ARCHIVING OF THE CLUSTER EDI DATA

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ABSTRACT

The Electron Drift Instrument (EDI) contribution to the Cluster Active Archive (CAA) is described. Data products, ingestion schedule and current status are presented.

1. INTRODUCTION

The EDI contribution to the CAA is completely described by the **I**nterface **C**ontrol **D**ocument (ICD). This paper presents the, for the user of the archive, most interesting aspects of this document.

Data products and documentation are going to be archived. The data range from complete set of raw data to auxiliary and final products. Documentation refers as well to the already mentioned ICD, as well as to the instrument user manual, instrument reference papers and software scripts. The ICD contains, in addition to the description of the convention on data formats, metadata and delivery to the archive, a section on instrument description, dealing with the scientific objectives of the EDI experiment, a hardware overview, and the description of the data processing chain and of the data products. The latter will be outlined in the following.

2. EXPERIMENT OVERVIEW

2.1 Principle of Operation

The basis of the electron-drift technique is the injection of weak beams of electrons and their detection after one or more gyrations in the ambient magnetic field. In the presence of a drift velocity $\mathbf{V}_d$, induced by an electric field $\mathbf{E}_\perp$ or a magnetic-field gradient $\nabla \mathbf{B}_\perp$, the circular electron orbits are distorted into cycloids. Their shape depends on whether the beam is injected with a component parallel or anti-parallel to the drift velocity. To be able to realize both types of orbits simultaneously, EDI uses two guns and two detectors. Fig.1 shows examples of these two orbits in the plane perpendicular to **B**, which we refer to as the $\mathbf{B}_\perp$ - plane. For each gun only one orbit-solution exists that connects it with the detector on the opposite side of the spacecraft. Knowledge of the positions of the guns, and of the firing directions that cause the beams to hit their detectors, uniquely determines the drift velocity. This is the basis of the triangulation technique. Through triangulation, one directly determines the 'drift-step' vector **d**, which is the displacement of the electrons after a gyro time T_g :

$$\mathbf{d} = \mathbf{V}_d T_g \quad (1)$$

The location in the $\mathbf{B}_\perp$ - plane, from which electrons reach the detector after one gyration, can be viewed as the 'target' for the electron beams.

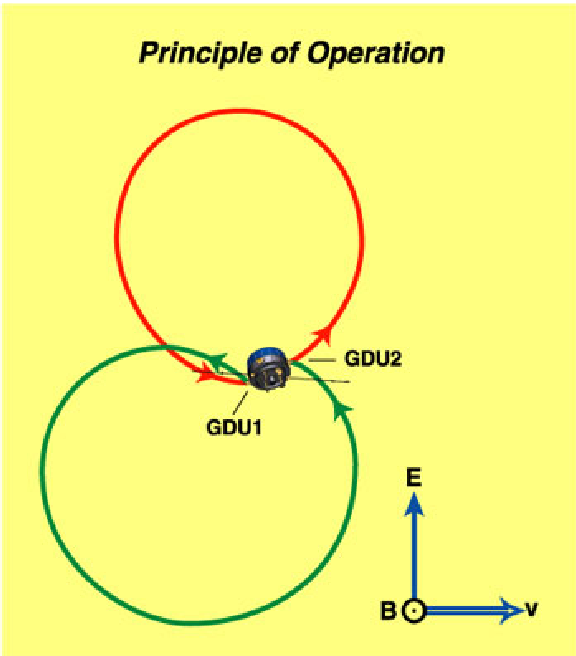

Fig.1. Principle of operation for EDI

As is evident from Fig.1, the two orbits differ in their length, and thus in the electron travel times. The electrons emitted with their velocity directed with a component parallel to V_d, i.e. away from the target, have a time of flight that is shorter than T_g while the electrons emitted towards the target have a time of flight that is longer than T_g:

$$T_{1,2} = T_g (1 \pm V_d/V_e) \quad (2)$$

where V_e is the electron velocity. From Eq. (2) it follows immediately that the difference between the two times-of-flight provides a measure of the drift velocity, V_d

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$$\Delta T = T_1 - T_2 = 2\,(V_d / V_e)\,T_g = 2\,(d / V_e) \qquad (3)$$

while their sum is twice the gyro time:

$$T_1 + T_2 = 2\,T_g \qquad (4)$$

Noting that $T_g = 2\pi m_e / eB$, this means that the time-of-flight measurements allow B to be determined as well. Drift velocities encountered on a Cluster orbit typically range from a few km/s to less than 1000 km/s, while the velocity of 1 keV electrons is 18728 km/s. According to Eq. (3), this implies that ΔT is only a small fraction of T_g, i.e., the drift introduces only a small variation in the two orbits and the associated times-of-flight. To make the difference visible, Fig 1 is drawn for unrealistically large magnetic and electric fields.

The triangulation and time-of-flight techniques complement each other ideally. While triangulation naturally becomes increasingly inaccurate if the target moves further and further away, the time-of-flight technique becomes more accurate because, according to Eq. (3), increases with increasing drift steps, and thus becomes easier to measure.

Under the assumption that the $\nabla \mathbf{B}_\perp$-drift can be ignored, the electric field can be computed according to:

$$\mathbf{E}_\perp \cong -\mathbf{V}_d \times \mathbf{B} \qquad (5)$$

So far we have tacitly assumed that the beam electrons are detected after a single gyration. Electrons that have gyrated N times will have a drift step and ΔT that is N times larger. Electrons having gyrated several times ('multi-runners') are indeed observed. We refer to N as the multi-runner order.

2.2 Implementation

Gun-Detector Characteristics

EDI consists of two gun-detector units (GDUs) and a controller unit. The GDUs are mounted on opposite sides of the spacecraft and have oppositely directed fields of view. The guns are capable of firing in any direction within more than a hemisphere (0-96° polar angle) to accommodate arbitrary magnetic and electric field directions. Similarly, the detectors can detect beams coming from any selectable direction within more than a hemisphere (0-100° polar angle). Beams have an angular width of approximately 1° at small polar emission angles, increasing to 4-by-1° at large polar angles. Electron energies can be switched between 0.5 keV and 1.0 keV. Separate calibration tables for the two energies are used to convert beam firing directions into the corresponding deflection voltages.

The flux-density of the returning electrons is proportional to $I_b B^3 / E$ (except when the drift step is small). To accommodate the large variations in B and E along the Cluster orbit, the beam currents, I_b, can be changed over more than two orders of magnitude (from 1 nA to several hundred nA). Beam currents are initialized based on the ambient magnetic field strength and then varied automatically based on the tracking success. Similarly, by using different combinations of high-voltages for the detector optics, a large variety of effective aperture areas A, and geometric factors G, can be realized. A and G determine the sensitivity to beam and background electrons, respectively. By choosing the right combination of G and A, adequate signal and signal-to-noise-ratio (SNR) levels can be maintained over a wide range of field strengths and background electron fluxes. Tables of the optics voltages that achieve specific combinations of G and A are referred to as 'Optics States'. The automatic Optics-State navigation is based on measured flux levels and magnetic field strength. See [1] and [2] for more details.

Time-of-Flight Measurements

In order to measure the electron times-of-flight, as well as to distinguish beam electrons from the background of ambient electrons, the electron beams are amplitude-modulated with a pseudo-noise (PN) code. Briefly, a set of 15 correlators analyzes the phasing of the detector counts relative to the beam code. Before beam acquisition has been achieved, all correlators will show the same counts (to within Poisson statistics) from the ambient electron background. Once the beam is acquired ('angle-track'), the correlator whose delay matches the electron flight-time will have the maximum number of counts. A delay-lock-loop continuously shifts the code-phases of the correlators to keep the maximum centred in a specific channel ('time-track'). By keeping track of the net change in code-phase, one obtains a measure of the changes in time-of-flight.

Commensurate with the number of correlators, EDI employs primarily a 15-chip code. This way the signal is recorded in one of the correlators regardless of the actual time-of-flight. But because the accuracy is related to the chip-length, T_{chip}, the code-duration is kept short, much shorter than T_g. The electron time of- flight is therefore equal to an integer number of code-lengths plus a fraction, of which only the fraction is measured by the correlators directly. However, by choosing a code-length equal to $T_g/5$ or $T_g/10$, where Tg is estimated from the on-board FGM data, the number of complete wrap-arounds of the code can be recovered unambiguously. To track small time-of-flight variations, the code is shifted with a resolution of typically $T_{chip}/32$. Simulations of the correlator performance indicate that the accuracy of individual time-of-flight measurements is about $T_{chip}/8$. To account for the large variations in T_g

along the Cluster orbit, the code-length can be varied between approximately 15 µs and 2ms.

A problem with the short code is that it does not discriminate against multi-runners. Regardless of how many times the electrons have gyrated before hitting the detector, the signal will appear in one of the 15 correlators. We therefore have introduced a second, much longer code. It has 127 chips, and its length can exceed 4 T_g. By placing the 15 correlators at a time-delay near T_g, only single-runners are detected (unless runners of order 5 or higher are present as well). As the increased chip-length implies lower accuracy in time-of-flight measurements, the long code is only used in strong (100 nT) fields where multi-runners most frequently occur.

Beam Acquisition and Tracking

To find the beam directions that will hit the detector, EDI sweeps each beam in the plane perpendicular to **B** at a fixed angular rate (typically 0.2°/ms) until a signal has been acquired by the detector. Once signal has been acquired, the beams are swept back and forth to stay on target. Beam detection is not determined from the changes in the count-rates directly, but from the square of the beam counts divided by the background counts from ambient electrons, i.e., from the square of the *instantaneous* signal-to-noise-ratio. The basic software loop that controls EDI operations is executed every 4ms. As the times when the beams hit their detectors are neither synchronized with the telemetry nor equidistant, **EDI does not have a fixed time-resolution**.

On-board Magnetic Field Data Handling

EDI searches for the drift-step target in the plane perpendicular to **B**, and therefore needs information on the local instantaneous field as frequently as possible. Flux-gate magnetometer data are available on board over the inter-experiment-link (IEL) with the FGM instrument. These data must firstly be time-tagged, because FGM sampling is not synchronized to the spacecraft clock, and then corrected for calibration angles, sensitivities, and offsets, and finally rotated by 6.5° to the spacecraft body axes. As the FGM data are available over the IEL only 16 times per second, the EDI controller constructs the field at higher frequencies using the analog signals from the three axes of the search-coil data provided by the STAFF instrument also over the IEL. To first order, the search coil signal is integrated and added periodically to the FGM values, after rotations that account for the different coordinate systems of the two magnetometers. An accuracy of better than 0.5 degree in the direction of **B** is required because the width of the beam is about 1°. Naturally, this poses stringent requirements on the calibration of the magnetometer data, as reconstructed by EDI from both the FGM and STAFF information, as described above. Errors of order 1 nT are of no concern to EDI if the total field is sufficiently large. However, for fields of 50 nT or less, beam-pointing errors can become larger than the beam width, causing loss of track if the error moves the beam off of the $\mathbf{B}_\perp$ plane. The EDI controller must maintain this accuracy throughout four operational ranges of the FGM data, and this requires constant updates of the four calibration matrices, and four sets of offsets for each axis. As an overall constraint on these numbers, the magnitude of the field is determined by time-of-flight information whenever there are beam hits. As a starting point, the spin-axis offset is adjusted to be consistent with this magnitude. Furthermore, the plane perpendicular to **B** is determined by the continual series of gun vectors that are successful. But as the beam-width is about one degree, and the tracking algorithm is able to keep the gun pointing only to within about 0.5 degrees of perpendicular to the varying **B** field, this information must be compiled statistically and used to correct the supplied calibration matrices for accuracy in the EDI coordinate system. This process is iterated by ground processing, and then uplinked to the controller, to improve the success rate of beam hits.

Ambient Electron Monitoring

When the electron beams are off, the EDI detectors allow for ambient electron measurements with very high sensitivity and time resolution, albeit at fixed energies of 0.5 or 1.0 keV. In this mode the two detectors which are facing opposite hemispheres are looking strictly into opposite directions. Either both detectors are looking in the plane perpendicular to **B** (pitch angle of 90º), or one detector is looking along **B** while the other is looking antiparallel to **B** (pitch angles of 0º and 180º). When looking in the plane perpendicular to **B** the two directions within the plane are determined by the cross product of the magnetic field vector **B** with a selectable but fixed vector **P** that is constant in the spinning instrument frame of reference. When looking parallel/antiparallell to **B** the two detectors switch roles every half spin of the spacecraft as the tip of the **B** vector spins outside the field of view of one detector and into the field of view of the other detector.

In nominal telemetry mode (NM) there are 16 counts samples per detector and per second. Each sample is accumulated over approximately 16 ms (1/64 seconds). In Burst mode (BM1) there are 128 counts samples per detector and per second, and the accumulation time is approximately 8 ms (1/128 seconds). Counts are accumulated synchronously by the two detectors and each counts sample pair is stored in telemetry with its corresponding look direction, expressed in spinning instrument coordinates (azimuth and polar angle). As the two look directions are antiparallel only one set of angles needs to be transmitted. As the spacecraft is spinning the look directions need to be maintained in order to point at a fixed pitch angle. The look directions reported in telemetry correspond to those used at the center of the respective sample accumulation time window.

AED are produced by the US CoI 's and are contingent on NASA support. The agreement is that data starting Oct 2004 will be delivered for ingestion in the CAA, since, until then, the detectors configuration for ambient operations and the calibration procedures were evolving continuously.

2.3 Operations and Limitations

The complex nature of the EDI operations and data processing has meant a long learning curve before the many control parameters, beam-recognition algorithms, and magnetometer calibrations had been adjusted sufficiently well that the instrument began to operate successfully under a wide range of ambient conditions. Still, when the magnetic field magnitude gets really low, and/or the background electron fluxes get high, tracking becomes difficult.

Low **B** magnitudes require high beam currents to overcome the beam divergence along large gyro orbits, and to get sufficient signal-to-background ratio. But large beam currents, in conjunction with the beam-modulation and –coding, lead to interference with the electric wave measurements by the WHISPER instrument. Moreover, the smaller B gets, the higher the requirement for very precise on-board magnetometer calibrations. Last but not least, rapid time-variations in magnetic and/or electric fields, as well as large fluxes of background electrons can also cause loss of track.

Because of the noted interference with the WHISPER measurements, EDI beam operations has been subject to a 6-orbit cycle, where high beam currents (up to 300 nA) were allowed in only two out of six orbits, while currents were limited to about 100 nA in another orbit and no beam operation was allowed outside 4 hours of perigee in the remaining three orbits.

3. DATA PROCESSING CHAIN

The data processing chain consists of **onboard, ground** and **science processing**. The onboard processing writes to telemetry the measured quantities and instrument parameters. The telemetry data: housekeeping (HK TM), science normal mode (NM TM) and science burst mode (BM TM), after having a DDS-header attached on ground – processing performed in ESOC, are input in the ground processing software.

The ground processing software consists of Merged Science File (MSF) production and the Pick-Library. The first merges the TM-packets and orders them in time and the second extracts the quantities needed by the science processing as input. The output of the science processing consists of time series of physical quantities contained in the science data products. A schematic representation of the data processing chain is given in Fig 2. The software, to be archived (TBA) for documentation only, is represented with white text on green background and the data products white on blue.

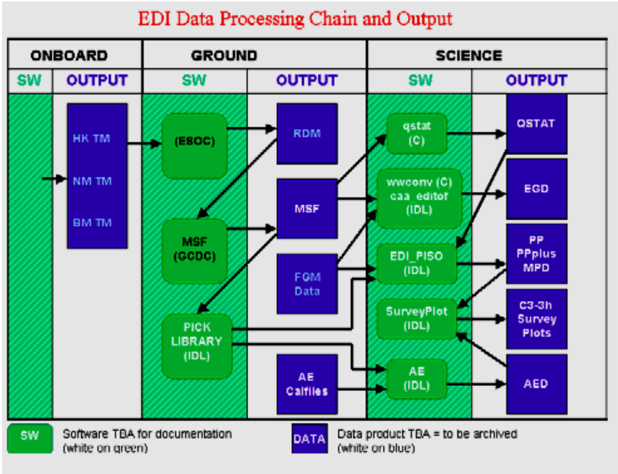

Fig.2. Data processing chain

4. INSTRUMENT DATA PRODUCTS

As we have learned from the instrument description section the EDI operates in two modes an active one, called **WW** (windshield wiper) or EF (electric field), when the electrons emitted by the guns are detected and a passive one, called ambient electron mode (**AE**), when the guns are not emitting. Whenever EDI operates in its active mode the electric field and the drift velocities of the electrons are measured. The data are analysed with 2 techniques: **triangulation** and **time-of-flight**. The technique which gives better results based on some error criteria produces the **winners**, the other the **losers**. All results are assigned a **quality** flag (**good/caution/bad**).

The data products, their acronyms, resolutions, formats are summarized in Table 1. Beside the main data products raw and auxiliary data products are being archived.

Raw data consisting of merged science files (MSF) are obtained by merging the housekeeping and science (burst (BM) and normal (NM) mode) telemetry files. They are in binary format and are input for the pick library that is used by all science processing programs.

Auxiliary are either data used internally by the main data production software (QSTAT and AECalf) or data dedicated to intercalibration (EGD) or timeinterval lists of the EDI operation modes (CLIST).

Table 1. EDI data products in the CAA

NR	CAA acronym	Format	Data Type	Name, content, time resolution, quality
1	**PP**	CDF	MAIN	**P**rime **P**arameter Electric Field, Drift Velocity, status, errors Winners with good/caution quality Spin resolution, time range = 1 day
2	**PPP**	CDF	MAIN	**P**rime **P**arameter **plus** Electric Field, Drift Velocity, status and errors – spin resolution, Winners+losers with good/caution/bad quality, daily file
3	**MPD**	CDF	MAIN	**M**erged **P**arameter **D**ata Electric Field, Drift Velocity, status and errors, 1-4 s resolution, Winners with good/caution/bad quality, daily file
4	**AED**	CDF	MAIN	**A**mbient **E**lectron **D**ata Relative electron fluxes at 0, 90, 180 degrees pitch angles – high resolution, time range = 1 day
5	**3hSPLOT**	PNG	MAIN (GRAPHICS)	**3-h**ourly **S**urvey **plot**s of MPD, AED and CLIST parameters for one spacecraft (usually C3), time range = 3 h
6	**EGD**	CEF	Auxiliary	**E**lectron **G**yrotime **D**ata Electron time-of-flight, error and GDU High resolution, time range = 1 day
7	**QSTAT**	ASCII	Auxiliary	**Q**uality **STAT**istics EDI detection efficiency (beam tracking performance) 10 min resolution, time range = 1 day
8	**CLIST**	CEF	Auxiliary	**C**aveat **List** List of time intervals of WW & AE operation modes Time range = 1 month
9	**AECalf**	ASCII	Auxiliary	**AE C**alibration **f**iles Used to convert raw data counts to relative particle fluxes
10	**MSF**	Binary	RAW	**M**erged **S**cience **F**iles Merged HK+NM+BM telemetry files, time range = 1 day

QSTAT contains a table of 24 rows (for each hour of the day) and 6 columns (for each 10 minutes of an hour) with detection efficiencies. The detection efficiency is defined as the percentage of the number of spin periods with at least 4 successful measurements per spin to the total number of spin periods.

AECalf (ambient electron calibration file) are used to transform particle counts into relative particle fluxes, they are to remove look-direction variations in the raw counts that are associated with the detector's effective geometric factor.

CLIST files contain a listing of time intervals with the 2 possible operation modes of EDI: **WW** and **AE**.

The EGD parameters are measurement time_tags with microsecond precision, time-of-flight (TOF) and its error (sigma_TOF) in microseconds, and the label of the used detector unit (DU).

An example of use of the EDI CAA auxiliary data is given in [3], where the QSTAT and EGD datasets are used to check and improve the calibration of the flux-gate magnetometer (FGM).

Main data products contain

- for the **WW** mode: time series of the 3 components of the electron drift velocity and of the 3 components of the electric field (cartesian components, GSE coordinates, corrected for spacecraft motion) with different qualities and time resolution (PP, PPP, MPD)

- for the **AE** mode: time series of ambient electron counts in the 3 detector looking directions (0º, 90º, 180º), the pitch angles and the status for **AE** mode.

- Graphics = overview plot of the main parameters for every 3 hours for 1 spacecraft.

Table 2. EDI PP (MPD) and PPP parameters

PP file variables (“winners” only)	**PP-Plus file variables**
Epoch	Epoch
Status	Status
V_ed_xyz_gse	V_ed_xyz_gse
E_xyz_gse	E_xyz_gse
Reduced_chi_sq	Reduced_chi_sq
	Drift_step_mag
	Drift_step_mag_error_inertial
	Drift_step_azi_error_inertial
	Nbeam
	Status_loser
	V_ed_xyz_gse_loser
	E_xyz_gse_loser
	Reduced_chi_sq_loser
	Drift_step_mag_loser
	Drift_step_mag_error_inertial_loser
	Drift_step_azi_error_inertial_loser
	Nbeam_loser

Table 2 gives an overview of the WW-mode main data products.

The exact nature and quality of the data is indicated in the 7 EDI status bytes described in detail in [4]. Status[0] byte is the data quality flag as defined for all Cluster experiments, it is: 0, 1, 2 for bad, use with caution and good data. The others define the percentage of 1 keV beams used in entire spin (Status[1]), the percentage of highest quality beams used in entire spin (Status[2]), the chosen “winner” method among Triangulation / Time-of-flight / simultaneous-time-of-flight with the ambiguity flag of the choice (Status[3]), percentage of Triangulation outliers (Status[4]), magnitude percentage error (Status[5]) and azimuthal error in degrees (Status[6]).

The following caveats must be observed:

• the measured electron drift velocity cannot always be separated into the electric-field and magnetic gradient induced parts; in such cases the computed electric fields are subject to contamination by magnetic gradient effects;

• the data quality is variable, and it is therefore mandatory that the status bytes be consulted before interpreting the data;

• the number of samples in the averages is variable.

5. SUMMARY OF EDI CONTRIBUTION

EDI contributes to the Cluster Active Archive with data: raw, auxiliary and main products and documentation. The main data products contain:

- Time series (resolution between 1 and 4 seconds**,** except (c)) of following physical quantities (with their errors) and with different qualities : (a) E = electric field vector in GSE, (b) V = drift velocity vector in GSE, (c) N = high resolution relative ambient electron fluxes at 0, 90 and 180 degrees pitch angles, at fixed energy (0.5 or 1.0keV)

- Graphics: Survey plots of the physical quantities and operation modes for 1 spacecraft with 3 hours time range

The auxiliary data contain time series of:

- EDI detection efficiencies (10 minutes resolution)

- TOF: electron time-of-flight (full resolution, not regularly spaced),

- Listing of instrument operation mode time intervals

- Calibration tables for the AE mode.

The documentation consists of:

- ICD – a complete description of the EDI contribution to the CAA

- Instrument Reference Papers and User Manual

- Program Scripts

EDI data production and delivery (conforming to ICD): the data for 2001 and 2002 is already ingested, production and ingestion of 2003 data to be done in 2005 (8 data products). Data from 2004 and 2005 (10 data products) TBD in 2006 and starting 2007 delivery of 10 data products will follow on a yearly basis.

References

[1] Paschmann G. et al., The Electron Drift Instrument on Cluster: overview of first results, *Annales Geophysicae* (2001) 19: 1273–1288

[2] Quinn, J. M., Cluster EDI convection measurements across the high-latitude plasma sheet boundary at midnight, *Annales Geophysicae* (2001) 19: 1669–1681

[3] Georgescu E. et al., Use of EDI Time-of-Flight Data for FGM Calibration Check on CLUSTER, this volume

[4] “Users Guide to the Cluster Science Data System”, DS–MPA–TN–0015,issue2