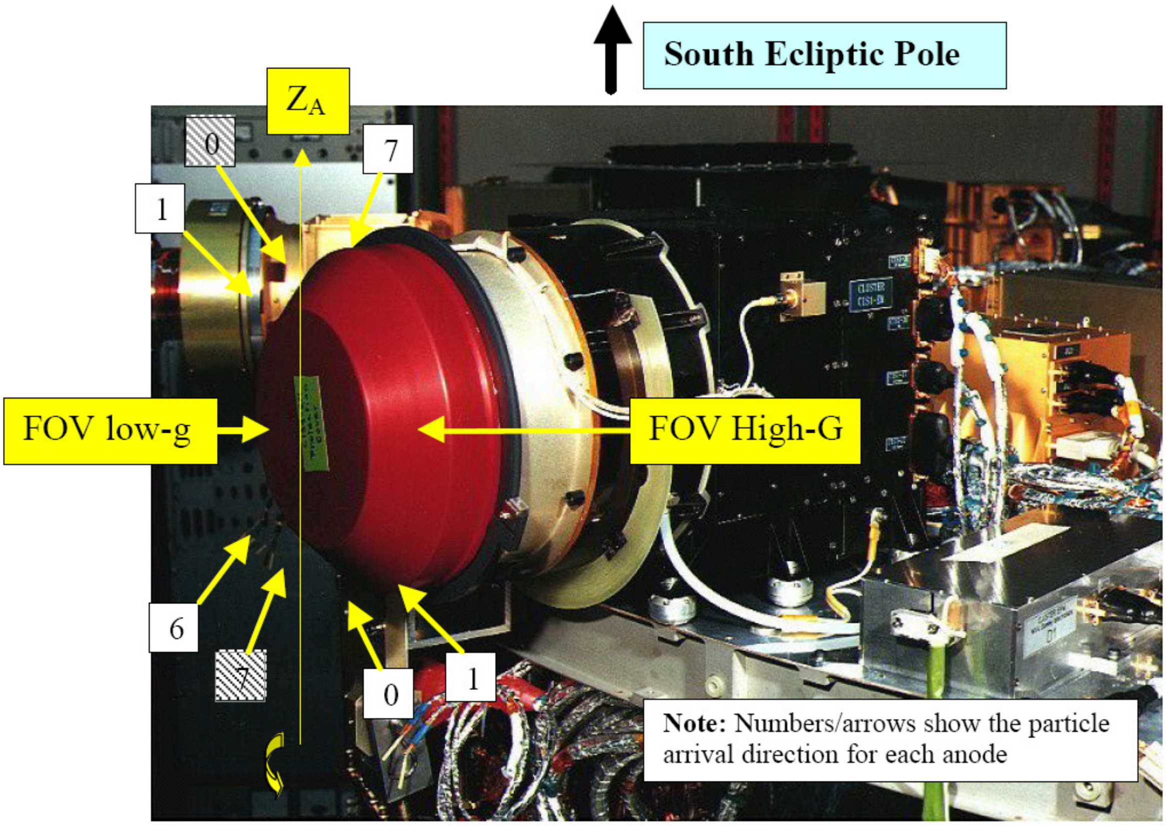

Figure 3.2.4 Schematic of the CIS-1 (CODIF) anodes field of view (High-G / low-g), with respect to the main axes.

The CODIF sensor primarily covers the energy range between 0.025 and 40 keV/q. With an additional Retarding Potential Analyser (RPA) device in the aperture system of the sensor, and with pre-acceleration for the energies below 25 eV/q, the range is extended to energies as low as the spacecraft potential. The retarding potential analyser operates only in the RPA mode, and provides an energy range between about 0.7 and 25 eV/q (with respect to the spacecraft potential). For the RPA aperture system, all anodes have the same geometric factor (on both sides), which is of 3.7×10^{-3} $cm^2 \cdot sr \cdot keV \cdot keV^{-1}$ (exact values vary between the spacecraft).

3.2.1.2 HIA (CIS-2) Overview

The HIA instrument is an ion energy-spectrometer, capable of obtaining full three-dimensional ion distributions with good angular and time resolution (one spacecraft spin). HIA combines the selection of incoming ions, according to the ion energy per charge by electrostatic deflection in a quadrispherical analyser, with a fast imaging particle detection system. This particle imaging is based on microchannel plate (MCP) electron multipliers and position encoding discrete anodes.

Basically the analyser design is a symmetrical quadrispherical electrostatic analyser, which has a uniform angle-energy response. The instrument has a uniform 360° × 5.6° disc-shaped field-of-view and narrow angular resolution capability. As for CODIF, ions are selected as a function of their *E/q* (energy per charge) ratio, by sweeping the high voltage applied between the two hemispheres. A cross section of the sensor showing the basic principles of operation is presented in Figure 3.2.5.

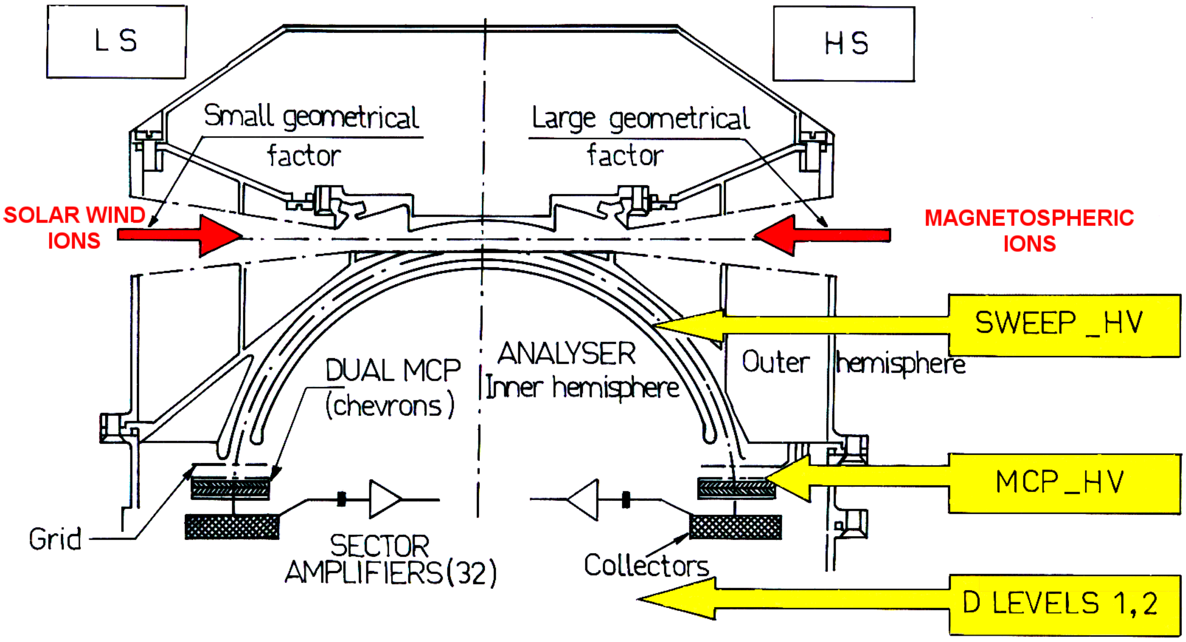

Figure 3.2.5 Cross sectional view of the HIA instrument.

In order to cover populations ranging from solar wind/magnetosheath ions to tail lobe and plasma sheet ions, a dynamic range of more than 10^5 is required. HIA therefore consists of two 180° field-of-view sections, with two different sensitivities (with a ~20 ratio), corresponding respectively to the high-sensitivity ("high-G", or "HS") and to the low-sensitivity ("low-g", or "LS") sections. The "low g" section allows detection of the solar wind and the required high angular resolution is achieved through the use of 8 sectors, 5.625° each, the remaining 8 sectors having 11.25° resolution plus there are two 22.5° wide sectors parallel to the spin axis that are not monitored (cf. Figure 3.2.6). The 180° "high G" section is divided into 16 sectors, 11.25° each. For each sensitivity section a full 4π steradian scan, consisting of 32 energy sweeps, is completed every spin of the spacecraft, i.e., 4 s, giving a full three-dimensional distribution of ions in the energy range ~ 5 eV/q – 32 keV/q. The field of view of the HIA anodes is shown in Figure 3.2.7.

The signal of each of the two sensitivity sections is amplified and gets through a discriminator ("Discriminator 1" for the HS section and "Discriminator 2" for the LS section). These discriminators set the threshold for the signal corresponding to a particle detection. In contrast to CODIF, which has fixed threshold levels for the discriminators, the HIA discriminator threshold levels are commandable. Each of the two instruments has also commandable high voltage levels for the MCPs (single command value per instrument). This allows to compensate, at some extent, for MCP gain fatigue (MCP aging), by raising slightly from time to time the MCP high voltage level.

The HIA geometry factor is ~ 7.0×10^{-3} $cm^2 \cdot sr \cdot keV \cdot keV^{-1}$ for the "high G" half (over 180°), and ~ 3.7×10^{-4} $cm^2 \cdot sr \cdot keV \cdot keV^{-1}$ for the "low g" half (exact values vary between the spacecraft). In contrast to CODIF, both sensitivity sides can be simultaneously selected to supply data, for some modes: solar wind/upstreaming ion modes. These data go however into separate telemetry products (for each of the sensitivity sides). The selected HIA sensitivity side is instrument mode dependent, and in some modes the two sensitivity sides can be operated simultaneously (in contrast to CODIF where only one sensitivity side can be operated at one time).

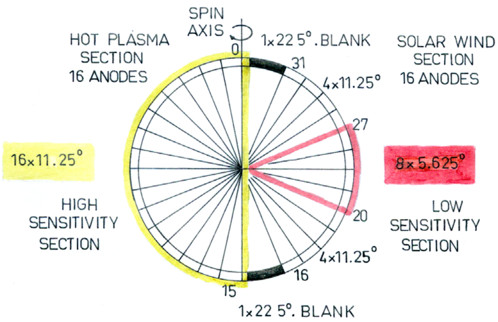

Figure 3.2.6 Principle of the HIA anode sectoring.

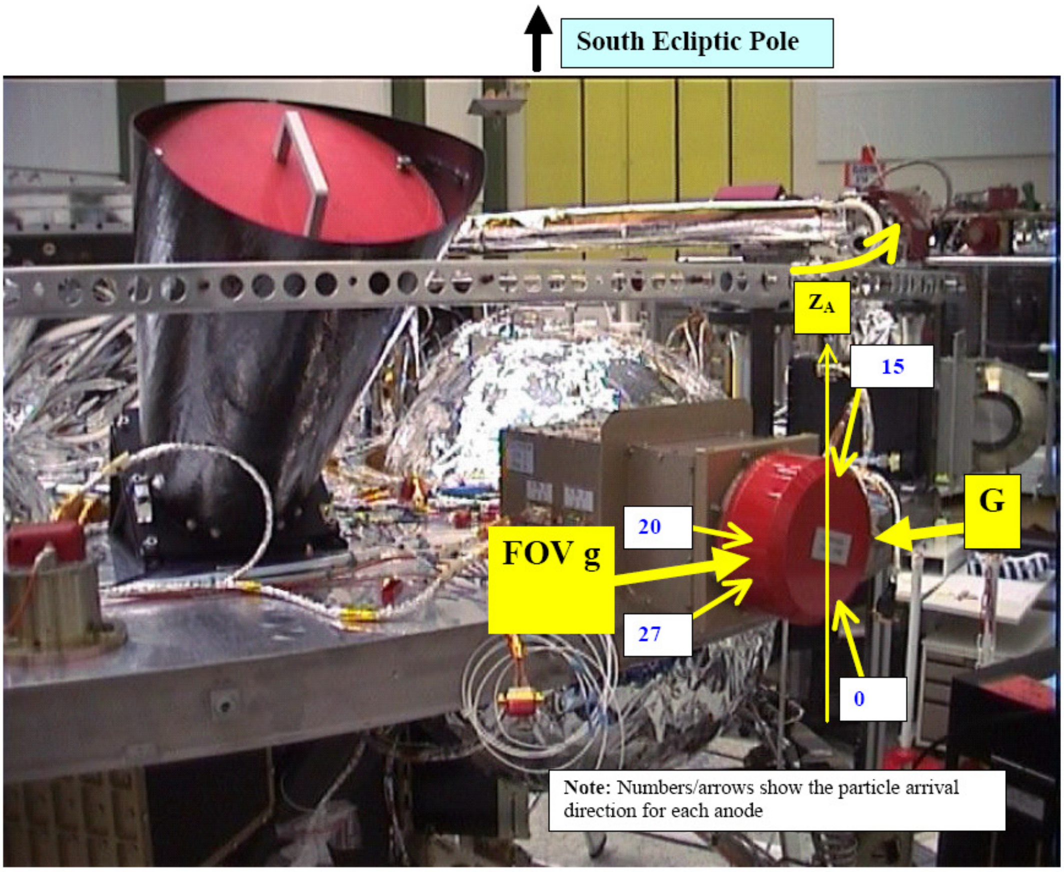

Figure 3.2.7 Schematic of the CIS-2 (HIA) anodes field of view (High-G / low-g), with respect to the main axes.

3.2.1.3 CIS Summary Characteristics

Table 3.2.1 gives the main features of the CIS experiment.

Sensor	Energy Range	Energy Resolution (FWHM)	Time Resolution		Mass Resolution M/ΔM	Angular Resolution (best)	Dynamics $(cm^2 \ sec \ sr)^{-1}$
			2D ms	3D s			
HIA	~ 5 eV/q – 32 keV/q	18%	62.5	4	-	~ 5.6° x 5.6°	10^4 – 2 x 10^{10}
CODIF	~ 0 - 40 keV/q Mass range: 1 – 32 amu	16%	125	4	~ 4 - 7	~11.2° x 22.5°	3×10^3 - 3×10^9

Sensor	Full Instantaneous Field of View	Geometrical Factor (Total) $cm^2.sr.keV/keV$
HIA	8° x 360°	7.0 x 10^{-3} for the HS half 3.7 x 10^{-4} for the LS half
CODIF	8° x 360°	1.9 x 10^{-2} for the HS half 2.1 x 10^{-4} for the LS half 3.0 x 10^{-2} cm^2 sr for the RPA

Table 3.2.1 Main features of the CIS experiment.

3.2.2 Operational Modes Overview

The CIS instruments have a large amount of flexibility either in the selection of the operational mode or in the reduction of the data necessary to fit the available telemetry bandwith. CIS can thus operate in any combination of the 6 Spacecraft Telemetry Modes and the 16 CIS Operational Modes. Note that the spacecraft mode that affects angular and energy resolution is resolution is given as a separate record-varying parameter.

Table 3.2.3 gives the 6 Cluster Spacecraft Telemetry Modes. There is an additional Telemetry Mode, the Housekeeping Mode (HKP), but during which no science data are collected. The Spacecraft Telemetry Modes most frequently used are the NM1 and the BM1 Mode, corresponding to normal and to burst telemetry rates.

Mode	BPS	Bytes/Blk	Blks /Frame	Bytes/ Frame
HKP	83,85	54	1	54
NM1	5 527,71	356	10	3 560
NM2	6 521,46	420	10	4 200
NM3	4 502,91	290	10	2 900
BM1	26 762,82	278	62	17 236
BM2	6 546,3	68	62	4 216
BM3	29 458,36	306	62	18 972

Table 3.2.3 Cluster Spacecraft Telemetry Modes and allocated CIS Telemetry Rate.

Table 3.2.4 gives the 16 CIS Operational Modes.

CIS Operational Mode		Mode Name	Angular resolution	Energy resolution/range
0	SW-1	Solar Wind / SW tracking – Mode 1		
1	SW-2	Solar Wind / 3D upstreaming ions – Mode 2		
2	SW-3	Solar Wind / SW tracking – Mode 3		
3	SW-4	Solar Wind / 3D upstreaming ions – Mode 4		
4	SW-C1	Solar Wind / SW tracking – Data Compression – Mode 1		
5	SW-C2	Solar Wind / 3D upstreaming ions – Data Compression – Mode 2		
6	RPA	RPA Mode		
7	PROM	PROM Operation		
8	MAG-1	Magnetosphere – Mode 1		
9	MAG-2	Magnetosphere – Mode 2		
10	MAG-3	Magnetosphere – Mode 3		.
11	MAG-4	Magnetosphere / Magnetosheath – Mode 1		
12	MAG-5	Magnetosheath – Mode 2		
13	MAG-C1	Magnetosphere – Data Compression – Mode 1		
14	MAG-C2	Magnetosheath – Data Compression – Mode 2		
15	CAL	Calibration / Test Mode		

Table 3.2.4 CIS Instrument Operational Modes.

Their characteristics are explained in Rème et al. (2001).

These 16 modes correspond to different energy sweeping schemes and different combinations of telemetry products transmitted. On-board calculated moments are always transmitted to the telemetry with a high-time resolution (1 spin), and a combination of 2D and 3D ion distribution functions, plus other telemetry products, are transmitted in parallel to on-board calculated moments, with a mode-dependent and product-dependent time resolution. Mode change is performed by time-tagged commands, according to the plasma populations anticipated along the Cluster orbit.

Magnetospheric Modes. They stay relatively simple modes, i.e. the full energy-angle ranges are systematically covered. For HIA the different telemetry products (including moments) are deduced from the 62E x 88Ω energy solid angle count rate matrices accumulated on the “high G” section. For CODIF they are deduced from the sensitivity side selected by command.

Solar wind tracking modes. They allow a precise and fast measurement (4s) of the ion flow parameters (H^+, He^{++}). For that, in the solar wind, for HIA the energy sweep range is automatically reduced, when the field-of-view of the “low g” section is facing the 45° sector centred in the solar wind direction. This energy sweep range is adapted every spin (Modes 0, 2, 4), centred on the main solar wind velocity by using a criterion based on the H^+ thermal and bulk velocities computed during the previous spin (solar wind beam tracking). This allows a higher energy resolution for the solar wind beam data.

Solar wind modes and upstreaming ions (Modes 1, 3, 5). The solar wind beam tracking is performed only once every ~16 spins (exact value can vary depending on mode number). During the remaining 15/16 spins a broader energy sweep is used for the solar wind detection by the “low g” section, allowing at the same time the detection of upstreaming ions by the “high G” section, which is then looking in the anti-sunward direction. Detailed 3D distributions for the solar wind (“low g” section) are then transmitted to the telemetry only during solar wind beam tracking (once every ~16 spins), but onboard calculated solar-wind moments are transmitted every spin. Moreover, detailed 3D distributions from the “high G” section (e.g. for upstreaming ions and/or for interplanetary disturbances) are included in the basic products transmitted to the telemetry.

Outside this 45° sector, the full energy sweep range is used (solar wind modes and solar wind modes with the priority on the upstreaming ions). However, when the field-of-view of the “high G” section is facing the 45° sector centred in the solar wind direction (cf. Fig. 3.2.8), the energy sweep stops (and “freezes”) above the solar wind alpha particles energy, to avoid a quick degradation of the MCPs by the intense solar wind beam (modes 0 – 5).

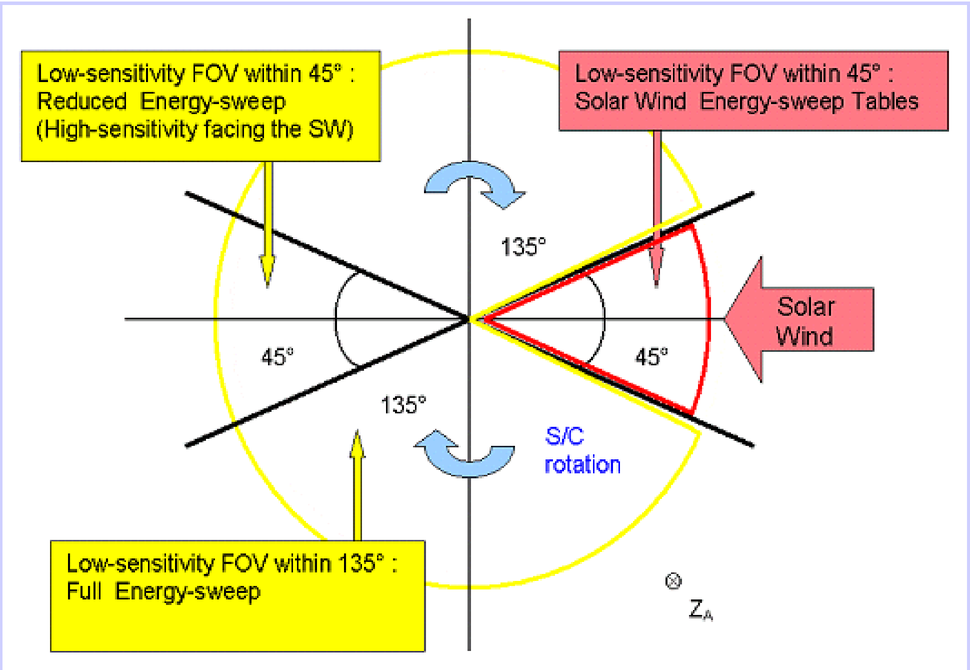

Figure 3.2.8 Schematic of the CIS-2 (HIA) energy-sweep scheme, as a function of the instrument field-of-view orientation in the spin plane (solar wind modes 0-5).

For CODIF, the reduced energy-sweep principle is also used when the field-of-view of the “high G” section is facing the 45° sector centred in the solar wind direction. Complete energy sweeping is used in the remaining part of the spin (cf. Fig. 3.2.9).

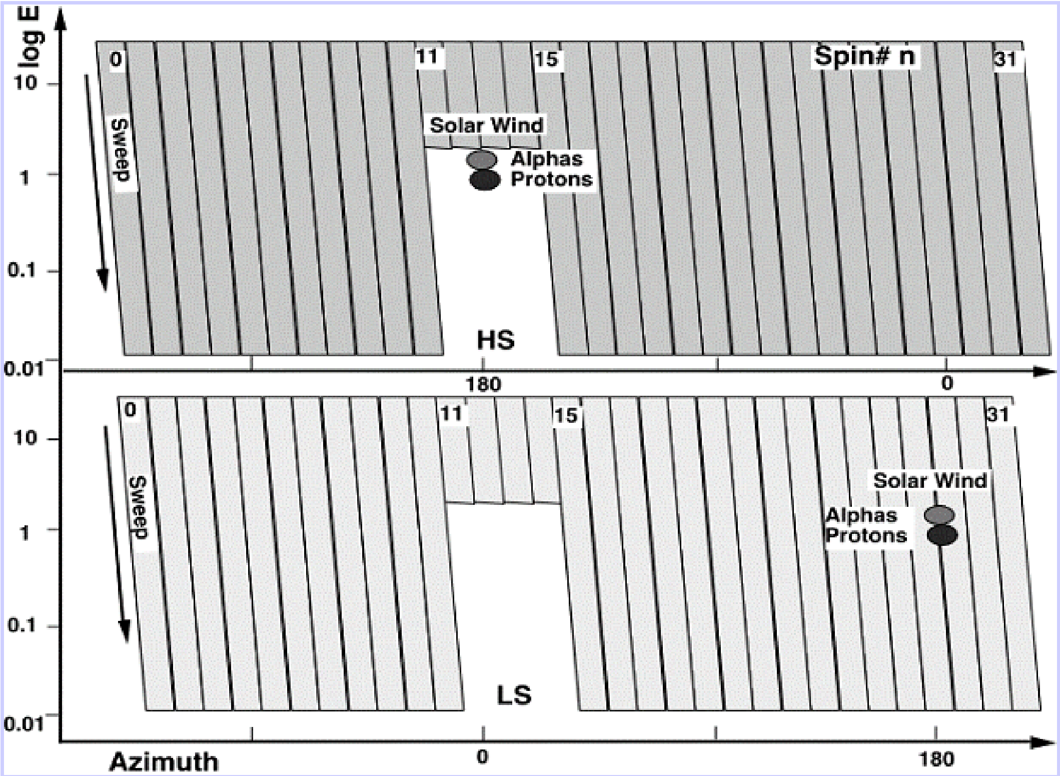

Figure 3.2.9

Schematic of the CIS-1 (CODIF) energy-sweep scheme, for solar wind modes, as a function of the spin phase: “high G” *field-of-view orientation (upper panel,) and* “low g” *field-of-view orientation (bottom panel). The energy “freeze”, during the reduced energy sweeps, is at about 2 keV.*

Magnetosheath modes. They are like magnetospheric modes. However, starting from 1 November 2003, the energy sweep scheme has been redefined for CODIF. With the new CODIF Magnetosheath Modes (modes 12 and 14), the energy sweeps are truncated and “freezed” at about 2 keV for 16 out of 32 sweeps (when the high-sensitivity side faces the magnetosheath mainstream flow), to save the MCP lifetime.

3.3 Data Processing Chain

3.3.1 Onboard Data Processing

Because of the high sensitivity and high intrinsic velocity-space resolution of the CIS instruments, continuous transmission of the complete 3D ion distributions sampled at the full time and angular resolution would require impossibly large bit rates. So, extensive on-board data-processing is a fundamental aspect of the CIS experiment. The instrument Data Processing System (DPS) analyses and compresses on-board the huge amount of data to maximise the scientific return despite the limited CIS telemetry allocation.

The first stage in the reduction of the CODIF data is to classify the data by species and position, and then to sum the counts in each mass/angle bin in an incrementing memory accumulator. The species determination is done by comparing the time-of-flight value of an event with a set of thresholds stored in a look-up table. There are 5 thresholds stored for each energy step, corresponding to a low threshold for H^+ and He^{++}, threshold between He^{++} and He^+, a top threshold for He^+, and a low and a high threshold for O^+. These accumulated counts are the input to both the moment calculation and to the transmitted distribution functions.

Moments of the distribution functions measured by the analysers are computed by the DPS and continuously transmitted with maximum time resolution (1 spin period or 4 s) for the CODIF (for four masses) and the HIA instruments. These moments include particle density *n*, the three components of the flow (bulk velocity) vector *V*, the six unique components of the momentum flux tensor, and the ion heat flux vector. From these, the full pressure tensor can be deduced as well as the temperature anisotropies $T_{//} / T_{\perp}$. To calculate moments, integrals over the distribution function are approximated by summing products of measured count rates with appropriate energy/angle weighting over the sampled distribution. Besides instrument sensitivity and calibration, the accuracy of computed moments is mainly affected by the finite energy and angle resolution, and by the finite energy range.

In parallel to the on-board calculated moments, a combination of 2D and 3D ion distribution functions, plus other telemetry products, are transmitted with a mode-dependent and product-dependent time resolution.

The list of the CIS telemetry products (more than 60 products in total) is given in *Ref. 3*. The time resolution of each telemetry product (in number of spins), as a function of the instrument operational mode and of the spacecraft telemetry mode, is given in the CIS calibration files (see below).

Due to the limited telemetry, data are compressed onboard. For a description of the compression scheme used, cf. Ref. 3.

3.3.2 Ground Data Processing

The first step in ground data processing is the decommutation and decompression of the CIS raw telemetry data [*Ref. 4*]. The output of this first step is the generation of the CIS Level 1 data files, organised in one file per telemetry product - spacecraft - day [*Ref. 5, 6*]. Calibrations are not applied to the Level 1 data, so as to constitute a data set stable in time (unaffected by calibration revisions). These data are not yet stored in the CAA.

Further data processing (Levels 2 and 3 or ion moments and distribution functions, respectively) uses these Level 1 data files as input, and applies to them the calibrations contained in the CIS calibration files, as described in the Appendix. The content of the calibration files include (cf. also section 3.4.5):

- For each telemetry product, on how many spins it was accumulated (as a function of CIS operational mode and of spacecraft telemetry mode).
- The instrument Geometric factors.
- The anode detection efficiencies.
- The parameters necessary to generate the Energy Sweep Tables.
- The CODIF Time-of-Flight nominal post-acceleration voltage.

- Etc.

A description of the CIS calibration files is given in "*CIS Data Processing: Calibration File Structure", Version 2* [*Ref. 7*].

3.4 Archival Data Products

The CIS data products at the CAA are:

3.4.1 CIS Level 1 data

The Level 1 files are not yet available at the CAA but are presently at IRAP. The logical formats of these files are defined in *Ref. 5*. Some Level 1 files are written in ASCII format and are described in *Ref. 6*.

The CIS Level 1 data:

- are decommutated, decompressed, and time-tagged telemetry data.
- are in raw instrument units (no corrections for MCP efficiencies etc.).
- represent the complete CIS Telemetry.
- are the input for all further data processing.
- are organised in one file per telemetry product - spacecraft – day.
- are flat files: each file is a time-series of equal-length records.
- Each data record is complete: time tag, product type, mode info, ...
- are in IEEE integers or floats (but some auxiliary files are ASCII).

Most Level 1 CIS data products lead to higher-level calibrated products, but some by their nature cannot be calibrated (e.g. CODIF TOF events), however they are essential for some types of data analysis.

3.4.2 CIS level 2 data: Ion moments

The CIS Level 2 data are moments of the particle distribution functions: ion density, velocity, temperature, and pressure.

They are delivered as 2 different datasets for CODIF and HIA.

In addition, a software is delivered that allows CAA users to calculate interactively moments from CIS 3-D distributions datasets.

3.4.2.1 HIA onboard moments

These moments are onboard calculated, then reprocessed on ground with the following steps:

- detection efficiency correction using total efficiency calibration coefficients (from calibration files)
- coordinate transformations to ISR2 and GSE systems (for ion bulk velocity)
- parallel and perpendicular temperature calculations using the B-field vector (FGM-CAA spin resolution)

They have 1-spin time resolution (~4 s), and are calculated from the full angular and energy resolution 3-D ion distributions.

They include ion density, bulk velocity vector (in both ISR2 and GSE frame), pressure tensor, total pressure, and temperatures (parallel and perpendicular to the magnetic field, and total temperature).

3.4.2.2 CODIF onground calculated moments

These moments are calculated on ground from the complete the 3-D ion distributions, with better calibration adjustments (per anode), but reduced time and energy resolution.

Ground moments are based on energies above 28 eV, so all low-energy ions are excluded.

They include density, bulk velocity vector, and temperatures (parallel and perpendicular to the magnetic field, and total temperature) for H^+, He^+ and O^+.

CODIF pre-calculated moments do no include:

- RPA mode data : not adapted for total moments (strongly limited coverage in energy range)
- He^{++} moments : inaccurate data, due to pollution by H^+ ions ("spillover").

3.4.2.3 Moments interactively calculated by users

A software tool is also delivered that allows CAA users to interactively calculate partial (or total) moments of the ion distributions, for selected energy and solid angle ranges: CODIF (all 4 ion species) and HIA data. Cf. section 3.4.6 for the software package necessary for such an interactive use.

Onboard calculated moments and on ground calculated moments from the 3-D ion distributions are complementary (cf. also table in Appendix 1) as they are based on different distribution functions and partially on different calibration values.

3.4.3 CIS Level 3 data

CIS Level 3 is composed of the following dataset categories:

3.4.3.1 3-D distribution functions

Are processed high-resolution data: 3-D ion distributions.

Most of the data take into account calibrations, corrections for MCP efficiencies etc.

Are giving measurements in several physical units, in separate files (cf. "*CIS: Particle Counts to Flux and to Moments of the Ion Distribution Function*", included as an Appendix in the present document):

- (differential) particle flux	(ions cm^{-2} s^{-1} sr^{-1} keV^{-1})
- particle energy flux	(keV cm^{-2} s^{-1} sr^{-1} keV^{-1})
- particle phase space density	(ions s^3 km^{-6})
- corrected-for-efficiency particle count rate	(ions s^{-1})
- raw particle counts	(number of ions per counter bin)

These data products are produced by correcting the Level 1 data for detector efficiencies (except for raw particle counts) and other information available from the calibration tables.

3-D distributions are given in the ISR2 pseudo-GSE reference frame (X sunward, Z is the spacecraft axis and northward pointing). Solid angles, defined in the distributions, correspond to particle arrival directions (direction of travel of the particle).

Archival files are constructed by joining files from similar data products (same ion species, different angular, energy or time resolution).

The onboard 3D distributions give the complete 16 azimuth × 8 elevation = 128 solid angles matrix which is reduced to a total of 88 solid angles in the telemetry products, where adjacent solid angles near the polar directions have been binned together (for some CIS telemetry products). On ground, via interpolation/repetition/division the DFs are reconstructed again into 128 angles.

Archival files are labelled so as to be easily understandable by the CAA user.

Archival files format is CEF.

The following data sets are produced:

- HIA, calibrated distribution functions:

- 3D, HS side, magnetospheric modes:	31 energies,	16×8 solid angles	(360°×180°);
- 3D, HS side, solar wind modes:	31 energies,	16×8 solid angles	(360°×180°);
- 3D, LS side, solar wind modes:	31 energies,	8×8 solid angles	(45°×45°);

- CODIF: calibrated distribution functions for H^+, He^+, He^{++} and O^+:

- 3D, HS side: 31 energies, 16×8 solid angles (360°×180°)
- 3D, LS side: 31 energies, 16×8 solid angles (360°×180°)
- 3D, RPA mode: 16 energies, 16×8 solid angles (360°×180°)

3.4.3.2 Omni-directional fluxes (1D)

In addition to the complete 3-D distribution functions, datasets for the omni-directional fluxes from HIA and CODIF are produced.

There are 3 datasets for CODIF (H^+, O^+, He^+), by merging the LS (low-sensitivity side) and HS (high-sensitivity side) data, and then 2 datasets for HIA (one for HS and one for LS) because HIA HS and LS can be operated simultaneously.

The datasets are obtained from CIS 3-D distributions, by summing the 8 elevations and 16 azimuthal bins, and contains data for 31 energy ranges.

3.4.3.3 Pitch-angle distributions

In addition to the 3D distributions, pitch-angle distributions (PADs) are also provided; these are given in particle flux units, as a function of the particle energy and pitch-angle (2D distributions), and their resolution is in 16 angular sectors covering the pitch angle range from 0° to 180°.

These following datasets are provided :

- CODIF HS side for H^+, O^+ and He^+
- CODIF LS side for H^+, O^+ and He^+
- CODIF RPA (merging HS & LS sides) for H+,O+ and He+
- HIA magnetospheric modes

All these datasets are provided with 31 energy bins resolution, except for CODIF RPA that offers 16 energy bins

3.4.3.4 CODIF uncalibrated products

Furthermore, the following CODIF uncalibrated data sets are available:

- 3D, HS side, 64 m/q ranges, low angular resolution:
  64 ion species × 8 energies, 4×3 solid angles (360°×180°).
  These are low angular resolution (4x3 solid angles) but high mass resolution (64 m/q ranges) 3D ion distributions, acquired from the CODIF HS side.
- 3D, LS side, 64 m/q ranges, low angular resolution:
  64 ion species × 8 energies, 4×3 solid angles (360°×180°).
  Same as above, but acquired from the CODIF LS side.
- Monitor Rates, HS side:
  16 azimuths × 16 energies × 18 counters.
  Contain ion count readouts from 18 CODIF instrument counters, acquired from the instrument HS side and organised in 16 azimuthal ranges x 16 energy bins. The content of each of the 18 counters is given in the corresponding variable name in the dataset, e.g. “Start Rate” (time-of-flight “start” counter readout), “Start/Stop Coincidence Rate” etc.
- Monitor Rates, LS side:
  16 azimuths × 16 energies × 18 counters.
  Same as above, but acquired from the CODIF LS side.
- Selected Events, HS side: for selected events (detected ions), for each ion:
  - Energy-sweep number (azimuth),
  - Energy step number,

- Start signal address (anode number),
- Time-of-Flight,
- Proton suppression flag;
- data collected during a specified Energy-sweep,
- synchronous with Monitor Rates collection.

  This dataset contains thus detailed information for each of the detected ions, which represent a sample of the detected ion population.

- Selected events, LS side:
  same as "Selected Events, HS side", but for the LS side.

These products are for expert users.

They represent either a sample of the detected ions ("Selected Events"), or a high-mass resolution collection of coarse 3D ion distributions ("64 m/q ranges"), or a read-out of internal to the instrument particle counters ("Monitor Rates").

They are more precisely described in [Ref. 12].

3.4.4 CIS modes

This dataset provides useful information about CIS instrument modes selection, availability of HS/LS sides data, instrument operational periods… that can help CAA users to select data.

3.4.5 CIS caveats

This dataset give general caveats for the CIS data, for specific data intervals, that can concern the whole CIS instruments, or just one of CODIF or HIA instrument.

They are essential to any analysis of CIS data (independently of the data level).

3.4.6 CIS Quality indexes

These datasets give quality flags for CIS data, for each of the four dataset families :

- 3D distributions
- omni-directional fluxes (1D)
- PAD's
- moments

Five datasets are defined: four for CODIF (separate for each ion species) and one for HIA

3.4.7 CIS Graphical data products

The graphic data to be archived are:

- Spectrograms currently accessible via both CAA and CIS Web sites
- 6-hour energy-time ion spectrograms.
- Pre-formatted displays in PNG

One can also access these plots via Spectrograms currently accessible on the CIS Web site http://cluster.irap.omp.eu/public/spectro/ .

3.4.8 CIS Calibration files

The CAA does not hold yet the CIS calibration files but the long-term archive will contain them. For a detailed description of these files (content, organisation, format etc.), see Ref 7.

These files are used together with level 1 files that both are the inputs to the CIS visualisation software (cl) and CIS production pipelines for the CAA datasets.

CIS calibration files:

- Are ASCII files, self-documented (including comments), machine-readable and human-readable.
- Include also calibration files catalogue: pointer to which calibration files to use for the given time period (detection efficiency evolution).
- Are updated regularly.

CIS Team will deliver also the calibration files structure document and calibration report.

3.4.9 CIS Data processing software

The CIS PI processing software will be included in the final archive (but is not currently available at the CAA):

- Various software packages: ***cl***, ***IFSIDL*****.**
- Will be delivered as IDL source code (+ instructions).
- Reads Level 1 CIS data and calibration files; interactive.
- Can read also (***cl*** software) any CDF or CEF (ASCII) file, for correlation studies.
- Generates high-resolution graphics (Level 3) and ASCII (CEF) data files.
- Large variety of graphics (spectrograms, distribution functions, PADs …).
- Will be available "as documents", for installation and execution on the end user's machine.
- Maintenance in the long-term will not be necessary (except *IFSIDL*), if CAA provides on-line visualisation tools for reading Level 3 data.[1]

In addition to the above software packages, one software package (written in C) was developed specially for the CAA users (and can be downloaded from http://caa.estec.esa.int/caa/software.xml) to calculate **interactively partial or total moments** of the ion distributions, for selected energy and solid angle ranges. The required input file is a CIS 3D distribution functions in CEF in particle count rate units and the output file is an ion moments file in CEF.

3.4.10 CIS Documentation

In addition to the present document, CIS documentation includes:

- A description of the instrument:
  H. Rème et al., *First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster Ion Spectrometry (CIS) experiment,* Annales Geophysicae, 19, 1303, 2001 [*Ref. 3*].
- Calibration documentation (*Ref. 7*, cf. section 3.4.5 of the present document).
- Various documents, reports etc. (*Ref. 5, 6,).*
- *CIS CAA User Guide*
- *CIS CAA Calibration Report*

[1] not clear what this is

4 . Product Provision – General Conventions and Considerations

4.1 Level 1 data products

Level 1 files are binary files, with no CEF metadata, that have to be used with CIS specific visualisation software: “cl”. A description of these files is given in ref 5, 6

4.2 Level 2 and level 3 data products

4.2.1 Format

All level 2 and level 3 data products are CEF (2.0) files.

4.2.2 Metadata description

Metadata for each CEF files is organised in multi-level specification files, which are described in separate CEH header files that are included when data is downloaded from CAA.

This hierarchical metadata description is composed of several CEF header files :

- CL_CH_MISSION.ceh:
  Mission level metadata description (maintained by the CAA)
- C[1234]_CH_OBS.ceh:
  Observatory level metadata description (maintained by the CAA)
- CL_CH_CIS.ceh:
  Experiment level metadata description
- C[1234]_CH_CIS-CODIF.ceh:
  Instrument level metadata description for CODIF products
- C[1234]_CH_CIS-HIA.ceh:
  Instrument level metadata description for HIA products

In addition for each level 2 or level 3 dataset, there is a specific metadata header file for the description of the variables of the dataset. All these six files will produce a complete metadata description of the dataset.

4.2.2.1 Mission level description

The file “CL_CH_MISSION.ceh” is provided and maintained by the CAA team at ESTEC.

4.2.2.2 Observatory level description

The files “C[i]_CH_OBS.ceh” are provided and maintained by the CAA team at ESTEC.

4.2.2.3 Experiment level metadata

```
! File : CL_CH_CIS.ceh
!
! Experiment level metadata
!
START_META = Experiment
  ENTRY    = "CIS"
END_META   = Experiment
```

```
START_META = Experiment_description
  ENTRY    = "Cluster Ion Spectrometry."
  ENTRY    = "The CIS (Cluster Ion Spectrometry) experiment is a comprehensive"
  ENTRY    = "ionic plasma spectrometry package onboard the Cluster spacecraft,"
  ENTRY    = "capable of obtaining full three-dimentional ion distributions"
  ENTRY    = "(about 0 to 40 KeV/e) with a time resolution of one spacecraft spin (4 sec)"
  ENTRY    = "and with mass-per-charge composition determination."
  ENTRY    = "The CIS package consists of two different instruments,"
  ENTRY    = "a time-of-flight ion Composition and Distribution Function analyser (CODIF, or
CIS-1)"
  ENTRY    = "and a Hot Ion Analyser (HIA, or CIS-2)."
END_META   = Experiment_description

START_META = Investigator_coordinates
  ENTRY    = "Iannis Dandouras>PI>Iannis.Dandouras@irap.omp.eu"
END_META   = Investigator_coordinates

START_META = Experiment_key_personnel
  ENTRY    = "Iannis Dandouras>PI>Iannis.Dandouras@irap.omp.eu"
  ENTRY    = "Henri Reme>Deputy-PI>Henri.Reme@irap.omp.eu"
  ENTRY    = "Claude Aoustin>Experiment Engineer>Claude.Aoustin@irap.omp.eu"
  ENTRY    = "Alain Barthe>Archival Engineer>Alain.Barthe@irap.omp.eu"
END_META   = Experiment_key_personnel

START_META = Experiment_references
  ENTRY    = "*CL_CD_CIS_CAAICD"
  ENTRY    = "*CL_CD_CIS_USERMAN"
  ENTRY    = "http://www.rssd.esa.int/index.php?project=CLUSTER&page=documentation"
  ENTRY    = "http://cluster.irap.omp.eu"
  ENTRY    = "Reme, H et al.>First multispacecraft ion measurements in and near the Earth's
magnetosphere with the identical Cluster ion spectrometry (CIS) experiment>Ann. geophys., 19,
1303, 2001"
END_META   = Experiment_references

START_META = Experiment_caveats
  ENTRY    = "http://cluster.irap.omp.eu/index.php?page=caveats"
END_META   = Experiment_caveats
```

4.2.2.4 Instrument level description (CODIF)

```
! Instrument level metadata
!
START_META = Instrument_name
  ENTRY    = "CIS-CODIF1"
END_META   = Instrument_name

START_META = Instrument_description
  ENTRY    = "CIS COmposition DIstribution Function analyser on Cluster C1"
  ENTRY    = "This is a mass-resolving ion energy sprectrometer providing"
  ENTRY    = "the 3D distribution functions separately for of the major ion species"
  ENTRY    = "It is based on the time-of-flight technique in combination"
  ENTRY    = "with an electrostatic analyser"

END_META   = Instrument_description

START_META = Instrument_type
  ENTRY    = "Electrostatic_Analyser"
  ENTRY    = "Micro-channel_Plate"
  ENTRY    = "Mass_Spectrometer"
END_META   = Instrument_type

START_META = Measurement_type
  ENTRY    = "Ion_Composition"
  ENTRY    = "Energetic_Particles"
  ENTRY    = "Thermal_Plasma"
END_META   = Measurement_type

START_META = Instrument_caveats
  ENTRY    = "http://cluster.irap.omp.eu/index.php?page=caveats"
END_META   = Instrument_caveats
```

4.2.2.5 Instrument level description (HIA)

```
! Instrument level metadata
!
START_META = Instrument_name
  ENTRY    = "CIS-HIA1"
END_META   = Instrument_name

START_META = Instrument_description
  ENTRY    = "CIS Hot Ion Analyser on Cluster C1"
  ENTRY    = "This is a not-mass resolving ion energy spectrometer"
  ENTRY    = "providing the 3D distribution functions of the detected ions"
  ENTRY    = "It is based on the selection of the incoming ions"
  ENTRY    = "by an electrostatic analyser"
END_META   = Instrument_description

START_META = Instrument_type
  ENTRY    = "Electrostatic_Analyser"
  ENTRY    = "Micro-channel_Plate"
END_META   = Instrument_type

START_META = Measurement_type
  ENTRY    = "Energetic_Particles"
  ENTRY    = "Thermal_Plasma"
END_META   = Measurement_type

START_META = Instrument_caveats
  ENTRY    = "http://cluster.irap.omp.eu/index.php?page=caveats"
END_META   = Instrument_caveats
```

5 . PRODUCT PROVISION – SPECIFIC DESCRIPTIONS

5.1 CIS Level 1 data

CIS Level 1 data are decommutated, decompressed, and time-tagged telemetry data (cf. section 3.4.1).

5.1.1 Formats

CIS Level 1 data are in IEEE integers or floats. Some auxiliary files, however, that go with the CIS Level 1 data (e.g. spacecraft attitude files) are ASCII.

5.1.2 Standards

- Time standards:CCSDS, as given in the Cluster DDID [*Ref. 4*].
  Data time-tagged at the start of the acquisition interval.
- Coordinate systems: Instrument-build
- Units: Raw counts

5.1.3 Production Procedures

Pipeline-processing, from the Raw Telemetry (Level 0) data.

5.1.4 Quality Control Procedures

Validated production software (in use since launch).

5.1.5 Delivery Procedures

Data available for retrieval, by the CAA, at the CIS Web site (in gz-compressed form): http://cluster.irap.omp.eu/private/data/L1/

(login has been provided to the CAA).

5.1.6 Product Specification

The data organisation and logical formats of these files are defined in "*Expérience CIS, Cluster Ion Spectrometry - Structure des fichiers de Niveau 1*" [*Ref. 5*]. Some Level 1 files are written in ASCII format and are described in "*Description syntaxique des jeux de données CIS*" [*Ref. 6*].

5.1.7 Metadata Specification

No metadata describing the content of these files, as there are non-CEF datasets, except metadata used to deliver external files to CAA.

5.2 CIS Level 2 data : Ion moments

There are two datasets for the moments of the particle distribution functions (cf. section 3.4.2) :

- CODIF onground calculated moments
- HIA reprocessed/corrected onboard moments

5.2.1 Formats

Both CODIF and HIA moments are CEF (2.0) files, *cf. Ref. 9*.

5.2.2 Standards

- Time standards: CSDS ASCII time standard
- Coordinate systems: GSE or ISR2 (Inverted despun SR coordinate system)
- Units: Density (particles cm-3)
  Velocity (km s-1)
  Temperature (MK)
  Pressure (nPa)

5.2.3 Production Procedures

- HIA onboard moments: Pipeline-processing, from CIS Level 1 data and calibration files.
- CODIF ground calculated moments: Pipeline-processing, from the CIS Level 3 data, from files in corrected-for-efficiency particle count rates (cf. section 5.3)

5.2.4 Quality Control Procedures

- Onboard calculated moments: validated production software (in use since launch).
- On ground calculated moments, from the 3-D ion distributions: comparison with the output of the interactive *cl* software (in use since launch), and validation for representative data intervals.

5.2.5 Delivery Procedures

Both HIA and CODIF moments are uploaded by CIS team on CAA server.

5.2.6 Product Specification

5.2.6.1 HIA onboard moments

Dataset title:	Ion Moments (High and Low sensitivity)
Dataset ID:	Cx_CP_CIS-HIA_ONBOARD_MOMENTS__yyyymmdd_Vnn.cef
Where:	Cx : refers to the spacecraft number (C1, C2, C3, C4)
	yyyymmdd: year, month, date of the data in the file
	Vnn: refers to version number (2 digits)

5.2.6.2 CODIF onground moments

Dataset titles:	H+ Moments (High sensitivity)

	H+ Moments (Low sensitivity)
	He+ Moments (High sensitivity)
	He+ Moments (Low sensitivity)
	O+ Moments (High sensitivity)
	O+ Moments (Low sensitivity)
Dataset id:	Cx_CP_CIS_CODIF_<ion>_<sensitivity>_MOMENTS.cef
Where:	<ion> refers to selected ion species (H1 for H+, O1 for O+, He1 for He+)
	<sensitivity> refers to instrument sensitivity side
	(LS: low-sensitivity, HS: high-sensitivity)

As an example, the complete dataset list for spacecraft 1 will be:

```
C1_CP_CIS-CODIF_HS_H1_MOMENTS__yyyymmdd_Vnn.cef
C1_CP_CIS-CODIF_HS_He1_MOMENTS__yyyymmdd_Vnn.cef
C1_CP_CIS-CODIF_HS_O1_MOMENTS__yyyymmdd_Vnn.cef

C1_CP_CIS-CODIF_LS_H1_MOMENTS__yyyymmdd_Vnn.cef
C1_CP_CIS-CODIF_LS_He1_MOMENTS__yyyymmdd_Vnn.cef
C1_CP_CIS-CODIF_LS_O1_MOMENTS__yyyymmdd_Vnn.cef
```

5.2.7 Metadata Specification

5.2.7.1 HIA onboard moments

The metadata for this dataset is described in the following files:

Cx_CH_CIS-HIA_ONBOARD_MOMENTS.ceh

where Cx refers to C1, C2, C3 or C4.

This dataset contains the following variables:

• time_tags :	ISO_TIME	s	Acquisition interval center time
• duration:	FLOAT	s	Half interval duration
• sensitivity:	INT	unitless	Sensitivity (0 : Low; 1:High)
• cis_mode	INT	unitless	CIS Operational Mode
• density	FLOAT	particles cm^-3	Density (in cm^-3)
• velocity_isr2	3 x FLOAT	km s^-1	Velocity in km s^-1 (ISR2)
• velocity_gse	3 x FLOAT	km s^-1	Velocity in km s^-1 (GSE)
• temperature	FLOAT	MK	Temperature in MK
• temp_par	FLOAT	MK	Temperature parallel to B in MK
• temp_perp	FLOAT	MK	Temperature perpendicular to B in MK
• pressure	FLOAT	nPa	Total Pressure
• pressure_tensor	3 x 3 x FLOAT	nPa	Pressure Tensor (GSE)

5.2.7.2 CODIF ground calculated moments

The metadata for this dataset is described in the following files:

Cx_CH_CIS-CODIF_<ion>_<sensitivity>_MOMENTS.ceh

where :

Cx: refers to spacecraft number (C1, C2, C3, C4)

<ion> refers to selected ion species (H1 for H+, O1 for O+, He1 for He+)

<sensitivity> refers to instrument sensitivity side (LS: low-sensitivity, HS: high-sensitivity)

E.g.: metadata description for H+ data, for spacecraft C1 in HS side, is described in the following file :

C1_CH_CIS-CODIF_H1_HS_MOMENTS.ceh

All of the CODIF ground moments datasets have the same structure:

• time_tags	ISO_TIME	s	Acquisition interval center time
• duration	FLOAT	s	Half interval duration
• density	FLOAT	particles cm^-3	Density (in cm^-3)
• velocity	3 x FLOAT	km s^-1	Velocity in km s^-1 (GSE)
• pressure	3 x 3 x FLOAT	nPa	Pressure Tensor (GSE)
• T	FLOAT	MK	Temperature in MK
• T_par	FLOAT	MK	Parallel temperature in MK
• T_perp	FLOAT	MK	Perpendicular temperarure in MK

5.3 CIS Level 3 data

There are 4 kinds of high-resolution data (cf. section 3.4.3):

- 3-D ion distributions (cf. section 3.4.3).
- Omni-directional fluxes (1D)
- Pitch-angle distributions
- Uncalibrated products

5.3.1 Formats

CIS level 3 data are in in CEF (2.0) format, cf. *Ref. 10.*.

5.3.2 Standards

- Time standards: CCSDS.
  Data time-tagged at the start of the acquisition interval.
- Coordinate systems: in the ISR2 pseudo-GSE reference frame
  (X sunward, Z is the spacecraft axis and northward pointing).
  Solid angles, defined in the distributions, correspond to particle arrival directions (direction of travel of the particle).
- Units: in several physical units in separate files :

- (differential) particle flux	(ions cm^{-2} s^{-1} sr^{-1} keV^{-1})
- particle energy flux	(keV cm^{-2} s^{-1} sr^{-1} keV^{-1})
- particle phase space density	(ions s^{3} km^{-6})
- corrected-for-efficiency particle count rate	(ions s^{-1})
- raw particle counts	(number of ions per counter bin)

(cf. Appendix 2 for unit conversion),

5.3.3 Production Procedures

Pipeline-processing :

- from the CIS Level 1 data and the calibration files (3D products)
- from CAA 3D datasets (moments, PAD's, omni-directional fluxes)

5.3.4 Quality Control Procedures

Validation for representative data intervals.

5.3.5 Delivery Procedures

Level 3 product are uploaded by CIS team on the CAA server.

5.3.6 Product Specification

5.3.6.1 CODIF and HIA 3D datasets

Filenames will have the following syntax:

```
C[1234]_CP_<instr>_<sensitivity>_<mode>_<entity>_< unit>__yyyymmdd_Vxx.cef
```

except for CODIF, where the <mode> field is missing: all modes for a given sensitivity side have been grouped together.

<instr>	: CIS-CODIF		
	| CIS-HIA		
<sensitivity>	: HS	High-sensitivity instrument side	
	| LS	Low-sensitivity instrument side	
	| RPA	RPA mode operation (High-sensitivity side, CODIF only)	
<mode>	: MAG	Magnetospheric modes	(used for HIA only)
	| SW	Solar Wind modes	(used for HIA only)
<entity>	: IONS	no mass discrimination (for HIA and for uncalibrated CODIF data)	
	| H1	Hydrogen +	(CODIF only)
	| He1	Helium +	(CODIF only)
	| He2	Helium ++	(CODIF only)
	| O1	Oxygen +	(CODIF only)
<unit>	: PF	Differential_Particle_Flux	
	| PEF	Particle_Energy_Flux	
	| PSD	Particle_Phase_Space_Density	
	| CS	Corrected_Particle_Count_Rate	(corrected for detection efficiency)
	| RC	Raw_particle_counts	

(cf. section 5.3.2)

<version> : V00 .. V99

One file per dataset per day (except for the RPA mode datasets: files generated only for the days where this mode was operated, once per month on the average).

For the Level 3 data sets that have been identified (cf. section 3.4.3), this results in the following:

- **HIA, calibrated distribution functions: 15 datasets**

3D, HS side, magnetospheric modes : 5 datasets (1 per physical unit)

```
C[1234]_CP_CIS-HIA_HS_MAG_IONS_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-HIA_HS_MAG_IONS_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-HIA_HS_MAG_IONS_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-HIA_HS_MAG_IONS_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-HIA_HS_MAG_IONS_PSD__yyyymmdd_Vxx.cef
```

3D, HS side, solar-wind modes : 5 datasets (1 per physical unit)

```
C[1234]_CP_CIS-HIA_HS_SW_IONS_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-HIA_HS_SW_IONS_CS__yyyymmdd_Vxx.cef
```

```
C[1234]_CP_CIS-HIA_HS_SW_IONS_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-HIA_HS_SW_IONS_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-HIA_HS_SW_IONS_PSD__yyyymmdd_Vxx.cef
```

3D, LS side, solar-wind modes : 5 datasets (1 per physical unit)

```
C[1234]_CP_CIS-HIA_LS_SW_IONS_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-HIA_LS_SW_IONS_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-HIA_LS_SW_IONS_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-HIA_LS_SW_IONS_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-HIA_LS_SW_IONS_PSD__yyyymmdd_Vxx.cef
```

- **CODIF, calibrated distribution functions: 60 datasets**

3D, HS side : 20 datasets (1 per ion species x 1 per physical unit)

```
C[1234]_CP_CIS-CODIF_HS_H1_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_H1_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_H1_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_H1_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_H1_PSD__yyyymmdd_Vxx.cef

C[1234]_CP_CIS-CODIF_HS_He1_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_He1_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_He1_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_He1_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_He1_PSD__yyyymmdd_Vxx.cef

C[1234]_CP_CIS-CODIF_HS_He2_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_He2_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_He2_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_He2_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_He2_PSD__yyyymmdd_Vxx.cef

C[1234]_CP_CIS-CODIF_HS_O1_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_O1_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_O1_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_O1_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_HS_O1_PSD__yyyymmdd_Vxx.cef
```

3D, LS side : 20 datasets (1 per ion species x 1 per physical unit)

```
C[1234]_CP_CIS-CODIF_LS_H1_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_H1_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_H1_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_H1_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_H1_PSD__yyyymmdd_Vxx.cef

C[1234]_CP_CIS-CODIF_LS_He1_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_He1_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_He1_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_He1_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_He1_PSD__yyyymmdd_Vxx.cef

C[1234]_CP_CIS-CODIF_LS_He2_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_He2_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_He2_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_He2_PEF__yyyymmdd_Vxx.cef
```

```
C[1234]_CP_CIS-CODIF_LS_He2_PSD__yyyymmdd_Vxx.cef

C[1234]_CP_CIS-CODIF_LS_O1_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_O1_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_O1_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_O1_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_LS_O1_PSD__yyyymmdd_Vxx.cef
```

3D, RPA mode : 20 datasets (1 per ion species x 1 per physical unit)

```
C[1234]_CP_CIS-CODIF_RPA_H1_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_H1_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_H1_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_H1_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_H1_PSD__yyyymmdd_Vxx.cef

C[1234]_CP_CIS-CODIF_RPA_He1_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_He1_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_He1_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_He1_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_He1_PSD__yyyymmdd_Vxx.cef

C[1234]_CP_CIS-CODIF_RPA_He2_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_He2_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_He2_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_He2_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_He2_PSD__yyyymmdd_Vxx.cef

C[1234]_CP_CIS-CODIF_RPA_O1_RC__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_O1_CS__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_O1_PF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_O1_PEF__yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_RPA_O1_PSD__yyyymmdd_Vxx.cef
```

5.3.6.2 Omni-directional fluxes (1D)

- CODIF, 1D products : available for 3 ion species (H+,O+,He+)

```
C[1234]_CP_CIS-CODIF_H1_1D_PEF_yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_O1_1D_PEF_yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_He1_1D_PEF_yyyymmdd_Vxx.cef
```

- HIA, 1D products : available for 2 sensitivities (HS, LS)

```
C[1234]_CP_CIS-HIA_HS_1D_PEF_yyyymmdd_Vxx.cef
C[1234]_CP_CIS-HIA_HS_1D_PEF_yyyymmdd_Vxx.cef
```

5.3.6.3 Pitch-angle distributions

- CODIF, PAD : available for 3 ion species (H+, O+, He+) and 2 sensitivities (HS, LS)

```
C[1234]_CP_CIS-CODIF_PAD_HS_H1_PF_yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_PAD_HS_O1_PF_yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_PAD_HS_He1_PF_yyyymmdd_Vxx.cef
```

```
C[1234]_CP_CIS-CODIF_PAD_LS_H1_PF_yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_PAD_LS_O1_PF_yyyymmdd_Vxx.cef
C[1234]_CP_CIS-CODIF_PAD_LS_He1_PF_yyyymmdd_Vxx.cef
```

- HIA, PAD : available only in HS and magnetospheric modes

```
C[1234]_CP_CIS-HIA_PAD_HS_MAG_IONS_PF_yyyymmdd_Vxx.cef
```

5.3.6.4 CODIF, uncalibrated data sets: 6 datasets

3D, HS side, 64 m/q ranges, low angular resolution: 1 dataset per spacecraft

```
C[1234]_CP_CIS-CODIF_HS_64M_IONS_RC__yyyymmdd_Vxx.cef
```

3D, LS side, 64 m/q ranges, low angular resolution: 1 dataset per spacecraft

```
C[1234]_CP_CIS-CODIF_LS_64M_IONS_RC__yyyymmdd_Vxx.cef
```

Monitor Rates, HS side: 1 dataset per spacecraft

```
C[1234]_CP_CIS-CODIF_HS_RAT_IONS_RC__yyyymmdd_Vxx.cef
```

Monitor Rates, LS side: 1 dataset per spacecraft

```
C[1234]_CP_CIS-CODIF_LS_RAT_IONS_RC__yyyymmdd_Vxx.cef
```

Selected Events, HS side: 1 dataset per spacecraft

```
C[1234]_CP_CIS-CODIF_HS_SEL_IONS_RC__yyyymmdd_Vxx.cef
```

Selected Events, LS side: 1 dataset per spacecraft

```
C[1234]_CP_CIS-CODIF_LS_SEL_IONS_RC__yyyymmdd_Vxx.cef
```

5.3.7 Metadata description

5.3.7.1 CIS 3D products

3D ion distributions are matrices organised in polar angular bins – azimuth angular bins – energy bins. These files are self-described:

- The polar and azimuth bin central values and edges (DELTA_PLUS, DELTA_MINUS) are given as support data variables in each file.
- The energy bin central values and edges (DELTA_PLUS, DELTA_MINUS) are given as support data variables in each file, with the exception of the HIA LS side solar wind modes datasets. In these, the instrument energy sweep tables can change from one spin to the other (cf. section 3.2.1), so the corresponding energy bin values are given in each data record.

Metadata for each 3D dataset is described in a separate CEF header file.

5.3.7.2 CIS-CODIF 3D Products

Header file : Cx_CP_CIS-CODIF_<sensitivity>_<ion>_<units>.ceh

These header files describe the following CEF variables :

Record varying variables:

- time_tags : Acquisition interval start time, ISO_TIME (s)
- duration : Interval duration, FLOAT (s)
- cis_mode : CIS Operational Mode, INT (unitless)
- tm_product : CIS Telemetry Product, INT (unitless)
- geom_factor : Geometric factor, FLOAT (cm2^2 sr KeV KeV^-1)
- codif_mcp_hv : CODIF MCP High-Voltage, FLOAT (volt)
- codif_acc_hv : CODIF Acceleration High-Voltage, FLOAT (volt)
- 3d_ions : CIS-CODIF 3D <ion> distributions , 8 x 16 x 31 x FLOAT (units varying with dataset)

Variables that are not record varying:

- theta : Polar bin edges (particle arrival direction), 8 x FLOAT (deg)
- phi : Azimuthal bin edges (particle arrival direction), 16 x FLOAT (deg)
- energy_table : Energy table, 31 x FLOAT (eV)
- delta_plus_energy_table : Delta plus energy table, 31 x FLOAT (eV)
- delta_minus_energy_table : Delta minus energy table, 31 x FLOAT (eV)

5.3.7.3 CIS-HIA 3D products

Header file: Cx_CH_CIS-HIA_HS_MAG_IONS_<units>.ceh

This header file describes HIA 3D data for HS side in Magnetospheric modes

Record varying variables:

- time_tags : Acquisition interval start time, ISO_TIME (s)
- duration : Interval duration, FLOAT (s)
- cis_mode : CIS Operational Mode, INT (unitless)

- tm_product : CIS Telemetry Product, INT (unitless)
- geom_factor : Geometric factor, FLOAT (cm2^2 sr KeV KeV^-1)
- hia_mcp_hv : HIA MCP High-Voltage, FLOAT (volt)
- hia_discri : HIA Discriminator level, FLOAT (volt)
- 3d_ions : CIS-HIA 3D ion distribution, 8 x16 x 31 x FLOAT
  (units varying with dataset)

Variables that are not record varying:

- theta : Polar bin edges (particle arrival direction), 8 x FLOAT (deg)
  given with DELTA_PLUS and DELTA_MINUS constant values
- phi : Azimuthal bin edges (particle arrival direction), 16 x FLOAT (deg)
  given with DELTA_PLUS and DELTA_MINUS constant values
- energy_table : Energy table, 31 x FLOAT (eV)
- delta_plus_energy_table : Delta plus energy table, 31 x FLOAT (eV)
- delta_minus_energy_table : Delta minus energy table, 31 x FLOAT (eV)

Header file: Cx_CH_CIS-HIA_HS_SW_IONS_<units>.ceh

This header file describes HIA 3D data for HS side in Solar-Wind modes.

Record varying variables:

- time_tags : Acquisition interval start time, ISO_TIME (s)
- duration : Interval duration, FLOAT (s)
- cis_mode : CIS Operational Mode, INT (unitless)
- tm_product : CIS Telemetry Product, INT (unitless) [Description in Ref. 6]
- geom_factor : Geometric factor, FLOAT (cm2^2 sr KeV KeV^-1)
- hia_mcp_hv : HIA MCP High-Voltage, FLOAT (volt)
- hia_discri : HIA Discriminator level, FLOAT (volt)
- 3d_ions : CIS-HIA 3D ion distribution, ['8', '16', '31'] x FLOAT (Kev cm^-2 s^-1 sr^-1 Kev^-1)

Variables that are not record varying:

- theta : Polar bin edges (particle arrival direction), 8 x FLOAT (deg),
  given with DELTA_PLUS and DELTA_MINUS constant values
- phi : Azimuthal bin edges (particle arrival direction), 16 x FLOAT (deg),
  given with DELTA_PLUS and DELTA_MINUS constant values
- energy_table : Energy table, 31 x FLOAT (eV)
- delta_plus_energy_table : Delta plus energy table, 31 x FLOAT (eV)
- delta_minus_energy_table : Delta minus energy table, 31 x FLOAT (eV)

Header file: Cx_CH_CIS-HIA_LS_SW_IONS_<units>.ceh

This header file describes HIA 3D data for LS side in Solar-Wind modes.

Record varying variables:

- time_tags : Acquisition interval start time, ISO_TIME (s)
- duration : Interval duration, FLOAT (s)
- cis_mode : CIS Operational Mode, INT (unitless)
- tm_product : CIS Telemetry Product, INT (unitless)
- geom_factor : Geometric factor, FLOAT (cm2^2 sr KeV KeV^-1)
- hvtbl : High-Voltage energy table, INT (unitless)
- hia_mcp_hv : HIA MCP High-Voltage, FLOAT (volt)
- hia_discri : HIA Discriminator level, FLOAT (volt)
- energy_table : Energy table, 31 x FLOAT (eV)
- delta_plus_energy_table : Delta plus energy table, 31 x FLOAT (eV)
- delta_minus_energy_table : Delta minus energy table, 31 x FLOAT (eV)
- 3d_ions : CIS-HIA 3D ion distribution, 8 x 8 x 31 x FLOAT
  (units varying with dataset)

Variables that are not record varying:

- theta : Polar bin edges (particle arrival direction), 8 x FLOAT (deg), given with DELTA_PLUS and DELTA_MINUS constant values
- phi : Azimuthal bin edges (particle arrival direction), 8 x FLOAT (deg), given with DELTA_PLUS and DELTA_MINUS constant values

5.3.7.4 Omni-directional fluxes (1D)

Header file: Cx_CH_CIS-CODIF_1D_<ion>_PEF.ceh

This header file describes CODIF omni-directional fluxes (1D), available for H+, O+, He+

Record varying:

- time_tags : Acquisition interval start time, ISO_TIME (s)
- duration : Interval duration, FLOAT (s)
- sensitivity : Instrument sensitivity, INT (Unitless)
- cis_mode : CIS Operational Mode, INT (unitless)
- tm_product : CIS Telemetry Product, INT (unitless)
- codif_mcp_hv : CODIF MCP High-Voltage, FLOAT (volt)
- codif_acc_hv : CODIF Post Acceleration High-Voltage, FLOAT (volt)
- flux : CIS-CODIF 1D <ion> distributions, 31 x FLOAT (Kev cm^-2 s^-1 sr^-1 Kev^-1)

Non record varying:

- energy_table : Energy table, 31 x FLOAT (eV)
- delta_plus_energy_table : Delta plus energy table, 31 x FLOAT (eV)
- delta_minus_energy_table : Delta minus energy table, 31 x FLOAT (eV)

Header file: Cx_CH_CIS-HIA_HS_1D_PEF.ceh

This header file describes HIA High-sensitivity omni-directional fluxes (1D).

Record varying:

- time_tags : Acquisition interval start time, ISO_TIME (s)
- duration : Interval duration, FLOAT (s)
- sensitivity : Instrument sensitivity, INT (Unitless)
- cis_mode : CIS Operational Mode, INT (unitless)
- tm_product : CIS Telemetry Product, INT (unitless)
- hia_mcp_hv : HIA MCP High-Voltage, FLOAT (volt)
- hia_discri : HIA Discriminator level, FLOAT (volt)
- flux : 1D CIS-HIA fluxes, 31 x FLOAT (Kev cm^-2 s^-1 sr^-1 Kev^-1)

Non record varying:

- energy_table : Energy table, 31 x FLOAT (eV)
- delta_plus_energy_table : Delta plus energy table, 31 x FLOAT (eV)
- delta_minus_energy_table : Delta minus energy table, 31 x FLOAT (eV)

Header file: Cx_CH_CIS-HIA_LS_1D_PEF.ceh

This header file describes HIA Low-sensitivity omni-directional fluxes (1D).

All variables are record varying:

- time_tags : Acquisition interval start time, ISO_TIME (s)
- duration : Interval duration, FLOAT (s)
- sensitivity : Instrument sensitivity, INT (Unitless)
- cis_mode : CIS Operational Mode, INT (unitless)
- tm_product : CIS Telemetry Product, INT (unitless)
- hia_mcp_hv : HIA MCP High-Voltage, FLOAT (volt)

- hia_discri : HIA Discriminator level, FLOAT (volt)
- energy_table : Energy table, 31 x FLOAT (eV)
- delta_plus_energy_table : Delta plus energy table, 31 x FLOAT (eV)
- delta_minus_energy_table : Delta minus energy table, 31 x FLOAT (eV)
- flux : CIS-HIA 1D ion distribution, 31 x FLOAT (Kev cm^-2 s^-1 sr^-1 Kev^-1)

5.3.7.5 Pitch-angle distributions

Header file: Cx_CH_CIS-CODIF_PAD_HS_<ions>_PF.ceh

This header file describes CODIF High-sensitivity PAD files, available for H+, O+ or He+ :

Record varying:

- time_tags : Acquisition interval start time, ISO_TIME (s)
- duration : Acquisition interval duration, FLOAT (s)
- cis_mode : CIS Operational Mode, INT (unitless)
- tm_product : CIS Telemetry Product, INT (unitless)
- Differential_Particle_Flux : Differential_Particle_Flux, 16 x 31 x FLOAT (Particles cm^-2 s^-1 sr^-1 Kev^-1)
- pitch_angle : Pitch angles center value (partical arrival direction), 16 x FLOAT (degrees), given with DELTA_PLUS and DELTA_MINUS constant values

Not record varying:

- energy_table : Energy table, 31 x FLOAT (eV)
- delta_plus_energy_table : Delta plus energy table, 31 x FLOAT (eV)
- delta_minus_energy_table : Delta minus energy table, 31 x FLOAT (eV)

Header file: Cx_CH_CIS-CODIF_PAD_LS_<ions>_PF.ceh

This header file describes CODIF Low-sensitivity PAD files, available for H+, O+ or He+ :

Record varying:

- time_tags : Acquisition interval start time, ISO_TIME (s)
- duration : Acquisition interval duration, FLOAT (s)
- cis_mode : CIS Operational Mode, INT (unitless)
- tm_product : CIS Telemetry Product, INT (unitless)
- Differential_Particle_Flux : Differential_Particle_Flux, 16 x 31] x FLOAT (Particles cm^-2 s^-1 sr^-1 Kev^-1)
- pitch_angle : Pitch angles center value (partical arrival direction), 16 x FLOAT (degrees), given with DELTA_PLUS and DELTA_MINUS constant values

Not record varying:

- energy_table : Energy table, 31 x FLOAT (eV)
- delta_plus_energy_table : Delta plus energy table, 31 x FLOAT (eV)
- delta_minus_energy_table : Delta minus energy table, 31 x FLOAT (eV)

Header file: Cx_CH_CIS-HIA_PAS_HS_MAG_IONS_PF.ceh

This header file describes HIA High-sensitivity Magnetospheric modes PAD files :

Record varying:

- time_tags : Acquisition interval start time, ISO_TIME (s)
- duration : Acquisition interval duration, FLOAT (s)
- cis_mode : CIS Operational Mode, INT (unitless)
- tm_product : CIS Telemetry Product, INT (unitless)
- Differential_Particle_Flux : Differential_Particle_Flux, 16 x 31 x (Particles cm^-2 s^-1 sr^-1 Kev^-1)

Not record varying:

- pitch_angle : Pitch angles center value, 16 x FLOAT (degrees)
- energy_table : Energy table, 31 x FLOAT (eV)
- delta_plus_energy_table : Delta plus energy table, 31 x FLOAT (eV)
- delta_minus_energy_table : Delta minus energy table, 31 x FLOAT (eV)

5.3.7.6 Uncalibrated (ancillary) products

To be done.

5.4 CIS Modes

5.4.1 Formats

CIS Modes data are in ASCII, in CEF (2.0) format, cf. *Ref. 10*.

5.4.2 Standards

Time standards:CCSDS.

Data time-tagged at the start of the acquisition interval.

5.4.3 Production Procedures

Pipeline processing from the CIS Level 1 HouseKeeping data

5.4.4 Quality Control Procedures

N/A

5.4.5 Delivery Procedures

CIS modes product are uploaded by CIS team on the CAA server.

5.4.6 Product Specification

Filenames have the following syntax:

```
Cx_CH_CIS-MODES__yyyymmdd_Vnn.ceh
```

Where Cx refers to C1, C2, C3, C4

5.4.7 Metadata Specification

Metadata are given in a separate CEH header file:

```
Cx_CH_CIS_MODES.ceh
```

Record varying:

- time_tags : Acquisition interval start time, ISO_TIME (s)
- tlm_rate : CIS Telemetry Rate, INT (unitless)
- cis_mode : CIS Operational Mode, INT (unitless)
- codif_operational : CODIF operational (0 : no, 1 : yes), INT (Unitless)
- hia_operational : HIA operational (0 : no, 1 : yes), INT (Unitless)
- cis_sw : CIS Solar-Wind mode (0 : no, 1 : yes), INT (Unitless)
- codif_sensitivity : CIS-CODIF sensitivity (0 : Low-g, 1 : High-G), INT (Unitless)
- codif_rpa : CODIF RPA mode (0 : no, 1 : yes), INT (Unitless)
- codif_msh : CODIF Magnetosheath mode (0 : no, 1 : yes), INT (Unitless)

Not record varying:

- cis_mode_key : CIS mode description table, 16 x CHAR (unitless)

The CIS mode key table gives a textual description of the record varying cis_mode value :

- 0 : SW-1>Solar Wind-Mode-1
- 1 : SW-2>Solar Wind-Upstreams-Mode-2
- 2 : SW-3>Solar Wind-Mode-3
- 3 : SW-4>Solar Wind-Upstreams-Mode-4
- 4 : SW-C1>Solar Wind-Data compression

- 5 : SW-C2>Solar Wind-Upstreams-Data compression
- 6 : RPA>CODIF:RPA-Mode and HIA:Magnetospheric-Mode
- 7 : PROM>PROM Operation
- 8 : MAG-1>Magnetospheric-Mode-1
- 9 : MAG-2>Magnetospheric-Mode-2
- 10 : MAG-3>Magnetospheric-Mode-3
- 11 : MAG-5>Magnetosheath-Mode-1
- 12 : MAG-1>Magnetosheath-Mode-2
- 13 : MAG-C1>Magnetospheric-Data Comp
- 14 : MAG-C2>Magnetosheath-Data Comp
- 15 : CALIBR>Calibration mode

5.5 CIS Caveats

This dataset give general caveats for the CIS data, for specific data intervals, that can concern the whole CIS instruments, or just one of CODIF or HIA instrument.
They are essential to any analysis of CIS data (independently of the data level).

5.5.1 Formats

CIS Caveats data are in ASCII, in CEF (2.0) format, cf. *Ref. 10*.

5.5.2 Standards

Time standards:CCSDS.

5.5.3 Production Procedures

Generated from internal Ascii database.

5.5.4 Quality Control Procedures

N/A

5.5.5 Delivery Procedures

CIS caveats products are uploaded by CIS team on the CAA server.

5.5.6 Product Specification

We are providing a dataset per instrument, with a separate file per year:

```
Cx_CP_CIS-CODIF_CAVEATS__yyyymmdd_hhmmss_yyyymmdd_hhmmss.Vnn.cef
Cx_CP_CIS-HIA_CAVEATS__yyyymmdd_hhmmss_yyyymmdd_hhmmss.Vnn.cef
```

5.5.7 Metadata Specification

Metadata are given in 2 separate files:

```
Cx_CH_CIS-CODIF_CAVEATS.ceh
Cx_CH_CIS-HIA_CAVEATS.ceh
```

Both files have the same structure:

- time_range : Validity time range, ISO_TIME_RANGE (s)
- instrument : Instrument, CHAR (unitless)
  (Should be CODIF, HIA or CIS for both instruments)
- caveat_key : Caveat key, CHAR (unitless)
- caveat : Caveat, CHAR (unitless)

The caveat_key variable allow us to make automatic recognition and processing of some special events (Reset, Eclipse…) while the caveat variable gives "human readable" information.

Here are some examples of such caveat_key:

- CALIB : calibration operations
- ECLIPSE : eclipse
- GAP : data gap (telemetry problem ?)
- MCP_DC : MCP Discharge
- PACC_DC : Post acceleration discharge
- RESET : Instrument RESET
- WRONG : Corrupted data

5.6 CIS quality indices

5.6.1 Formats

CIS quality indices are in ASCII, in CEF (2.0) format, cf. *Ref. 10*.

5.6.2 Standards

Time standards: CCSDS

5.6.3 Production Procedures

Pipeline processing from the CIS caveats databases, data control, magnetospheric regions control and specific tools.

Time tags are extracted from CAA Auxiliary SPIN TIME dataset.

5.6.4 Quality Control Procedures

Manual check of specific intervals

5.6.5 Delivery Procedures

Uploaded by CIS team on the CAA server

5.6.6 Product Specification

Filenames have the following syntax:

```
Cx_CP_CIS-CODIF_H1_QUALITY__yyyymmdd_Vnn.cef
Cx_CP_CIS-CODIF_O1_QUALITY__yyyymmdd_Vnn.cef
Cx_CP_CIS-CODIF_He1_QUALITY__yyyymmdd_Vnn.cef
Cx_CP_CIS-CODIF_He2_QUALITY__yyyymmdd_Vnn.cef
Cx_CP_CIS-HIA_QUALITY__yyyymmdd_Vnn.cef
```

Where Cx refers to C1, C2, C3, C4

5.6.7 Metadata Specification

Metadata are given in a separate CEF header file:

```
Cx_CH_CIS-CODIF_H1_QUALITY.ceh
Cx_CH_CIS-CODIF_O1_QUALITY.ceh
Cx_CH_CIS-CODIF_He1_QUALITY.ceh
Cx_CH_CIS-CODIF_He2_QUALITY.ceh
Cx_CH_CIS-HIA_QUALITY.ceh
```

The following variables are defined:

- time_tags : Acquisition interval center time, ISOTIME (s)
- quality_3D: Quality index for 3D distributions data (integer)
- quality_PAD: Quality index for Pitch-Angle Distributions (integer)
- quality_1D: Quality index for omni-directional fluxes (integer)
- quality_MOM: Quality index for momenta (integer)
- caveats_key: CIS specific flag referring to the type of event triggering the quality index (ASCII comma separated tags in a single string)

The quality indexes values are defined below:

- -1: Removable data (CIS specific, for internal use)
- 0: Not applicable (used by CIS to flag no science data tacking periods)
- 1: Major problems, check caveats
- 2: Minor problems, check caveats
- 3: Good for publication (default CIS data quality index value, unless a data quality issue is identified, degrading the quality index value)
- 4: Excellent data high has received special treatment

Description of caveats_keys is given in CIS User Guide: Section 5.6 and Appendix B, that contains the list of the caveat keys ("flags"), and the corresponding data quality index value for each of the datasets. Discussion of the issues that degrade the CIS data quality, and graphical examples, are given in sections 6.2 and 6.3 of the CIS User Guide.

5.7 CIS graphical data products

CIS Graphical data products are 6-hour energy-time ion spectrograms (cf. section 3.4.4).

5.7.1 Formats

Pre-formatted displays in PNG.

5.7.2 Standards

- Coordinate systems: in pseudo-GSE.
- Units: corrected-for-efficiency particle counts per second (directly proportional to the particle energy flux).

5.7.3 Production Procedures

Pipeline-processing, from the CIS Level 1 data and the calibration files.

5.7.4 Quality Control Procedures

Validation for representative data intervals.

5.7.5 Delivery Procedures

CIS graphical products are uploaded by CIS team on the CAA server.

5.7.6 Product Specification

Given at two levels of resolution: browsing and detailed.

5.7.7 Metadata Specification

No metadata for these files.

5.8 CIS Calibration files

CIS Calibrations files: cf. section 3.4.5. These files are not yet stored in the CAA.

5.8.1 Formats

ASCII files.

5.8.2 Standards

Self-documented ASCII files (including comments), machine-readable and human-readable.

5.8.3 Production Procedures

Combination of manual editing and computer processing.

5.8.4 Quality Control Procedures

Control of the resulting CIS Level 2 files (ion density) and CIS Level 3 files: cross-calibration checking between anodes, sensors, satellites and experiments (WHISPER-measured density), in representative regions of space. Cf. [*Ref. 2*].

5.8.5 Delivery Procedures

Data available for retrieval, by the CAA, at the CIS Web site:

http://cluster.irap.omp.eu/private/software/CALIBRATIONS/

(login has been provided to the CAA).

5.8.6 Product Specification

cf. "*CIS Data Processing: Calibration File Structure, Version 2*" : [*Ref. 7*].

5.8.7 Metadata Specification

No metadata for these files.

5.9 CIS Data processing software

CIS Data processing software: cf. section 3.4.6.

5.9.1 Formats

- *IDL source code* and *IDL Virtual Machine executable* : *cl* and *IFSIDL* software packages.
- *C source code* : Software package allowing the CAA user to read the CIS Level 3 CEF files and interactively calculate partial or total moments.

5.9.2 Standards

N/A

5.9.3 Production Procedures

N/A

5.9.4 Quality Control Procedures

- *cl* and *IFSIDL* software packages : software in use since launch.
- Software package for interactively calculating partial or total moments : cf. section 5.2.4.

5.9.5 Delivery Procedures

Software available for retrieval, by the CAA, at the CIS Web site: http://cluster.irap.omp.eu

(login has been provided to the CAA).

5.9.6 Product Specification

- *cl* and *IFSIDL* software packages :

  CESR IDL software for processing and plotting CIS Level-1 and Level-2 data.
- Software package for interactively calculating partial or total moments :

  cf. section 5.2.

5.9.7 Metadata Specification

N/A

5.10 CIS Documentation

CIS Documentation: cf. section 3.4.8.

5.10.1 Formats

PDF files.

5.10.2 Standards

N/A

5.10.3 Production Procedures

N/A

5.10.4 Quality Control Procedures

N/A

5.10.5 Delivery Procedures

Documentation available for retrieval, by the CAA, at the CIS Web site:

http://cluster.irap.omp.eu/private/CAA/DOCS/

(login has been provided to the CAA).

5.10.6 Product Specification

N/A

5.10.7 Metadata Specification

N/A

6 APPENDIX:

”CIS : PARTICLE COUNTS TO FLUX AND TO MOMENTS OF THE ION DISTRIBUTION FUNCTION” DOCUMENT

Version 4.0
November 2006

Centre d'Etude Spatiale des Rayonnements

CIS :

Particle Counts to Flux

and to Moments of the Ion Distribution Function

I. DANDOURAS for the CIS Team

0.0 REFERENCE DOCUMENTS

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1 INTRODUCTION - SCOPE

The CIS (Cluster Ion Spectrometry) experiment onboard the 4 Cluster spacecraft [*Ref. 1*] is capable of obtaining full three-dimensional ion distributions with good time resolution (one spacecraft spin) and with mass-per-charge composition determination. The CIS package consists of two different instruments, the time-of-flight ion Composition Distribution Function Analyser (CODIF, or CIS-1), and the Hot Ion Analyser (HIA, or CIS-2): http://cluster.irap.omp.eu.

During the first level of data processing, the CIS data are organised in Level-1 files [*Ref. 2*]: decommutated, decompressed, and time-tagged data, organised in a time series of records. Each record has a header (same for all telemetry products), and then a data section, specific to each product. For 3D and 2D distributions, the data section is a set of particle counts, *C*, each one for a given solid angle and energy bin.

During Level-3 processing these particle counts data can be transformed :

1. First in "corrected counts", C_{cor_eff} , i.e. taking into account corrections to compensate for the ion detection efficiencies.
2. Then in (differential) particle flux *F* (or *flux*) (ions $cm^{-2}\ s^{-1}\ sr^{-1}\ keV^{-1}$).
3. Or in particle energy flux *PEF* (or F_E or J_E) (keV $cm^{-2}\ s^{-1}\ sr^{-1}\ keV^{-1}$).
4. Or in phase space density *PSD* (or *fdist* or *f* or *VDF*) ($s^3\ km^{-6}$).

The necessary calibration data needed to perform this processing are in the CIS calibration files [*Ref. 3*]: 3DCO Calibration Files, unless otherwise stated.

2 CONVERSION TO CORRECTED COUNTS

If *C* is the "raw" number of counts (from the Level-1 files) and C_{cor_eff} is the "corrected" (for detection efficiency) number of counts, then:

$$C_{cor\_eff} = \frac{C}{Eff(E,\theta)} \qquad [2.1]$$

where the detection efficiency $Eff(E,\theta)$ ($Eff \leq 1$) is a function of the ion energy *E*, detection anode (giving the particle arrival direction elevation θ), ion species *m* (CODIF separates ion species, whereas HIA does not), time history of the detector, and flight model.

2.1 CODIF

For CODIF, and for each of the four main ion species detected (H^+, He^{++}, He^+, O^+), the detection efficiency is given by [*Ref. 4*] :

$Eff(PF, E, m) = (M_0 + M_1*E + M_2*E^2 + M_3*E^3\ ) * Abs\_Eff$ [2.2]

where :

- M_0 .. M_3 : efficiency calibration coefficients, depending on the ion mass *m* (4 sets, for H^+, He^{++}, He^+, and O^+), and on the detection anode *PF* (*PF1* … *PF8* for the high sensitivity HS side and *PF10* … *PF15* for the low sensitivity LS side, corresponding to the different particle arrival directions in elevation θ); values given in the `anode_effic_coeff_table` section of the calibration tables.

- *E* : total ion energy (ion energy + post-acceleration energy), in keV.

  Ion energy is given in the `anal_k_factor`, `energy_sweep_table_mag`, `energy_sweep_table_sw`, `energy_sweep_table_prom`, and `rpa_energy_table` sections of the calibration files, and the results are in eV (to be converted here in keV). In fact these tables give the *E/q*, where *q* is the ion charge in electron charge units (*q* = 1 except for He^{++} ions, where *q* = 2).

  Post acceleration is given by the Time-of-Flight post-acceleration voltage *PAC* (in V), in the `post_accel_volt` section of the calibration tables (to be converted here in kV), and the particle charge *q*.

  The total ion energy is thus given by $E = q * (E/q + PAC)$ [2.3]

- *Abs_Eff* : absolute efficiency (one value for the HS side and one value for the LS side), given in the ABSEFF Calibration Files. *Abs_Eff* keeps track of the overall efficiency evolution of the instrument, as a function of time, whereas the M_0 .. M_3 coefficients provide for the anode cross-calibrations, which also evolve as a function of time but in a much slower rate.

2.2 HIA

For HIA, the ion detection efficiency is given by [*Ref. 5*] :

$Eff(PF, E)^{-1} = Norm\_\Theta * Eff(E) * Cheff(\Theta) *[\ 1\ /\ T(E)\ ]$ [2.4]

where :

- *Norm_E* and *Norm_Θ* : Energy and anode normalisation coefficients (one value for the HS side and one value for the LS side), given in the `fitting_param` section of the calibration tables.

- *Eff(E)* : Energy-dependent efficiency term, given by the linear relationship:

  *Eff(E) = A * E + B*, where:

  A, *B* : linear coefficients, (one value for the HS side and one value for the LS side), given in the `fitting_param` section of the calibration tables.

  E : ion energy, in eV, is given in the `anal_k_factor`, `energy_sweep_table`, and `energy_sweep_table_prom` sections of the calibration files.

- *Cheff(Θ)* : Anode - dependent efficiency coefficients, given in the `anode_effic_table` section of the calibration tables (`theta_efficiency` column).

- *T(E)* : MCP energy-dependent efficiency, given by [*Ref. 6, 7*] :

  $T(E) = T_0 + T_1*(E+E_g) + T_2*(E+E_g)^2$ for $E_{j-1} < (E+E_g) < E_j$ [2.5]

  where E and E_g are respectively the ion energy and the acceleration energy due to the MCP bias voltage (both in eV). The T coefficients, E_g and the energy domain boundaries E_j are given in the `MCP_fitting_param` section of the calibration tables.

3 CORRECTION FOR DEAD TIME

The corrected (for detection efficiency) number of counts, C_{cor_eff} , can be further corrected for the instrument dead time effects [e.g. *Ref. 12*].

The simplified formula for dead time correction (which for more accuracy should also take into account the sum of counts accumulated on the previous energy steps, and both the MCP dead-time and the amplifier dead-time effects, *Ref.* [13]), is :

$$C_{cor} = \frac{C_{cor\_eff}}{1 - \frac{\tau}{\Delta t}.C_{cor\_eff}} \quad [3.1]$$

where :

- C_{cor} is the corrected (for dead time and for detection efficiency) number of counts.

- τ is the instrument dead time, given in the `dead_times` section of the calibration tables.

- Δt is the particle accumulation time (cf. section 4, but here limited to one spin).

For CODIF the situation is more complex, due to the combined effect of the start-MCP dead time, the stop-MCP dead time, and, most important, the dead time of the time-of-flight unit: once an ion has triggered a “start” signal, no more ion can be detected until a “stop” signal is detected, within a valid time-of-flight window. Correction for dead time effects is thus not possible without modelling the instrument response, and saturation effects are expected on the data, in the presence of high ion fluxes.

4 CONVERSION TO PARTICLE FLUX

The relationship between the corrected number of counts C_{cor} and the (differential) particle flux F is given by:

$$F\ (\mathrm{cm^{-2}\ s^{-1}\ sr^{-1}\ keV^{-1}}) = \frac{C_{cor}}{G\ (\mathrm{cm^2\ sr}) \cdot \Delta t\ (\mathrm{s}) \cdot \Delta E\ (\mathrm{keV})} \quad [4.1]$$

or:

$$F\ (\mathrm{cm^{-2}\ s^{-1}\ sr^{-1}\ keV^{-1}}) = \frac{C_{cor}}{G\ (\mathrm{cm^2\ sr}) \cdot \Delta t\ (\mathrm{s}) \cdot E(\mathrm{keV}) \cdot \Delta E / E\ (\mathrm{keV/keV})}$$

or:

$$F\ (\mathrm{cm^{-2}\ s^{-1}\ sr^{-1}\ keV^{-1}}) = \frac{C_{cor}}{g_E\ (\mathrm{cm^2\ sr\ keV/keV}) \cdot \Delta t\ (\mathrm{s}) \cdot E(\mathrm{keV})} \quad [4.2]$$

where:

- G : geometric factor (for the given anode), in cm^2 sr. If the data product is summed over several anodes, then G is the sum of the geometric factors of the corresponding anodes.
- g_E : energy-independent geometric factor (for the given anode), in cm^2 sr keV keV^{-1}. It includes the instrument energy resolution $\Delta E/E$. If the data product is summed over several anodes, then g_E is the sum of the geometric factors of the corresponding anodes. g_E is given in the `geom_factor` section of the calibration tables. Note that $\Delta E/E$ is a constant for an electrostatic analyser (independent of energy).
- E : average ion energy (in keV) of the energy steps for the given data counter. Values calculated from the energy tables in the calibration files (results to be converted in keV from eV). The data counter actually includes ions detected in the [$E-\Delta E/2$, $E+\Delta E/2$] energy bin.

- Δt : accumulation time, given by

$$\Delta t\,(\mathrm{s}) = \frac{N_{spins} * P_{spin}(\mathrm{s})}{N_{\phi} * N_{E}} \qquad [4.3]$$

where :

N_{spins} is the number of spins over which the data product was accumulated, and is given in the `accumulation_spin_table` section of the calibration tables.

P_{spin} is the spin period (in sec.), and is given (in msec) in the data record headers of the Level 1 files [*Ref. 2*].

N_{ϕ} is the number of azimuths (Energy sweeps) per spin, for the data product. The value of N_{ϕ} is specific to each data product [*Ref. 8, 9, 10*]. For solid angles near the polar directions (elevation $|\theta| > 45°$, depending on the data product), where adjacent solid angles might have been binned together [*Ref. 11*] :

For CODIF:

The counts of the adjacent solid angles have just been summed together [*Ref. 8*]. For these polar directions N_{ϕ} must thus be divided by the number of elementary solid angles binned together.

For HIA:

Initially the counts of the adjacent solid angles have been averaged onboard [*Ref. 9*]. N_{ϕ}, in this case, remains unchanged with respect to the non-binned solid angles of the same data product.

On the 24 April 2001 (DOY 114) a modification has been performed on the onboard software, and starting from this day the adjacent polar solid angles are summed together, in the 3D-88 angle TM products. For these TM products and for these polar directions N_{ϕ} must thus be divided by the number of elementary solid angles binned together. This modification is effective from:

s/c # 1 : Year 2001 DOY 114 10:40 UT
s/c # 3 : Year 2001 DOY 114 14:30 UT

N_E is the number of energy steps per sweep, for the data product, including “dead” steps (i.e. those used for the electrostatic analyser high voltage flyback). The following table thus applies:

Number of energy steps in the data product	N_E
62	64
31	32
16	16 [32 for the lowest energy step E_{15}, E_0 being the highest energy step]
8	8 [8×(4/3) for the lowest energy step E_7, E_0 being the highest energy step]

5 CONVERSION TO PARTICLE ENERGY FLUX

The relationship between the corrected number of counts C_{cor} and the particle energy flux F_E is given by:

$$F_E\ (\text{keV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{keV}^{-1}) = \frac{C_{cor} \cdot E(\text{keV})}{G\ (\text{cm}^2\ \text{sr}) \cdot \Delta t\ (s) \cdot \Delta E\ (\text{keV})} \qquad [5.1]$$

or:

$$F_E\ (\text{keV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{keV}^{-1}) = \frac{C_{cor} \cdot E(\text{keV})}{g_E\ (\text{cm}^2\ \text{sr keV/keV}) \cdot \Delta t\ (\text{s}) \cdot E(\text{keV})}$$

or:

$$F_E\ (\text{keV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{keV}^{-1}) = \frac{C_{cor}}{g_E\ (\text{cm}^2\ \text{sr keV/keV}) \cdot \Delta t\ (\text{s})} \qquad [5.2]$$

Particle energy flux is thus directly proportional to the (corrected) counting rate.

6 CONVERSION TO PHASE SPACE DENSITY

The relationship between the corrected number of counts C_{cor} and the distribution function phase space density *fdist* (also called velocity distribution function) is given by [e.g. *Ref. 14*]:

$$fdist = \frac{C_{cor}}{g_v \cdot v^4 \cdot \Delta t} \qquad [6.1]$$

where :

v (or v_i) : average particle velocity for the given energy bin E_i ; since $E_i = \frac{1}{2} m v_i^2 \rightarrow v_i^2 = 2E_i / m$,

m being the ion mass.

g_v : velocity geometric factor (for the given anode). It includes the instrument velocity resolution $\Delta v/v$. Since $E \propto v^2 \rightarrow \Delta E/E = 2\, \Delta v/v \rightarrow$

$$g_E = 2\, g_v \quad [6.2]$$

Equation [6.1] thus becomes :

$$fdist = \frac{C_{cor}}{0.5 g_E \cdot \frac{4E_i^2}{m^2} \cdot \Delta t} = \frac{C_{cor} \cdot m^2}{2 g_E \cdot E_i^2 \cdot \Delta t} \quad [6.3]$$

Given [5.2], [6.3] becomes:

$$fdist = F_E \cdot \frac{m^2}{2E_i^2} \quad [6.4]$$

or:

$$fdist\ (s^3\ km^{-6}) = F_E\ (keV\ cm^{-2}\ s^{-1}\ sr^{-1}\ keV^{-1})\ \frac{(N_m \cdot 1.6726 \cdot 10^{-27} (kg))^2}{2(E_i(eV) \cdot 1.6022 \cdot 10^{-19} (J/eV))^2} \cdot 10^{22}\ (cm^2/m^2\ m^6/km^6)$$

[6.5]

N_m being the ion atomic mass number (1 for protons).

7 MOMENTS CALCULATION

7.1 Density

Ion density n is the zero-order moment of the 3D ion distribution function [e.g. *Ref. 15*], given by:

$n = \iiint fdist(v)\, d^3v$, v : ion velocity

From [6.1], and taking into account the finite angular and velocity resolution of the instrument, this becomes:

$$n = \sum_i \frac{\Delta v_i}{g_v \cdot v_i^4} \sum_j v_i \cdot \Delta\phi_j \sum_k \cos\theta_k \cdot v_i \cdot \Delta\theta_k \frac{C_{cor}}{\Delta t}$$

or in practice, and considering equally sized angular bins:

$$n = \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \frac{\Delta v_i}{v_i^2} \sum_j \sum_k \cos\theta_k \cdot \frac{C_{cor}}{\Delta t} \qquad [7.1]$$

or, from [6.2] :

$$n\ (\text{cm}^{-3}) = \frac{\Delta\phi(\text{rad}) \cdot \Delta\theta(\text{rad})}{0.5 g_E(\text{cm}^2\text{sr keV/keV})} \cdot \sum_i \frac{\Delta v_i}{v_i^2} \frac{1}{(\text{cm/s})} \sum_j \sum_k \cos\theta_k \cdot \frac{C_{cor}}{\Delta t(\text{s})} \qquad [7.2]$$

where:

$\Delta\phi$ and $\Delta\theta$: azimuth and elevation size (in rad) of each elementary solid angle in the phase space, corresponding to the C_{cor} measurement.

θ_k : average elevation of detection anode k.

j : azimuth index.

v_i : average particle velocity (in cm/s) for energy bin i :

$$E_i = \frac{1}{2} m\, v_i^2 \rightarrow v_i = \sqrt{\frac{2E_i}{m}}\text{, or}$$

$$v_i\ (\text{cm/s}) = \sqrt{\frac{2E_i(\text{eV}) \cdot 1.6022 \cdot 10^{-19}(\text{J/eV})}{N_m \cdot 1.6726 \cdot 10^{-27}(\text{kg})}} \times 100\ \text{cm/m}$$

Δv_i : size in phase space (in cm/s) for particles detected in energy bin i ($\Delta v_i = v_{max\,i} - v_{min\,i}$).

Note 1 : Density calculation results are sensitive to the accuracy of g_E and to the accuracy of corrections for detection efficiencies. They are also sensitive to eventual detector saturation in the presence of high ion fluxes (dead time effects).

Note 2 : The density calculated here in reality is the ion partial density in the energy domain covered by the instrument, typically 25 eV/q to 40 keV/q for CODIF and 5 eV/q to 32 keV/q for HIA. In the presence of cold plasma at energies below the instrument energy threshold, or of hot plasma at energies above the instrument upper energy limit, this partial density evidently is lower than the total plasma density.

Note 3 : The instrument energy domain is always defined with respect to the spacecraft potential. Spacecraft charging to a positive floating potential, as can be the case in low density plasmas when the ASPOC ion emitter for spacecraft potential control is not operating, repels the low-energy ions which in these cases cannot be detected by CIS [*Ref. 1*, *16*]. This effect results in a further increase of the difference between the partial density, measured by CIS, and the total density.

Note 4 : Eventual instrument background counts due to penetrating particles, from the radiation belts around perigee passes or during SEP (Solar Energetic Particles) events, can result in an overestimation of the density calculated here.

Note 5 : The entire velocity phase space, corresponding to the instrument energy domain, is not covered during all modes. This can be the case during solar wind modes, and some magnetosheath modes, where the summations in equations [7.1] and [7.2] are limited by the instrument operation to a subset of the phase space, in velocity and in solid angle coverage [cf. *Ref. 1* and http://cluster.cesr.fr:8000/ - link to "Caveats"].

7.2 Velocity

Ion bulk velocity vector $\underline{V}$ is the first order moment of the 3D ion distribution function, given by:

$$\underline{V} = \frac{1}{n} \iiint \underline{v}\, fdist(v)\, d^3v$$

or in practice:

$$V_x = \frac{1}{n} \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \frac{\Delta v_i}{v_i} \sum_j \cos\phi_j \sum_k \cos^2\theta_k \cdot \frac{C_{cor}}{\Delta t}$$

$$V_y = \frac{1}{n} \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \frac{\Delta v_i}{v_i} \sum_j \sin\phi_j \sum_k \cos^2\theta_k \cdot \frac{C_{cor}}{\Delta t}$$

$$V_z = \frac{1}{n} \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \frac{\Delta v_i}{v_i} \sum_j \sum_k \sin\theta_k \cdot \cos\theta_k \cdot \frac{C_{cor}}{\Delta t} \qquad [7.3]$$

which gives :

$$V_x\,(\mathrm{cm/s}) = \frac{1}{n(\mathrm{cm}^{-3})} \frac{\Delta\phi(\mathrm{rad}) \cdot \Delta\theta(\mathrm{rad})}{0.5 g_E(\mathrm{cm^2 sr\ kev/keV})} \cdot \sum_i \frac{\Delta v_i}{v_i} \sum_j \cos\phi_j \sum_k \cos^2\theta_k \cdot \frac{C_{cor}}{\Delta t(\mathrm{s})}$$

V_y (cm/s) = …, V_z (cm/s) = ... [7.4]

Note 1 : The plasma bulk velocity components in eq. [7.3] and [7.4] are given in the same reference frame as the 3D ion distribution function: the instrument-build system in the CIS Level-1 data files, or in pseudo-GSE in the CIS Level-3 data files delivered for archival to the CAA (http://caa.estec.esa.int/caa/): *X* sunward, *Z* is the spacecraft axis and northward pointing. A coordinate transformation is then necessary to transform these vector components to the GSE system [*Ref. 17*], or to any other system.

Note 2 : Bulk velocity results are independent of the accuracy of g_E, and of the accuracy of the absolute efficiency values, due to the division by *n* (which includes 1/ g_E, and cancels g_E from the denominator in equation [7.4]). Results error bars, however, are sensitive to counting statistics.

Note 3 : The V_z term is very sensitive to the anode cross-calibrations, and in particular to those of the anodes looking in directions away from the spacecraft spin plane (high absolute values of $\sin\theta_k$: polar anodes). In some cases the efficiency calibration coefficients cannot completely compensate for strongly asymmetrically decreased efficiencies of such polar anodes, which results in a residual offset of V_z (e.g. case of CODIF onboard Cluster-sc3).

Note 4 : The spacecraft orbital velocity $\underline{v_{sc}}$ has here been assumed to be negligible. For more accurate calculations, however, velocity composition between $\underline{V}$ and $\underline{v_{sc}}$ might have to be considered.

7.3 Pressure

Ion pressure tensor ***P*** is the second order moment of the 3D ion distribution function, given (in the plasma centre of mass reference frame) by :

$$\boldsymbol{P} = m \iiint (\underline{v}-\underline{V}) \cdot (\underline{v}-\underline{V})\, fdist(v)\, d^3v \qquad [7.5]$$

or

$$\boldsymbol{P} = m\,[\boldsymbol{M} - n\,\underline{V}\cdot\underline{V}] \qquad [7.6]$$

where ***M*** is the tensor in the measurement reference frame:

$$\boldsymbol{M} = \iiint \underline{v}\cdot\underline{v}\, fdist(v)\, d^3v \qquad [7.7]$$

In practice:

$$M_{xx} = \frac{\Delta\phi\cdot\Delta\theta}{g_v}\cdot\sum_i \Delta v_i \sum_j \cos^2\phi_j \sum_k \cos^3\theta_k \cdot \frac{C_{cor}}{\Delta t}$$

$$M_{yy} = \frac{\Delta\phi\cdot\Delta\theta}{g_v}\cdot\sum_i \Delta v_i \sum_j \sin^2\phi_j \sum_k \cos^3\theta_k \cdot \frac{C_{cor}}{\Delta t}$$

$M_{zz} = \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \Delta v_i \sum_j \sum_k \sin^2\theta_k \cos\theta_k \cdot \frac{C_{cor}}{\Delta t}$

$M_{xy} = \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \Delta v_i \sum_j \sin\phi_j \cos\phi_j \sum_k \cos^3\theta_k \cdot \frac{C_{cor}}{\Delta t}$

$M_{yz} = \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \Delta v_i \sum_j \sin\ \phi_j \sum_k \sin\theta_k \cos^2\theta_k \cdot \frac{C_{cor}}{\Delta t}$

$M_{xz} = \frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \Delta v_i \sum_j \cos\phi_j \sum_k \sin\theta_k \cos^2\theta_k \cdot \frac{C_{cor}}{\Delta t}$ [7.8]

From [7.6] and [7.8] the pressure tensor elements, in the plasma centre of mass reference frame, are:

$P_{xx} = m \cdot \left[\frac{\Delta\phi \cdot \Delta\theta}{g_v} \cdot \sum_i \Delta v_i \sum_j \cos^2\phi_j \sum_k \cos^3\theta_k \cdot \frac{C_{cor}}{\Delta t} - n \cdot V_x \cdot V_x \right]$

$P_{yy} = \ldots$ [7.9]

which gives :

P_{xx} (nPa) = $N_m \cdot 1.6726 \cdot 10^{-24}$(g) ·

$\left[\frac{\Delta\phi(\text{rad}) \cdot \Delta\theta(\text{rad})}{0.5 g_E(\text{cm}^2\text{sr kev/keV})} \cdot \sum_i \Delta v_i(\text{cm/s}) \sum_j \cos^2\phi_j \sum_k \cos^3\theta_k \cdot \frac{C_{cor}}{\Delta t(\text{s})} - n\,(\text{cm}^{-3}) \cdot V_x \cdot V_x\,(\text{cm/s})^2 \right] \cdot 10^8$

(nPa/(dyn cm^{-2}))

P_{yy} (nPa) = … [7.10]

The pressure tensor

$$\mathbf{P} = \begin{matrix} P_{xx} & P_{xy} & P_{xz} \\ P_{yx} & P_{yy} & P_{yz} \\ P_{zx} & P_{zy} & P_{zz} \end{matrix}$$

can then be diagonalised, which for gyrotropic plasmas (distributions isotropic in the planes perpendicular to the magnetic field direction) gives:

$$\mathbf{P'} = \begin{matrix} P_{xx}' & 0 & 0 \\ 0 & P_{yy}' & 0 \\ 0 & 0 & P_{zz}' \end{matrix} \qquad [7.11]$$

For non gyrotropic plasmas there are non-zero off-diagonal terms in [7.11], which can indicate the presence of shear stresses in the plasma.

Note 1 : Non-zero off-diagonal terms can also result from anode cross-calibration effects (cf. note on Vz, in section 7.2).

Note 2 : Alternatively, the ***P'*** tensor can be obtained from the ***P*** tensor not by diagonalising it, but by performing a rotation operation from the initial reference system (instrument-build or pseudo-GSE, cf. note in section 7.2) to a system where its *Z* axis is aligned to the magnetic field direction.

7.4 Temperature

The temperature tensor ***T*** (or ***T'***) is obtained from the pressure tensor ***P*** (or ***P'***) from the equation of state:

$$\mathbf{P'} = n \cdot k \cdot \mathbf{T'} \qquad [7.12]$$

where k is the Boltzmann's constant: $k = 1.380622 \times 10^{-23}$ J K^{-1}.

For each of the components of the temperature tensor we thus have:

$$T_{xx}'(\mathrm{K}) = \frac{P'_{xx}(\mathrm{Pa})}{n(\mathrm{m}^{-3}) \cdot k} \rightarrow T_{xx}'(\mathrm{MK}) = \frac{P'_{xx}(\mathrm{nPa}) \cdot 10^{-9}(\mathrm{Pa/nPa}) \cdot 10^{-6}(\mathrm{MK/K})}{n(\mathrm{cm}^{-3}) \cdot 10^{6}(\mathrm{cm}^3/\mathrm{m}^3) \cdot 1.380622 \times 10^{-23}(\mathrm{J/K})} \rightarrow$$

$$T_{xx}'(\mathrm{MK}) = \frac{P'_{xx}(\mathrm{nPa}) \cdot 10^{2}}{n(\mathrm{cm}^{-3}) \cdot 1.380622}, \qquad T_{yy}'(\mathrm{MK}) = \ldots \qquad [7.13]$$

One can then define a scalar temperature :

$$T = \frac{T_{xx}' + T_{yy}' + T_{zz}'}{3} \qquad [7.14]$$

and a parallel T_{par} and perpendicular T_{perp} to the magnetic field temperature :

$$T_{par} = T'_{zz}, \qquad T_{perp} = \frac{T_{xx}' + T_{yy}'}{2} \qquad [7.15]$$

assuming the *Z* axis of the ***T'*** (or ***P'***) tensor corresponds to the magnetic field direction.

Expressing the temperature not in temperature units (K or MK) but in energy units (eV) actually gives the average ion energy in the distribution :

T (eV) = T (K) · $\frac{1.380622 \times 10^{-23}\,(\mathrm{J/K})}{1.6022 \cdot 10^{-19}\,(\mathrm{J/eV})} \cdot \frac{3}{2}$ → T (eV) = 1.2925559 x 10^{-4} · T (K)

or T (eV) = 1.2925559 x 10^{2} · T (MK) [7.16]

The factor 3/2 corresponds to the 1/2 $k\,T$ average particle energy per degree of freedom, multiplied by the three degrees of freedom for the movement of each particle in the 3D space.